Small-scale CMB cosmology
ACT, Planck and beyond

Renée Hlozek
Lyman Spitzer Jr. Postdoctoral Fellow
Spitzer-Cotsen Fellow in the Society of Fellows of the Liberal Arts
TED 2014 Senior Fellow
Princeton University

I'm talking about...

ACT results:

arXiv:1302.1841 arXiv:1301.0824 arXiv:1301.0776 arXiv:1301.1037

and

arXiv.org > astro-ph > arXiv:1312.3313

Astrophysics > Cosmology and Extragalactic Astrophysics

Planck Data Reconsidered

David Spergel, Raphael Flauger, Renee Hlozek

(Submitted on 11 Dec 2013)

Please ask me about other work too!

arXiv.org > astro-ph > arXiv:1312.2593

Astrophysics > Cosmology and Extragalactic Astrophysics

A Tale of Two Redshifts

Bruce A. Bassett, Yabebal Fantaye, Renée Hložek, Cristiano Sabiu, Mat Smith

(Submitted on 9 Dec 2013)

arXiv.org > astro-ph > arXiv:1303.3008

Astrophysics > Cosmology and Extragalactic Astrophysics

Axiverse cosmology and the energy scale of inflation

David J. E. Marsh, Daniel Grin, Renée Hlozek, Pedro G. Ferreira

(Submitted on 12 Mar 2013 (v1), last revised 23 Oct 2013 (this version, v3))

arXiv.org > astro-ph > arXiv:1111.5328

Search or

Astrophysics > Cosmology and Extragalactic Astrophysics

Photometric Supernova Cosmology with BEAMS and SDSS-II

Renée Hlozek, Martin Kunz, Bruce Bassett, Mat Smith, James Newling, Melvin Varughese, Rick Kessler, Joe Bernstein, Heather Campbell, Ben Dilday, Bridget Falck, Joshua Frieman, Steve Kulhmann, Hubert Lampeitl, John Marriner, Robert C. Nichol, Adam G. Riess, Masao Sako, Donald P. Schneider

(Submitted on 22 Nov 2011)

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The death of the universe - Renée Hlozek

TED-Ed Original

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Let's Begin...

The shape, contents and future of the universe are all intricately related. We know that it's mostly flat; we know that it's made up of baryonic matter (like stars and planets), but mostly dark matter and dark energy; and we know that it's expanding constantly, so that all stars will eventually burn out into a cold nothingness. Renée Hlozek expands on the beauty of this dark ending.

Watch

Think

Dig Deeper

Discuss

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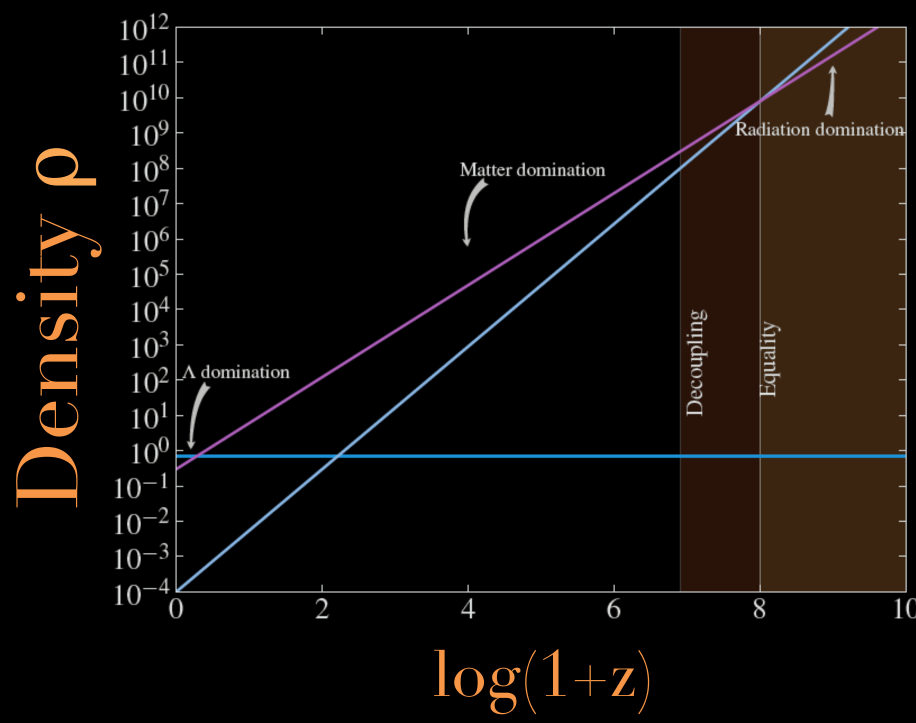
The Cosmic Microwave Background



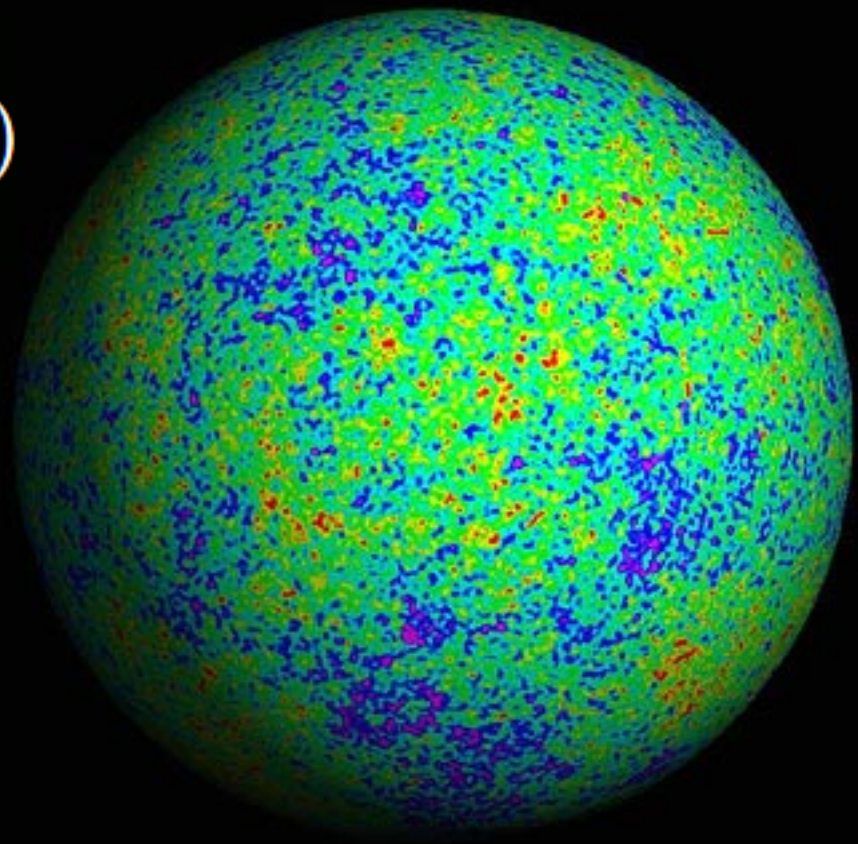
Linear theory → 'clean physics'

Basic elements well understood
→ numerical codes

The Cosmic Microwave Background

$$T(\hat{n}) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\hat{\mathbf{n}})$$

$$C_\ell = \frac{1}{(2\ell+1)} \sum_{m=-\ell}^{\ell} \langle |a_{\ell m}|^2 \rangle$$



Linear theory → 'clean physics'

Basic elements well understood
→ numerical codes

Credit: NASA/WMAP

CMB Power Spectrum

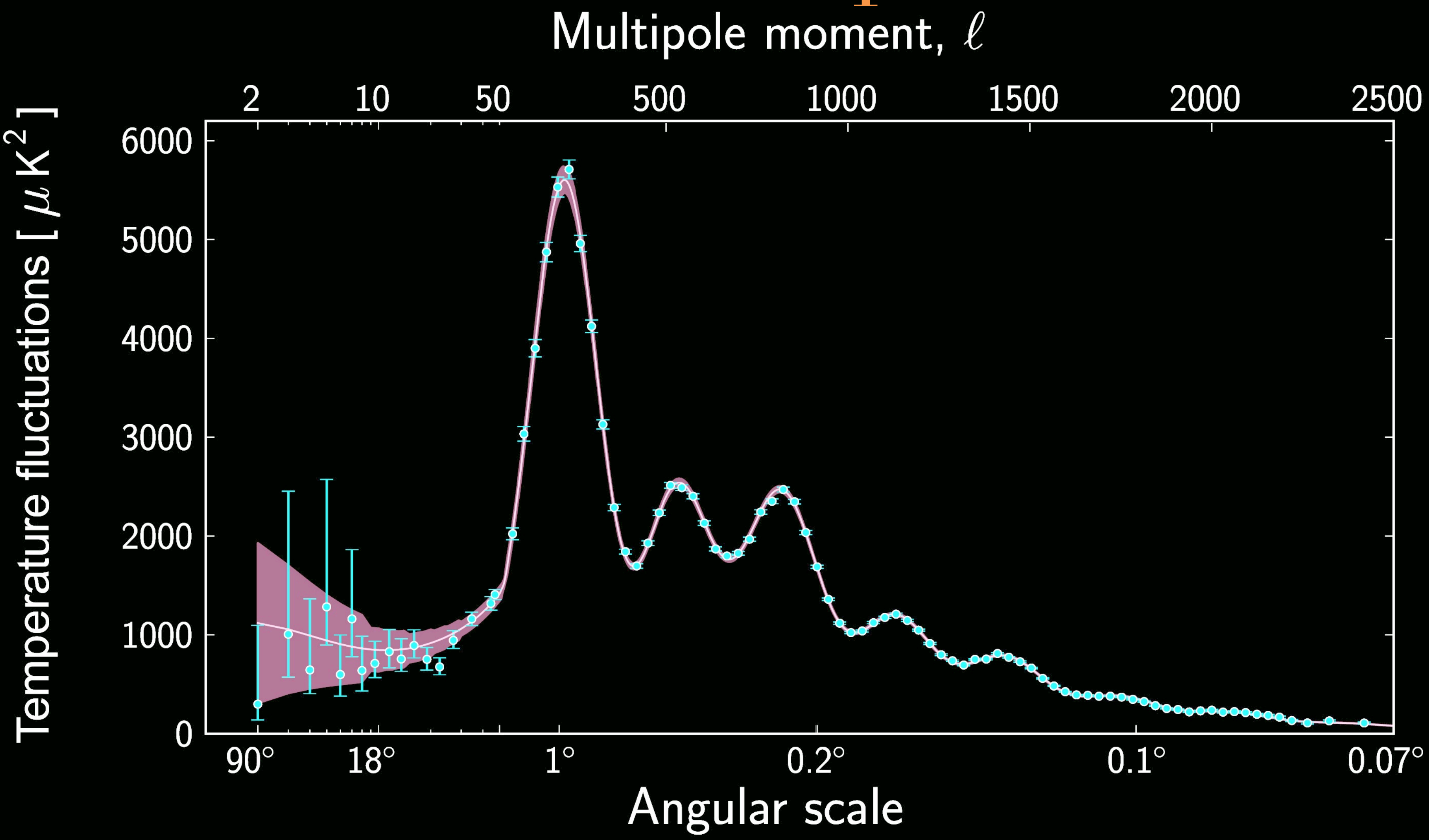


Image credit: Erminia Calabrese for Planck

Basic cosmological model

"Just 6 numbers":

$\Omega_b h^2$ $\Omega_c h^2$ Ω_Λ

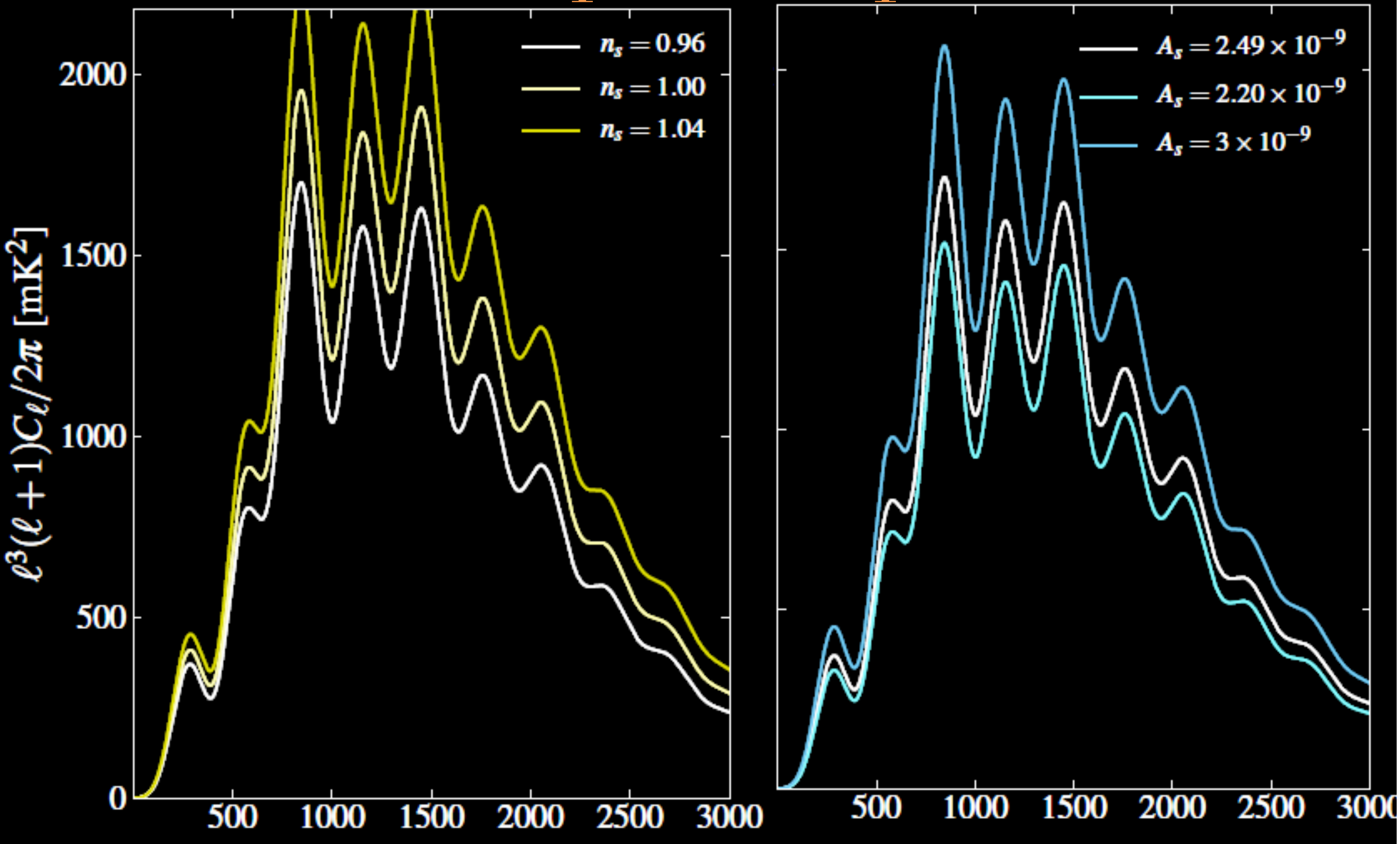
$\Delta^2_{\mathcal{R}}$ n_s

Densities of the universe

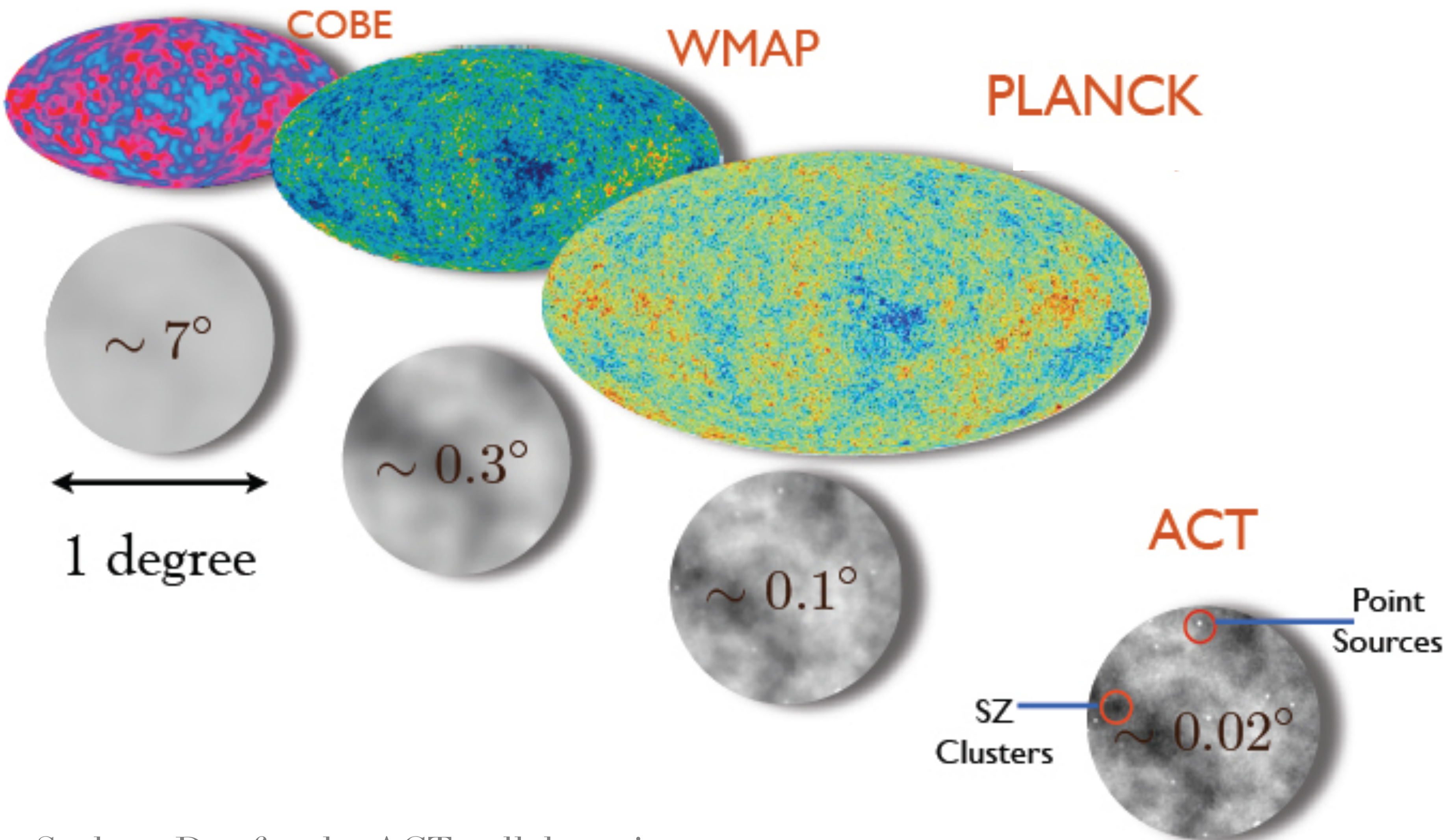
Initial conditions

τ Reionization physics

The CMB power spectrum



ACT probes new scales



Atacama Cosmology Telescope ACT

...observing the birth and evolution of the universe

Pontificia Universidad Católica de Chile
University of Oxford
Stony Brook University
West Chester University of Pennsylvania
National Aeronautics and Space Administration Goddard Space Flight Center (NASA GSFC)
University of British ColumbiaInstituto Nacional de Astrofisica, Óptica y Electrónica (INAOE)
Carnegie Mellon University
University of Pennsylvania
Haverford College
Institute for Advanced Study (IAS)
National Institute of Standards and Technology (NIST)

University of California, Berkeley
Canadian Institute for Theoretical Astrophysics (CITA)
Princeton University
Cardiff University
University of Michigan
University of KwaZulu-Natal
University of Miami
University of Pittsburgh
Academia Sinica
Rutgers, The State University of New Jersey
Cornell University
The Johns Hopkins University

arXiv:1302.1841 arXiv:1301.0824 arXiv:1301.0776 arXiv:1301.1037

The Telescope

Located in Cerro Toco, Northern Chile

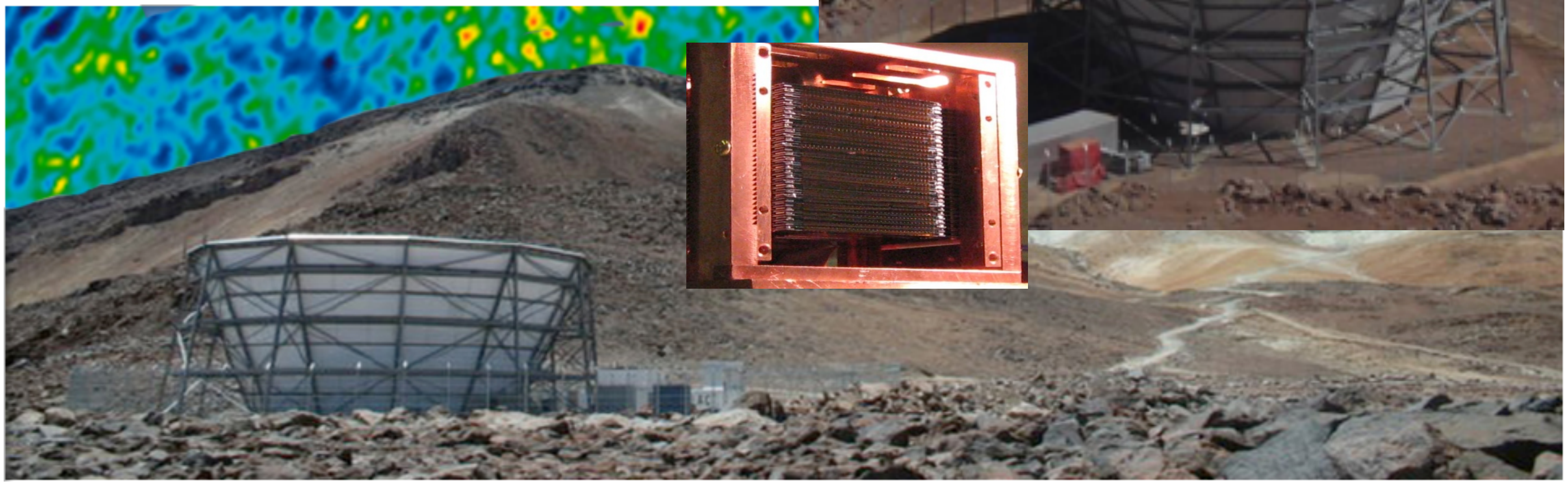
High and dry: 5200 m above sea level, 0.49mm PWV

6m off-axis Gregorian primary

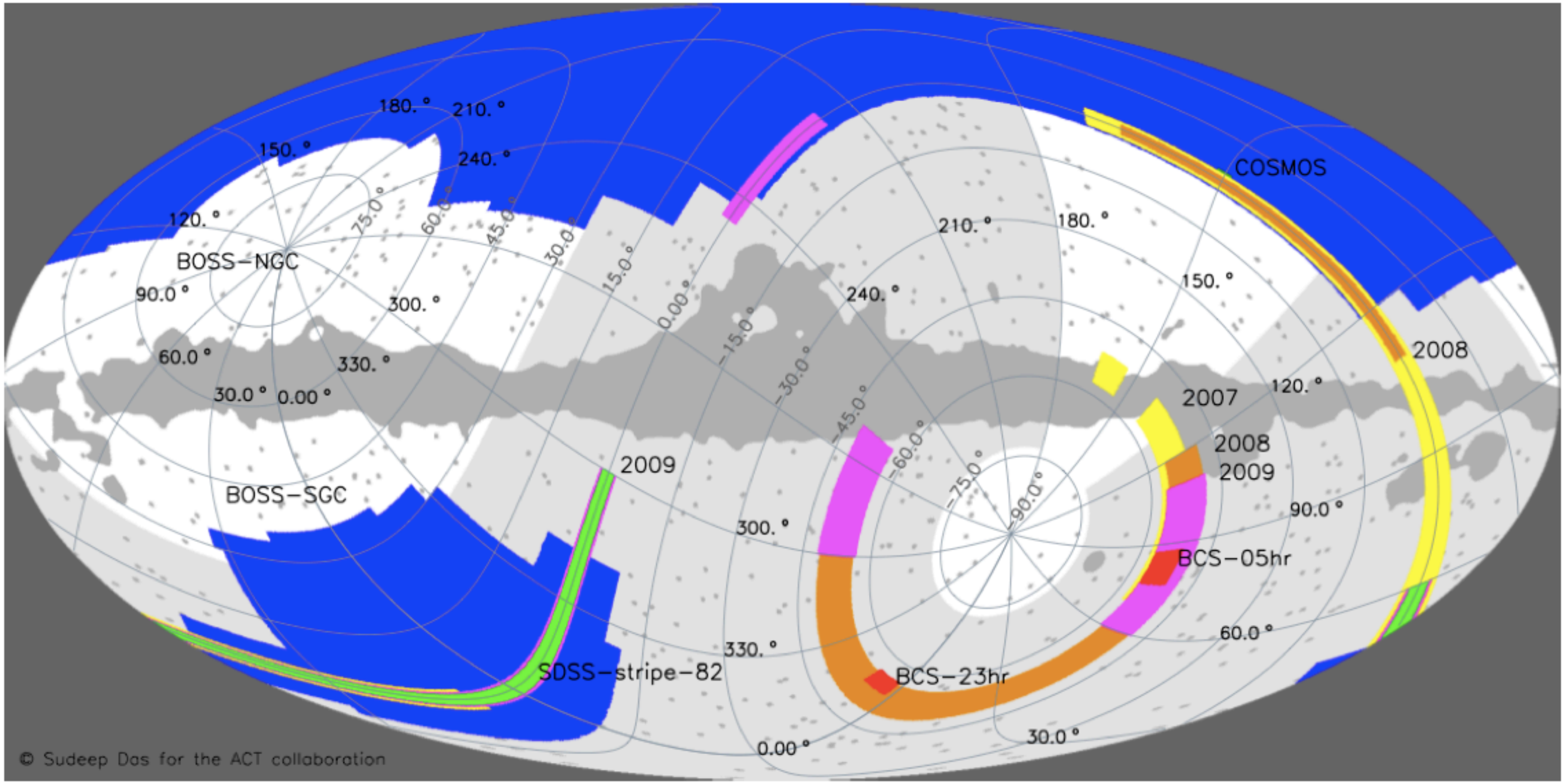
1' resolution

3 frequency channels:

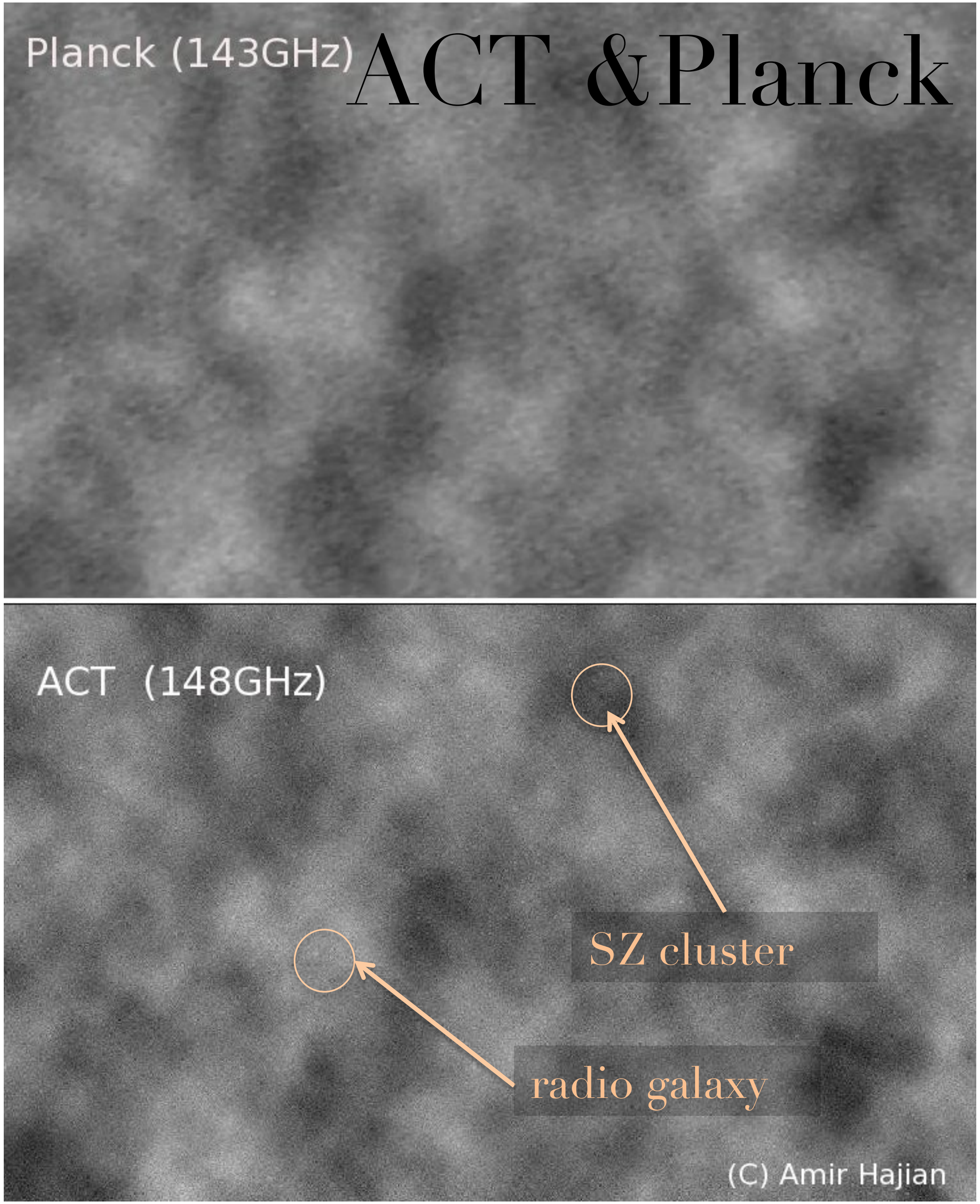
148, 218, 277 GHz



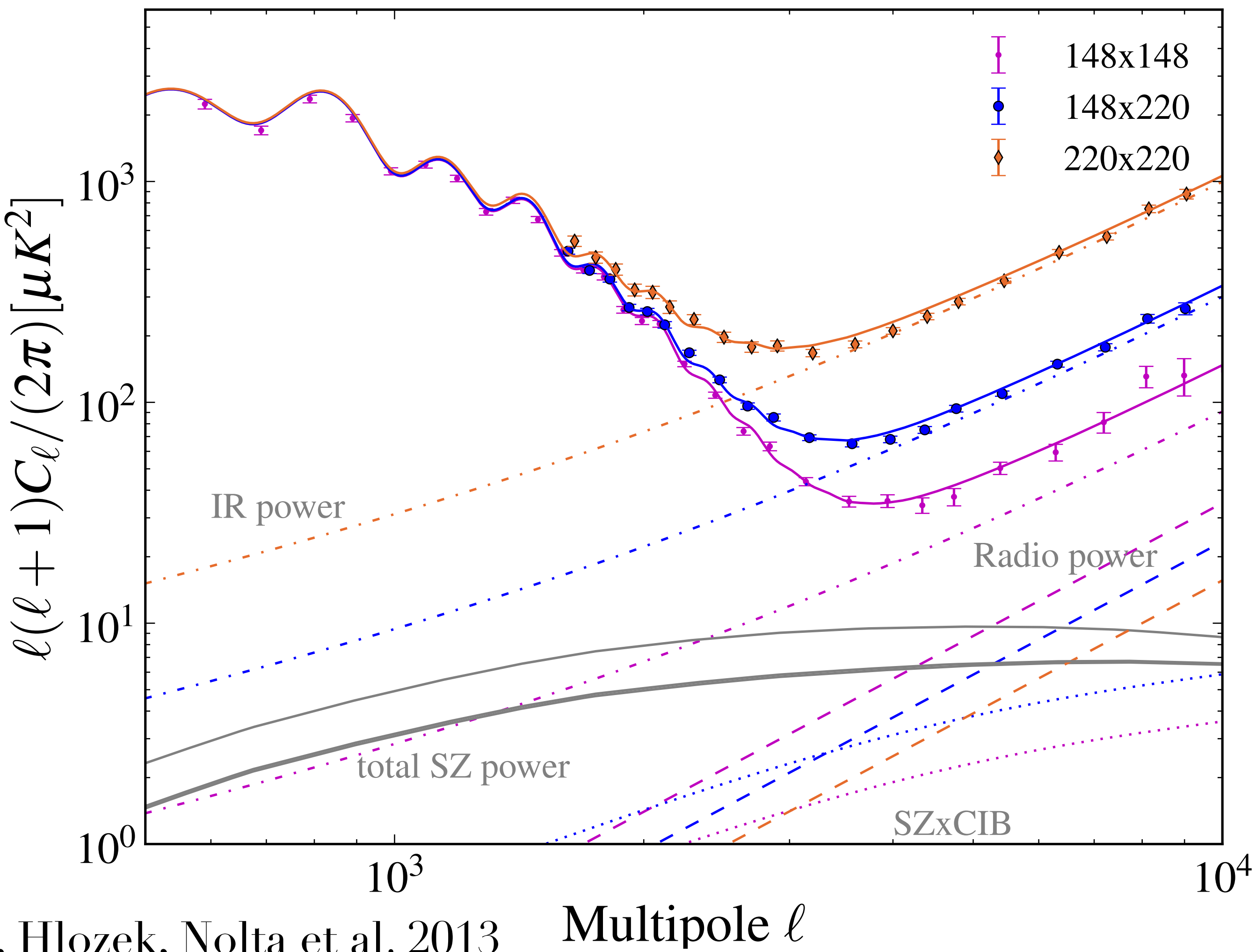
Results in this talk use full data from two frequencies (148+220 GHz).



2007	2009	Stripe 82	BCS
2008	ACT Range	BOSS	Masked


ACT &Planck
Planck (143GHz)
ACT (148GHz)
SZ cluster
radio galaxy
(C) Amir Hajian

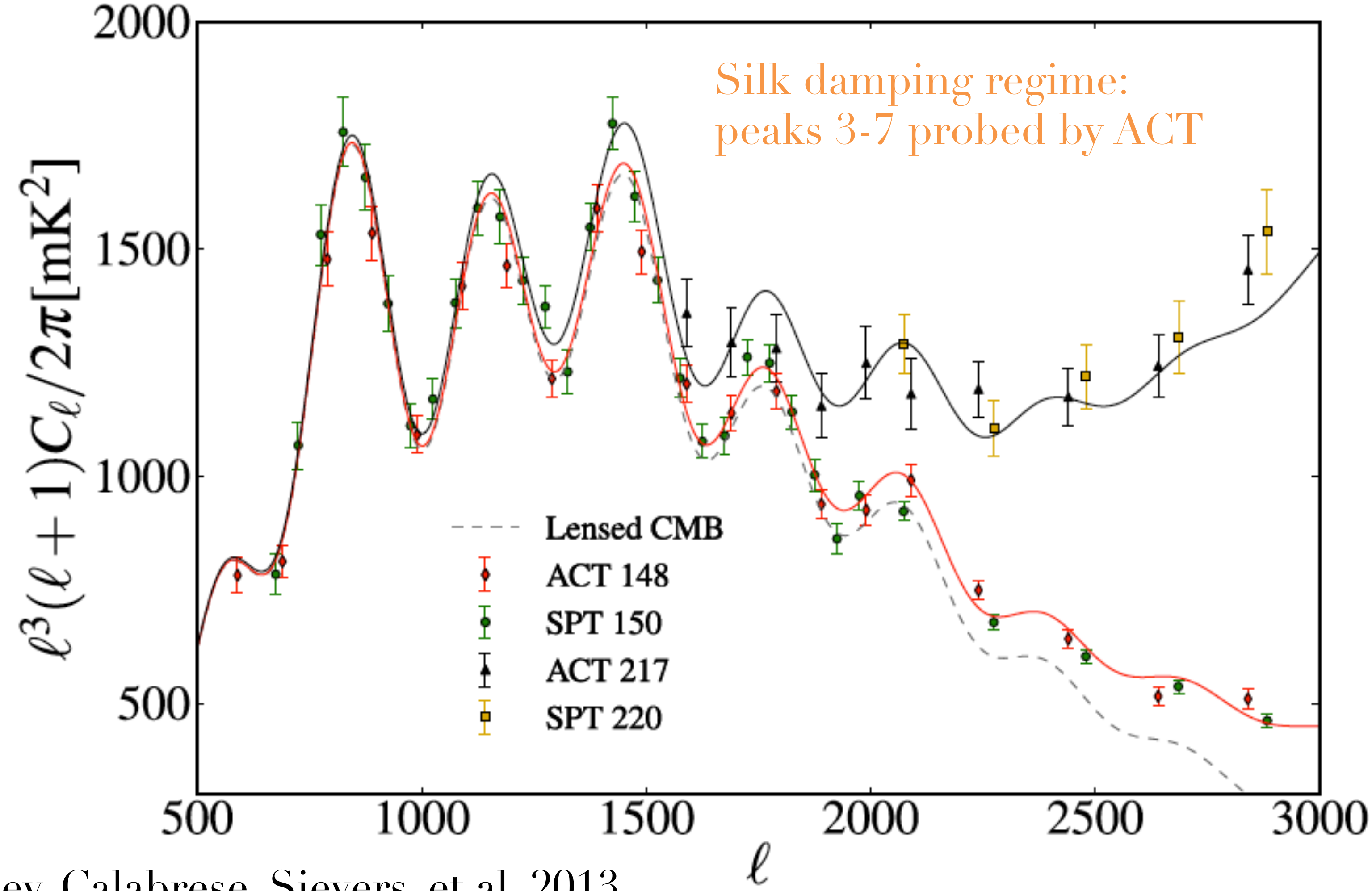
The ACT components



Sievers, Hlozek, Nolta et al. 2013

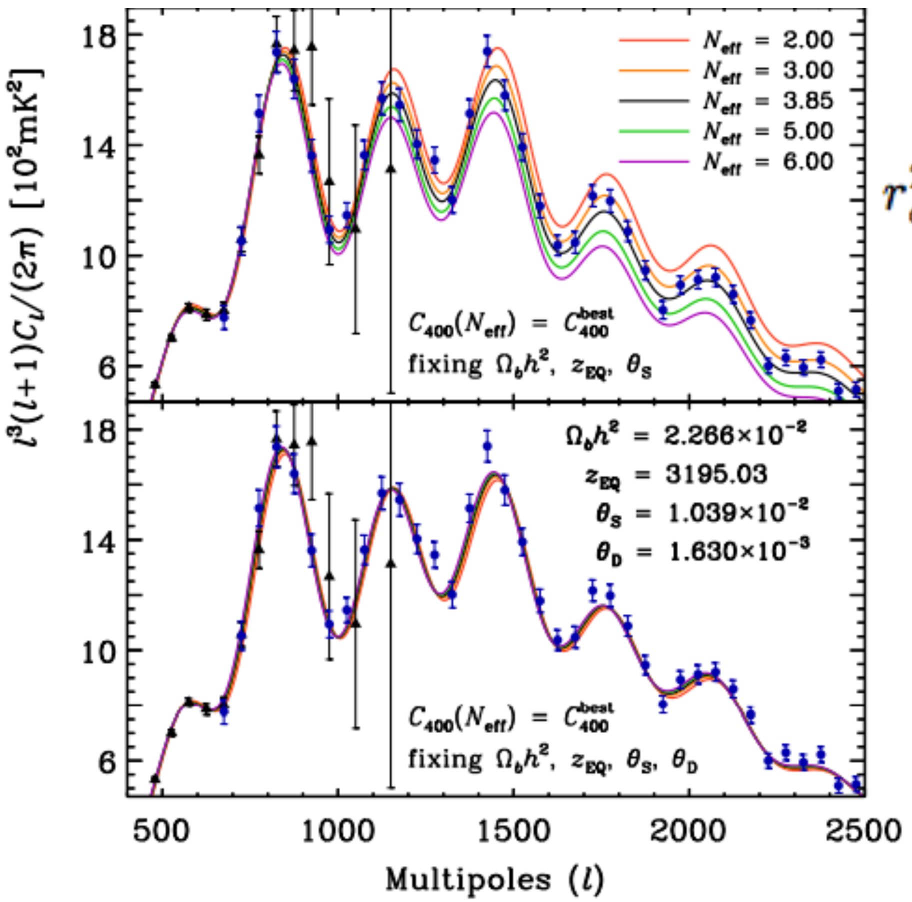
Renée Hlozek – Cornell

Where is ACT's power?



Dunkley, Calabrese, Sievers, et al. 2013

Effective relativistic species



$$r_d^2 = \pi^2 \int_0^{a_*} \frac{da}{a^3 \sigma_T n_e H} \left[\frac{R^2 + \frac{16}{15}(1+R)}{6(1+R^2)} \right]$$

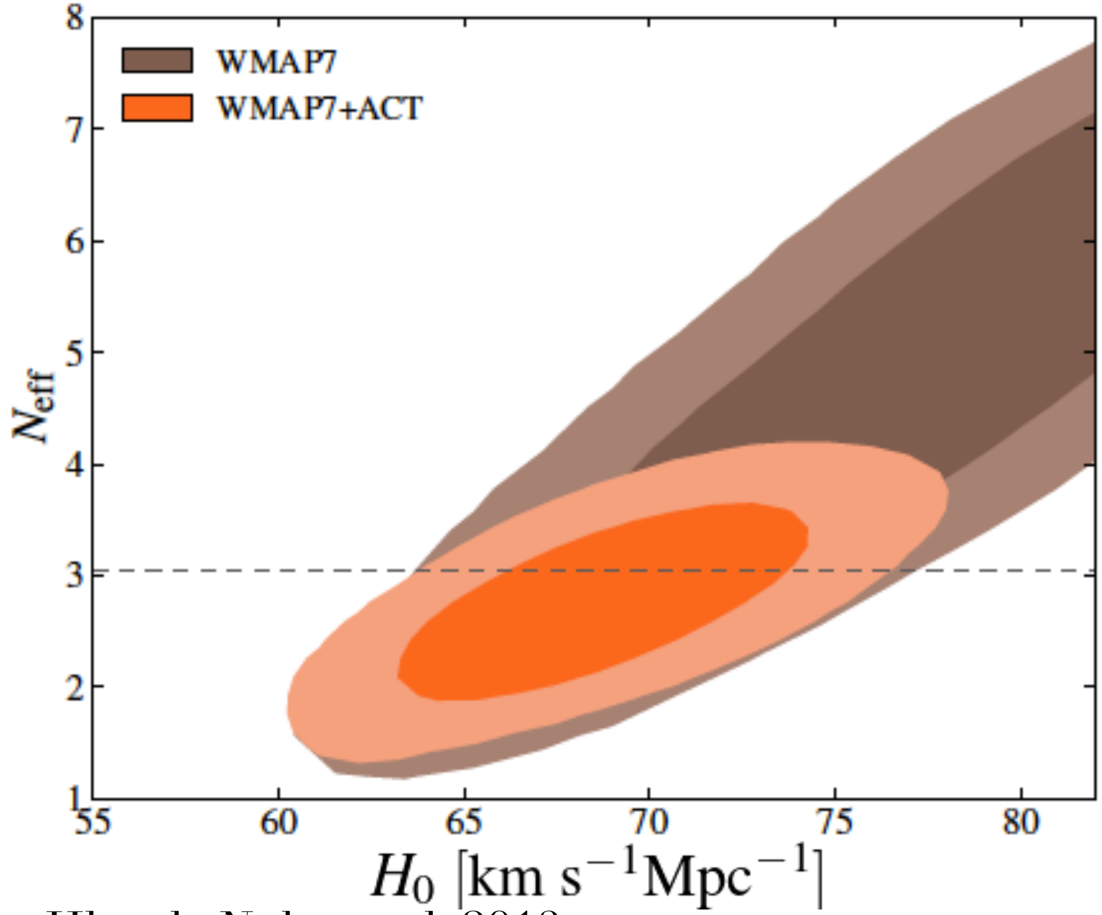
$$r_s = \int_0^{t_*} c_s \, dt/a = \int_0^{a_*} \frac{c_s \, da}{a^2 H}$$

$$R = 3\rho_b/(4\rho_\gamma)$$

Hou, Keisler, Knox et al. 2011

Effective relativistic species

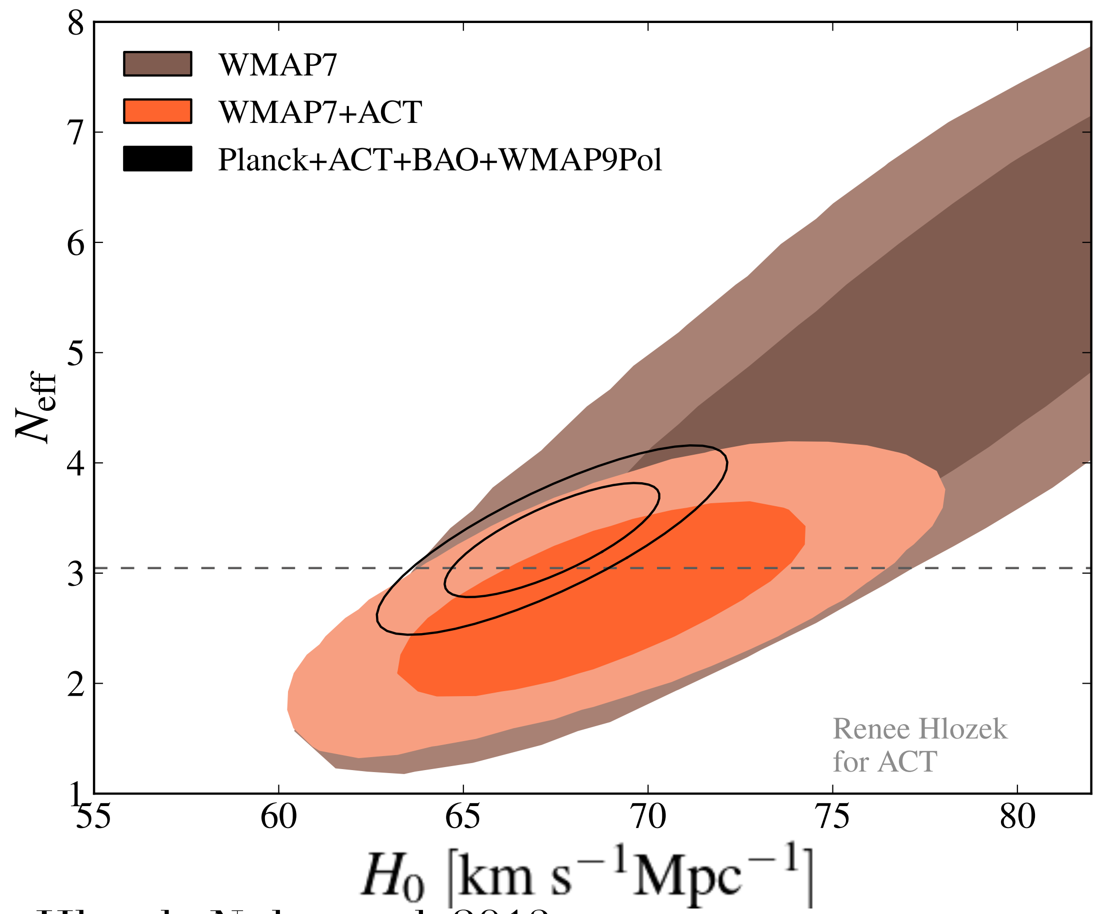
Consistent with 3 neutrino model.



Sievers, Hlozek, Nolta et al. 2013

Effective relativistic species

Consistent with 3 neutrino model.

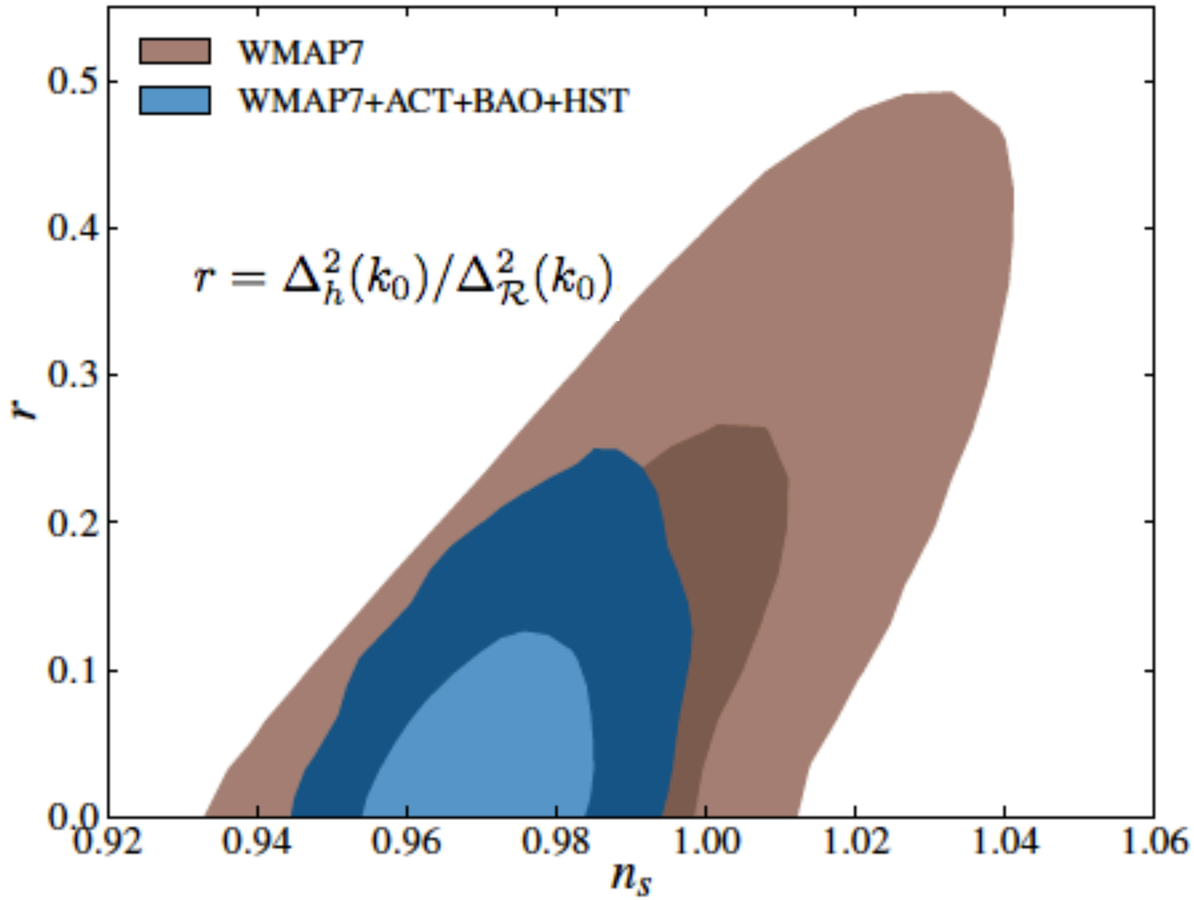


Sievers, Hlozek, Nolta et al. 2013

Inflationary parameters

Sievers, Hlozek, Nolta et al. 2013

Changes in model for Recfast v1.5 compared to Recfast 1.4.2



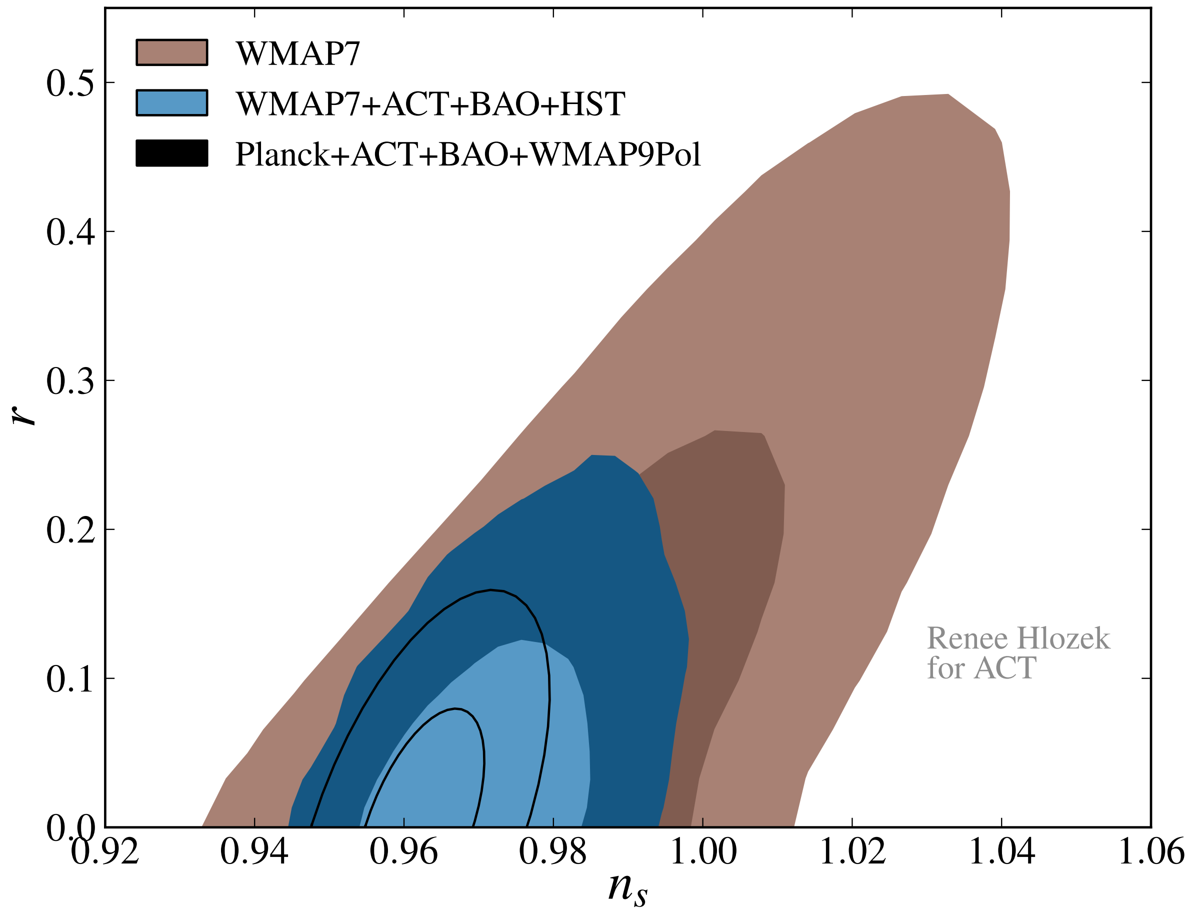
$r < 0.19$ (WMAP7 + ACT + BAO+H_0, 95% CL)

$r_{0.002} < 0.11$ Planck

Inflationary parameters

Sievers, Hlozek, Nolta et al. 2013

Changes in model for Recfast v1.5 compared to Recfast 1.4.2

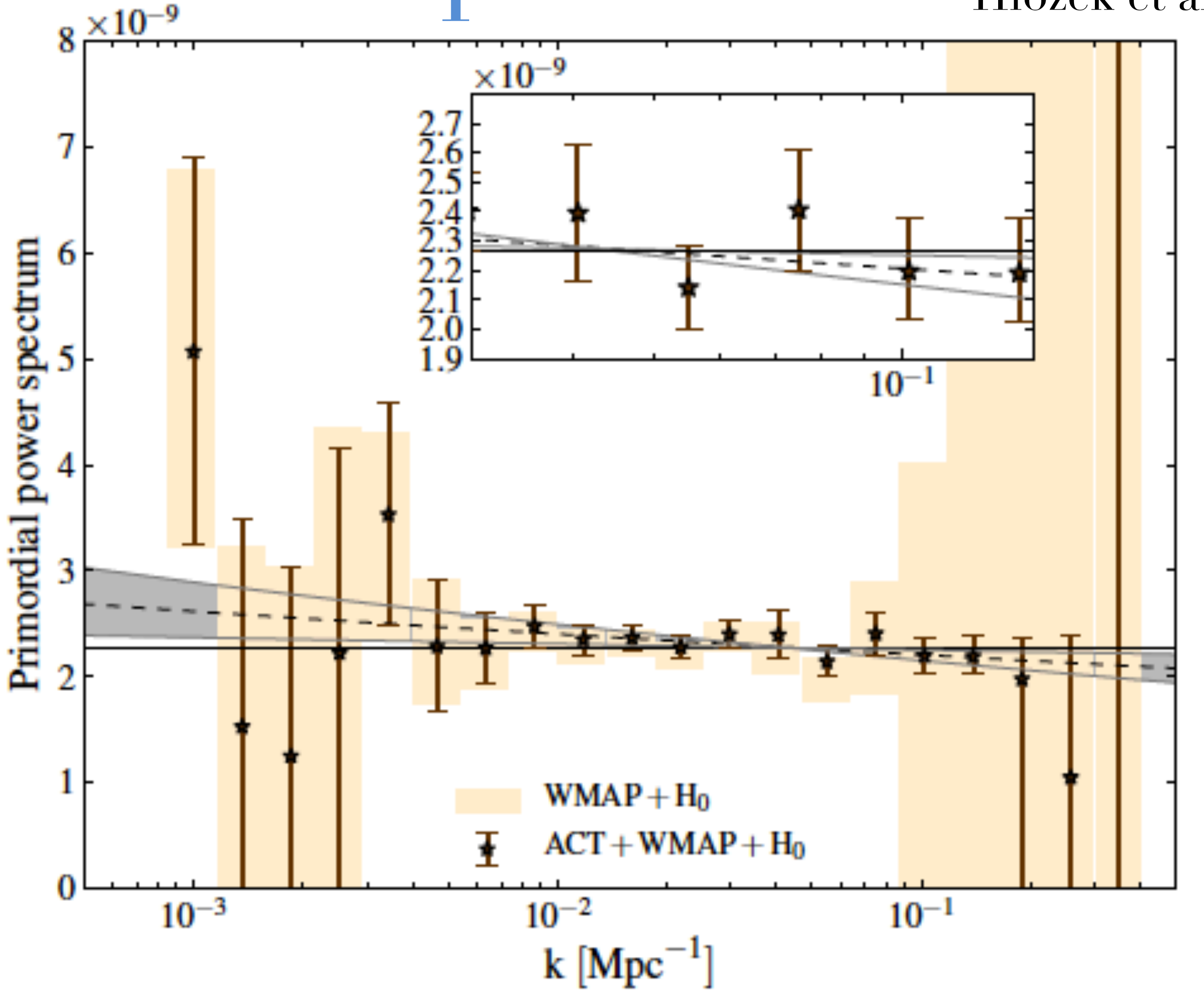


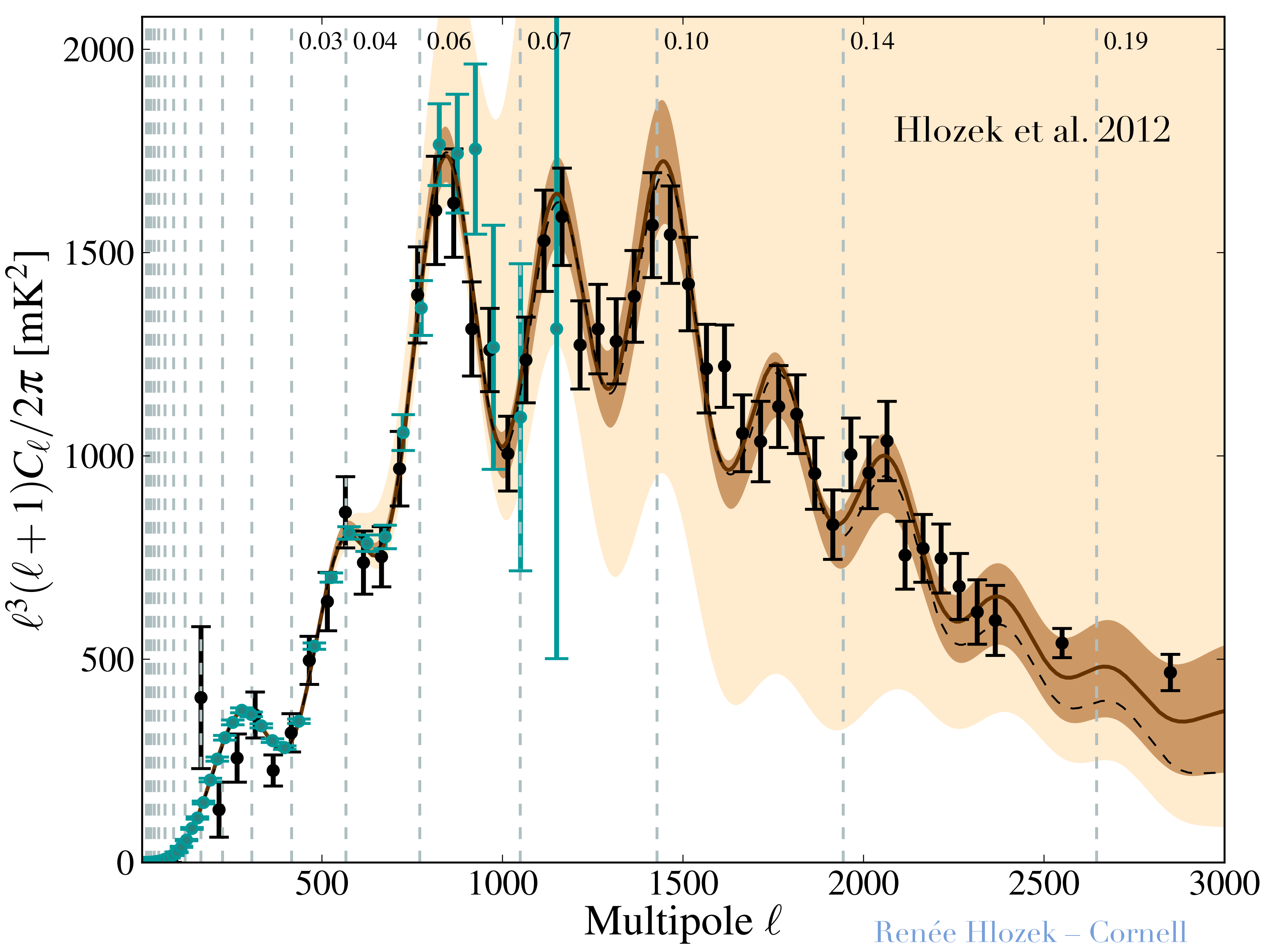
$r < 0.19$ (WMAP7 + ACT + BAO+H_0, 95% CL)

$r_{0.002} < 0.11$ Planck

Constraints on the primordial power

Hlozek et al. 2012





0.03
0.04
0.06
0.07
0.10
0.14
0.19
Hlozek et al. 2012
2000
1500
1000
500
0
500
1000
1500
2000
2500
3000
$\ell^3(\ell+1)C_\ell/2\pi$ [mK^2]
Multipole ℓ
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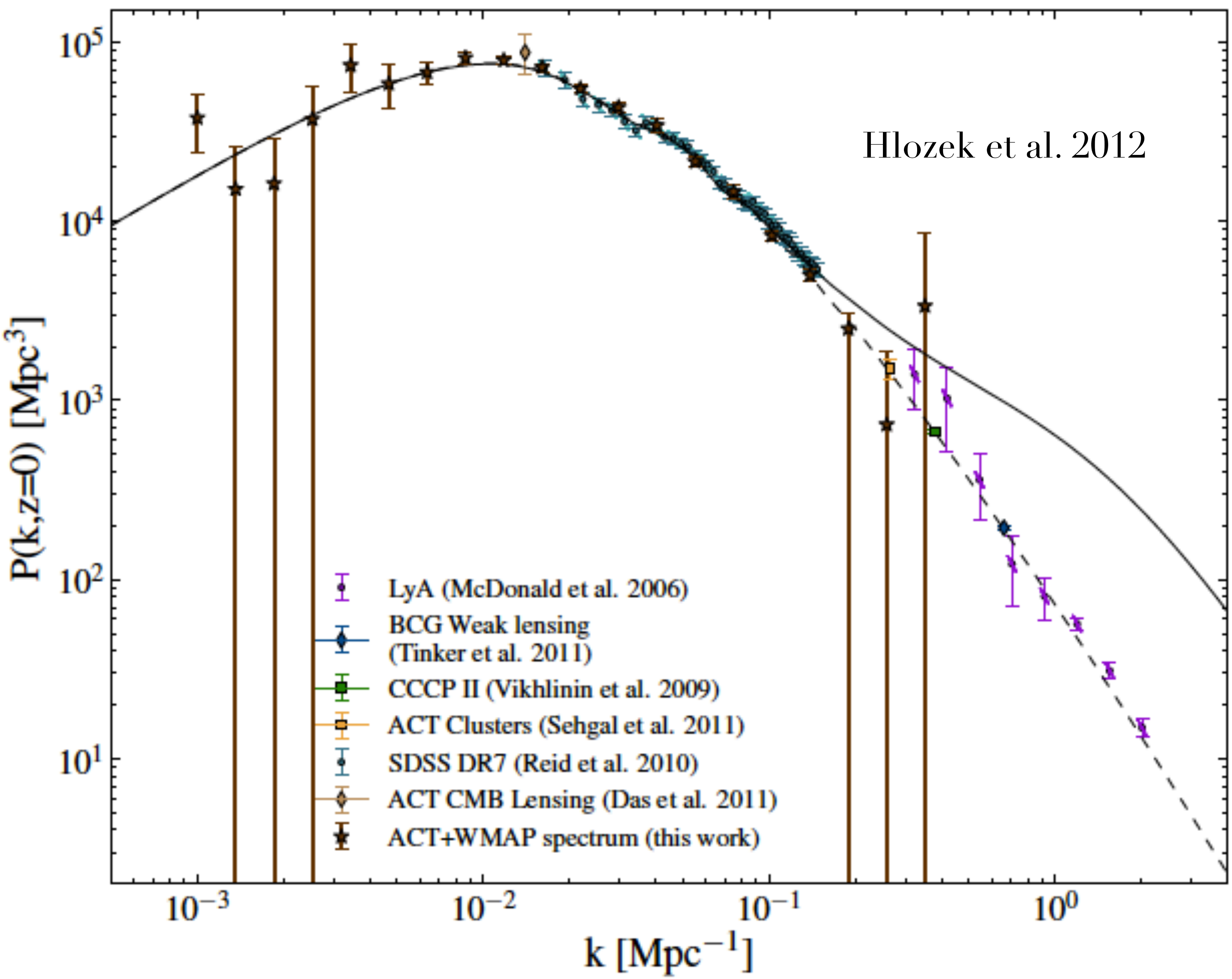

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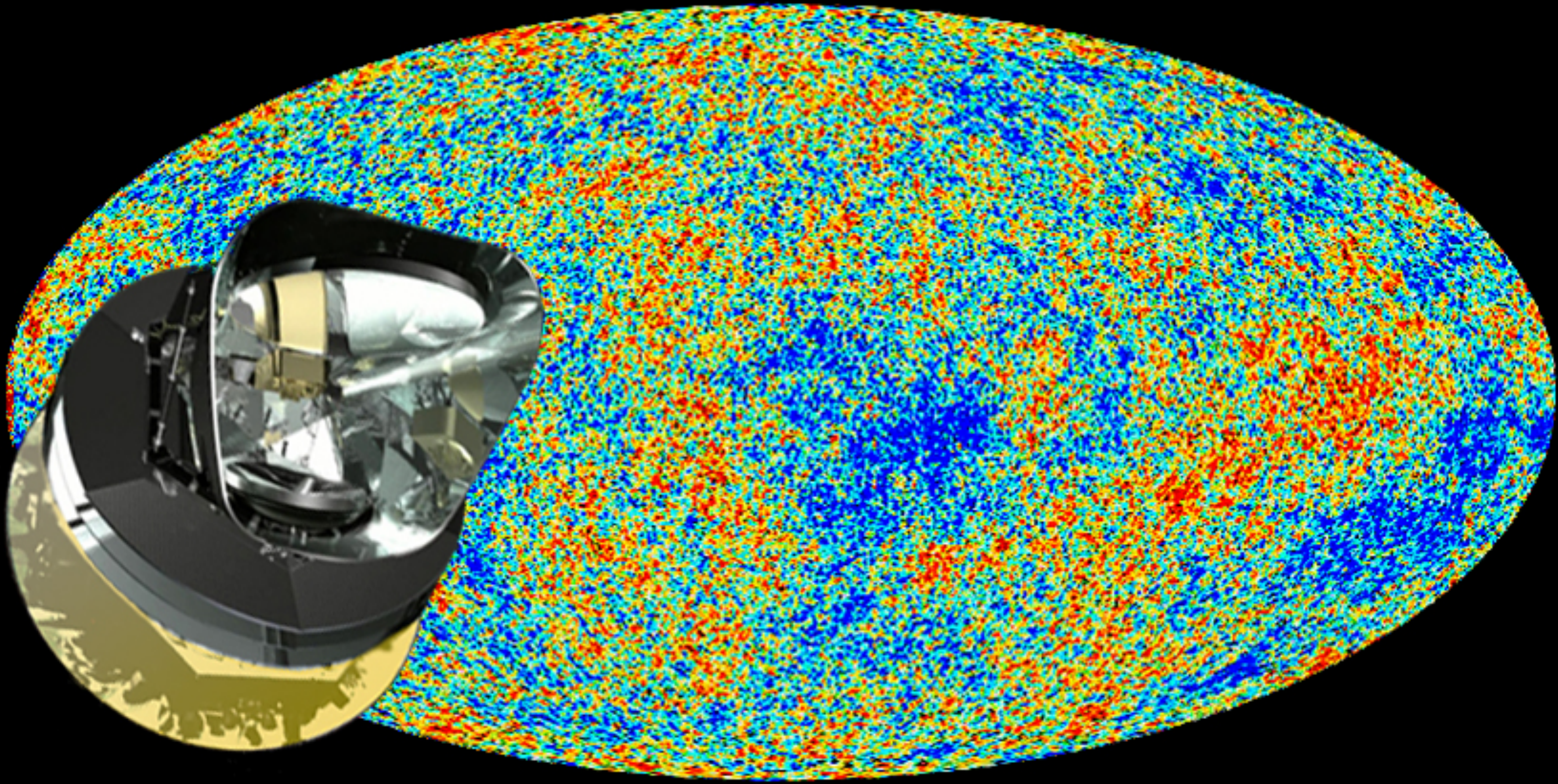
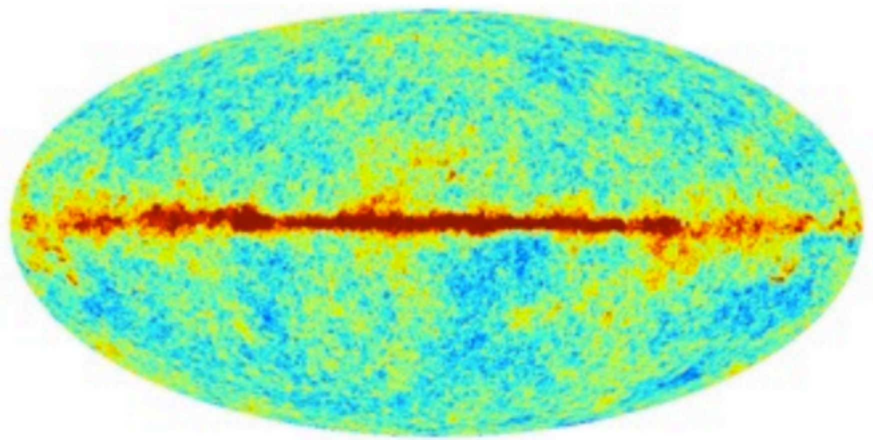
Planck Data Reconsidered

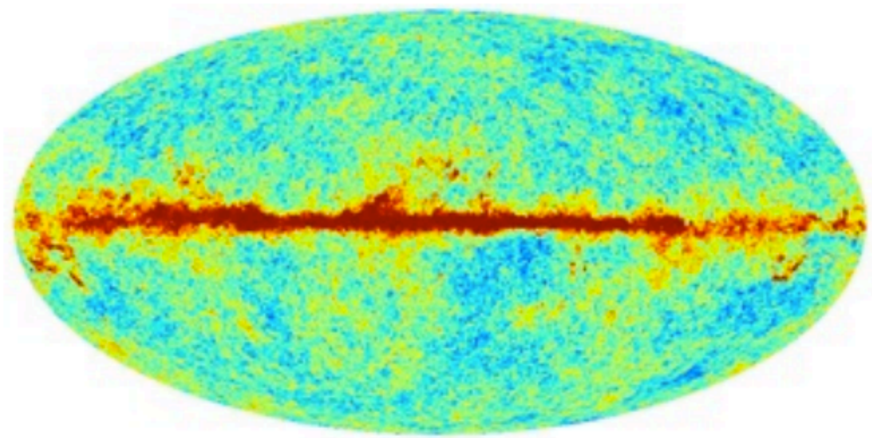


arXiv:1312.3313

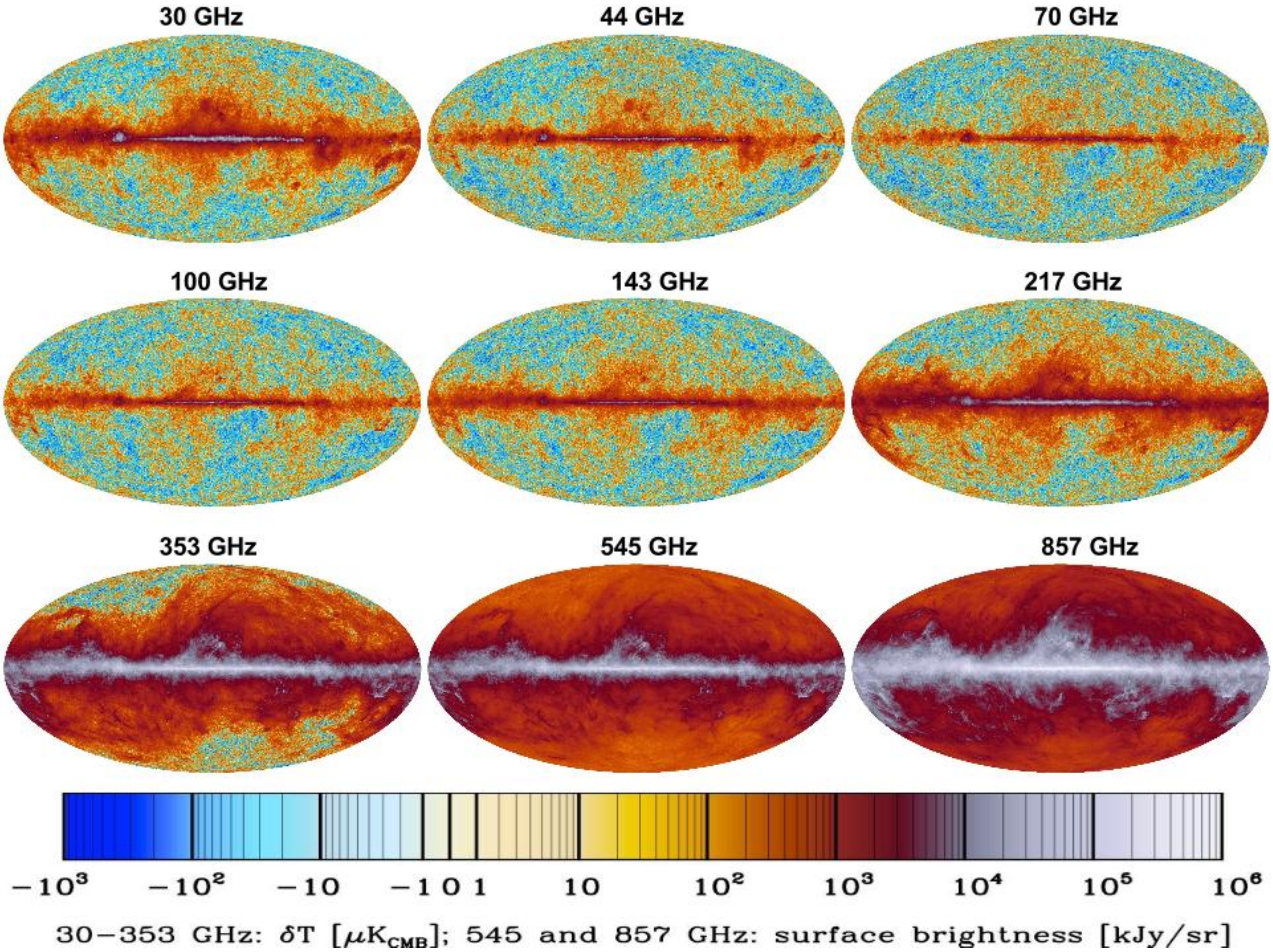
Consistent cosmological picture

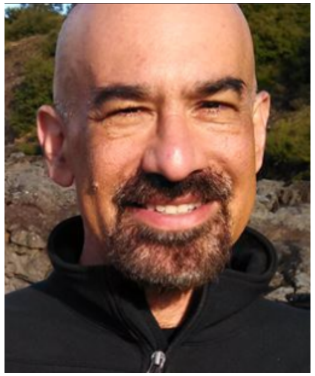


WMAP 94 GHz



Planck 100 GHz


30 GHz
44 GHz
70 GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
857 GHz
−10³ −10² −10 −1 0 1 10 10² 10³ 10⁴ 10⁵ 10⁶
30−353 GHz: δT [μK_CMB]; 545 and 857 GHz: surface brightness [kJy/sr]



Planck consistency

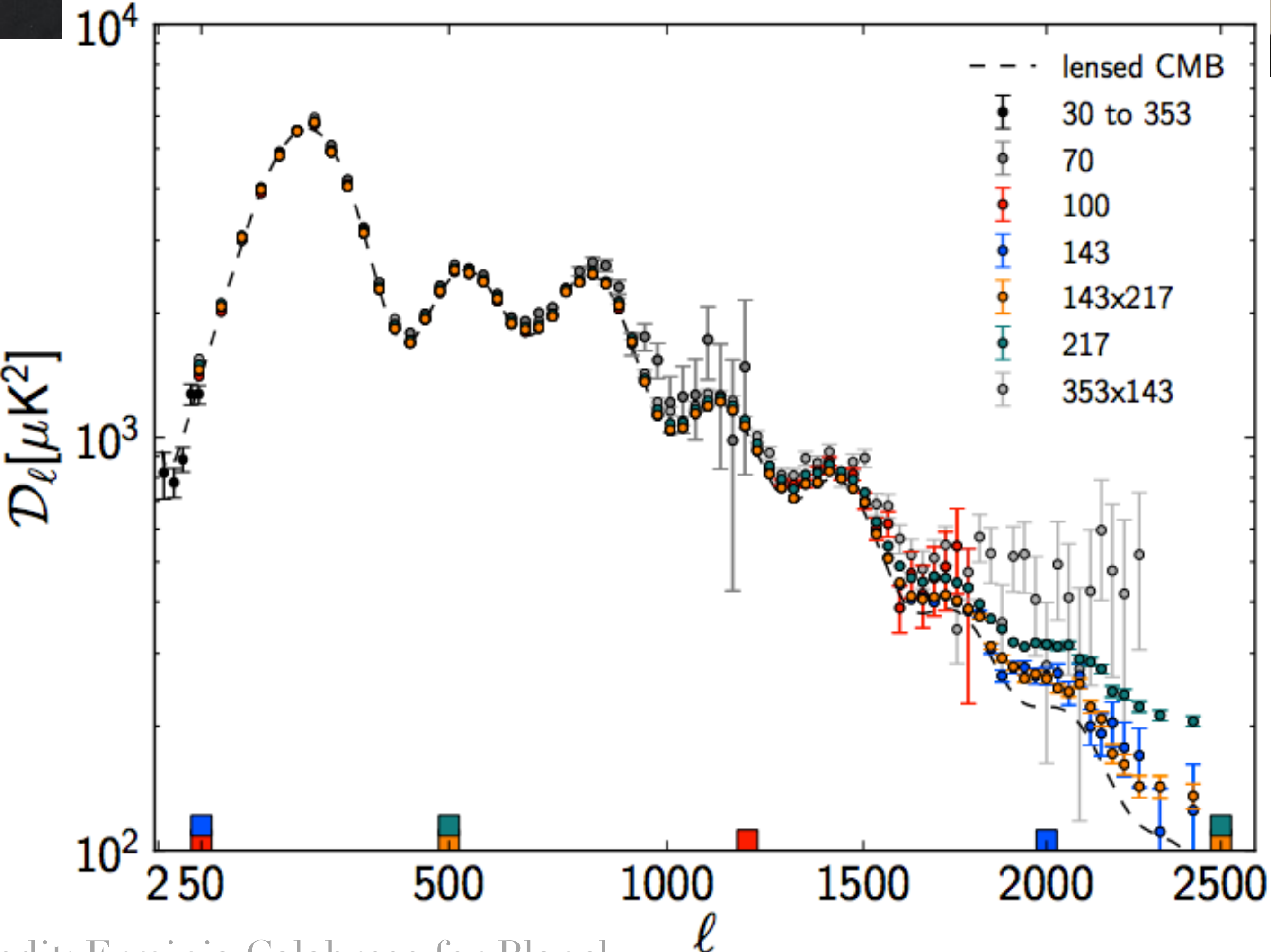


Image credit: Erminia Calabrese for Planck

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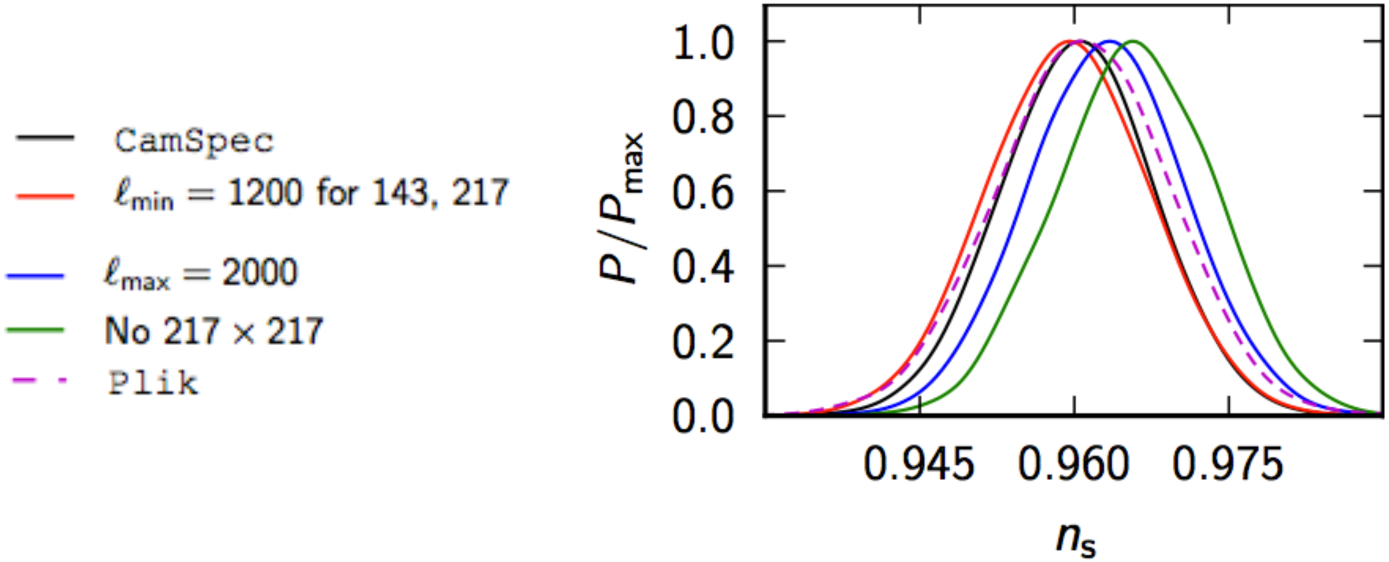
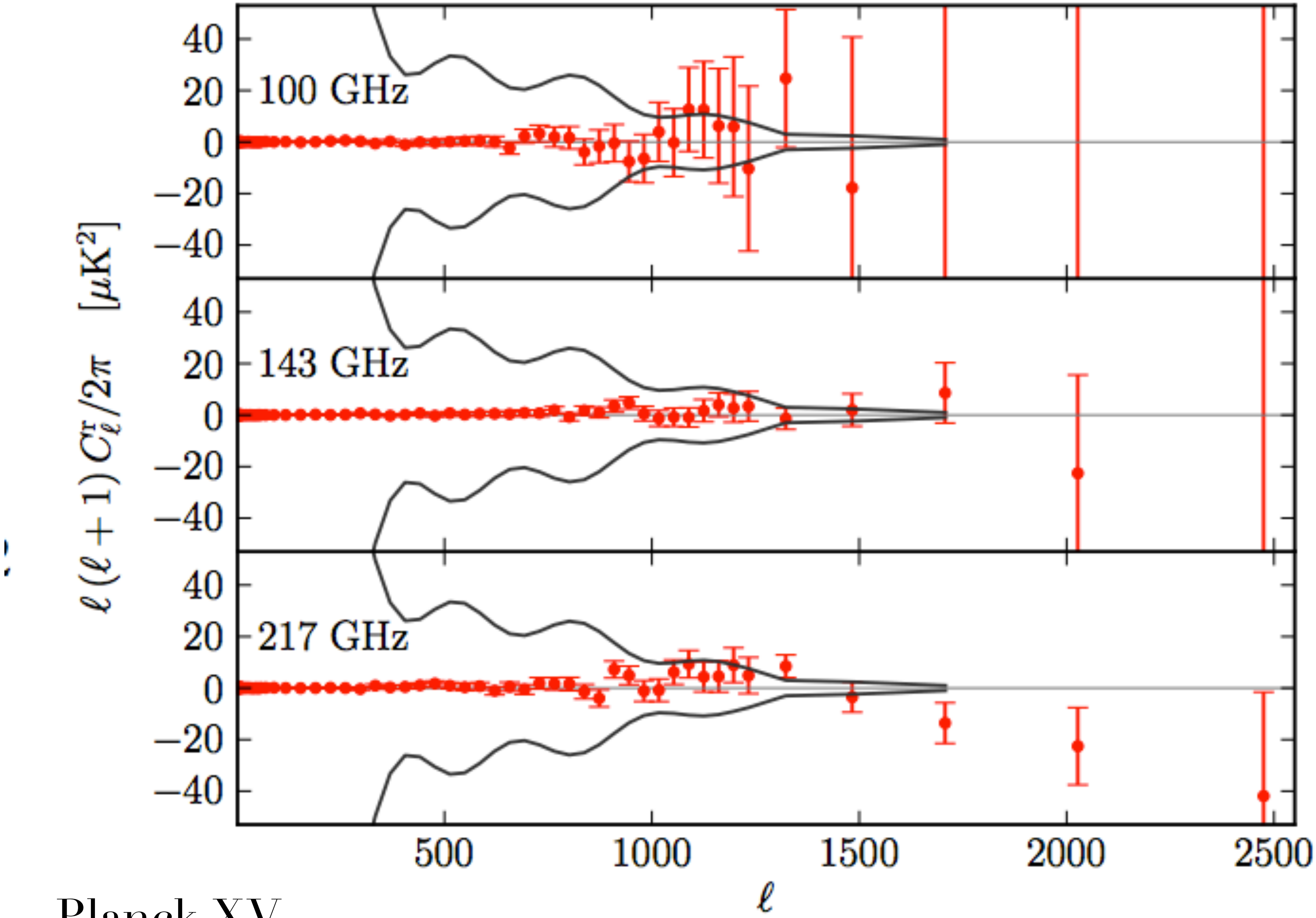
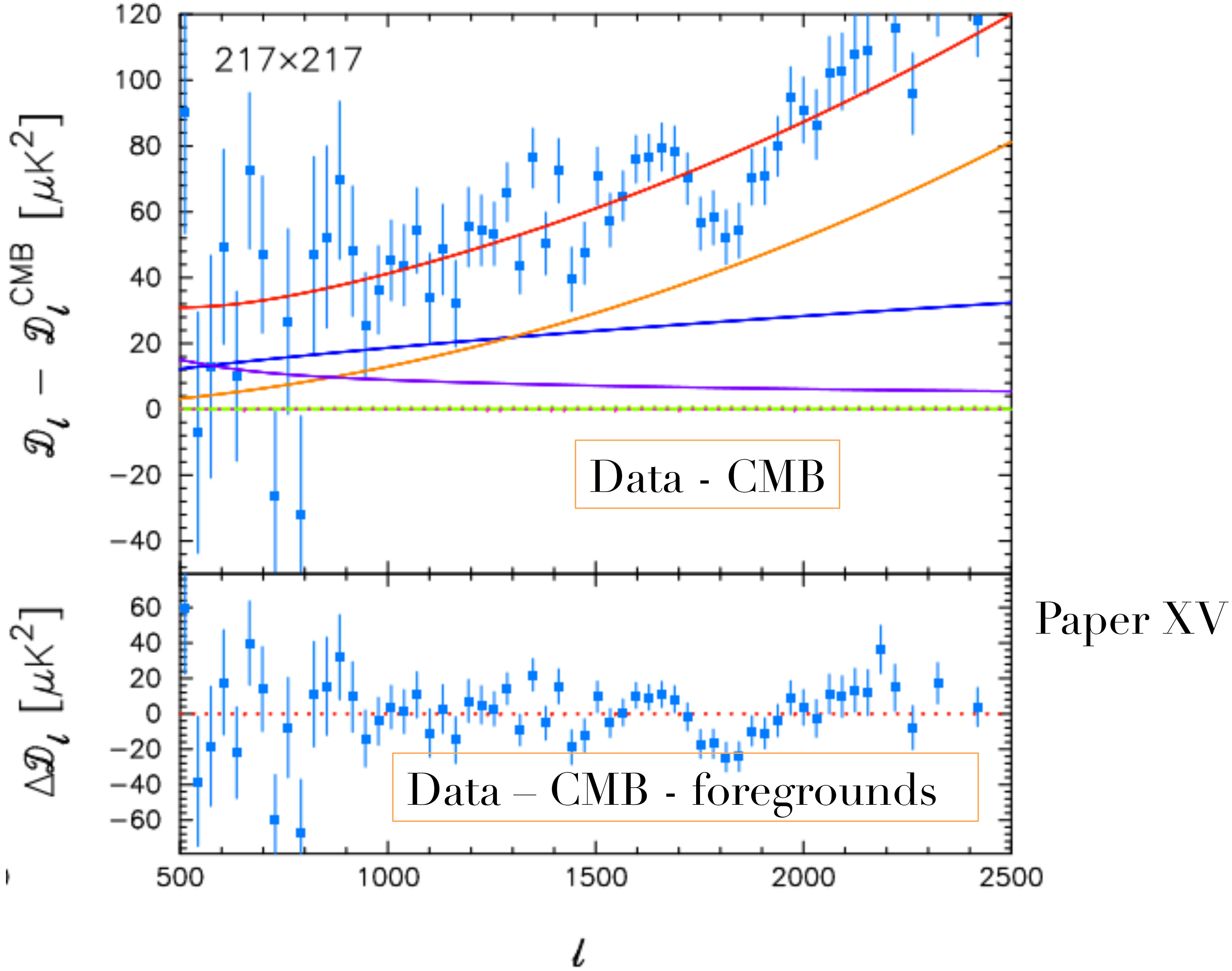
Planck consistency



	Planck Analysis	No 217 × 217	WMAP9+ACT
$10\ \Omega_c h^2$	1.199±0.026	1.181± 0.027	1.146±0.043
n_s	0.9603±0.0073	0.9661±0.0077	0.973 ± 0.011
H_0	67.3±1.2	68.1±1.2	69.7 ± 2.0
$100\ \Omega_b h^2$	2.205± 0.028	2.226 ±0.029	2.260 ±0.041
Ω_m	0.315± 0.016	0.305 ±0.016	0.284 ±0.024


100 GHz
143 GHz
217 GHz
$\ell(\ell+1)\,C_\ell^{\mathrm{r}}/2\pi\quad[\mu\mathrm{K}^2]$
ℓ
40
20
0
−20
−40
500
1000
1500
2000
2500

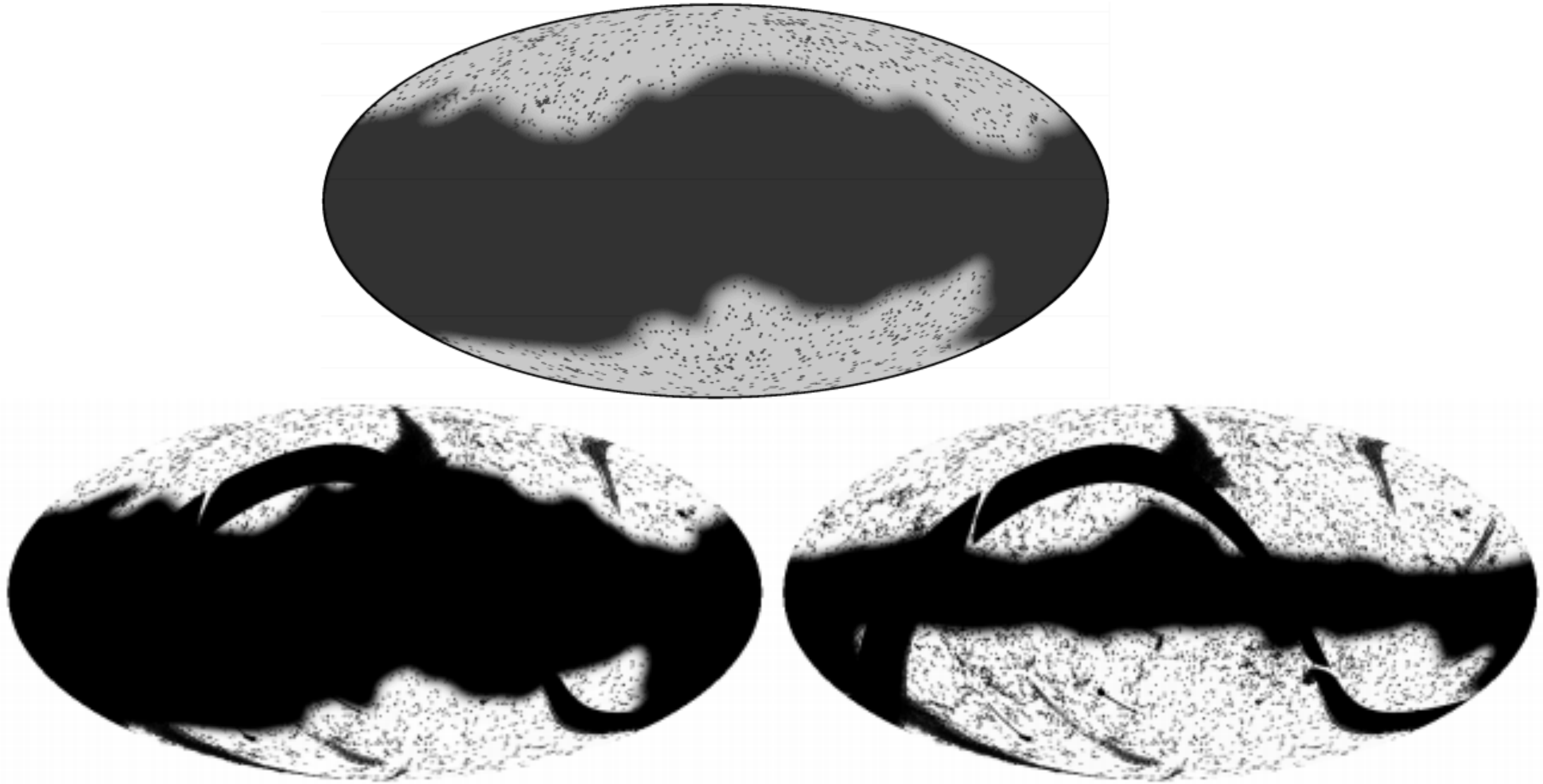
Planck XV


217×217
Data - CMB
Data – CMB - foregrounds
$\mathcal{D}_\ell - \mathcal{D}_\ell^{\mathrm{CMB}}\ [\mu\mathrm{K}^2]$
$\Delta\mathcal{D}_\ell\ [\mu\mathrm{K}^2]$
ℓ
Paper XV

From data to model fits

- TODs mapped – CMB maps at different frequencies (NB: detector set vs season)

- Make a mask for galactic emission and point sources



- Remove residual galactic emission from spectra

- Create covariance matrix

$$\tilde{\mathcal{M}} = \left(\begin{array}{c|c|c|c}
(100\times100)\times(100\times100) & (100\times100)\times(143\times143) & (100\times100)\times(217\times217) & (100\times100)\times(143\times217) \\ \hline
(143\times143)\times(100\times100) & (143\times143)\times(143\times143) & (143\times143)\times(217\times217) & (143\times143)\times(143\times217) \\ \hline
(217\times217)\times(100\times100) & (217\times217)\times(143\times143) & (217\times217)\times(217\times217) & (217\times217)\times(143\times217) \\ \hline
(143\times217)\times(100\times100) & (143\times217)\times(143\times143) & (143\times217)\times(217\times217) & (143\times217)\times(143\times217)
\end{array}\right).$$

Planck XV

- Covariance matrix includes noise model, mode coupling matrix, pixel window function and beam transfer function…

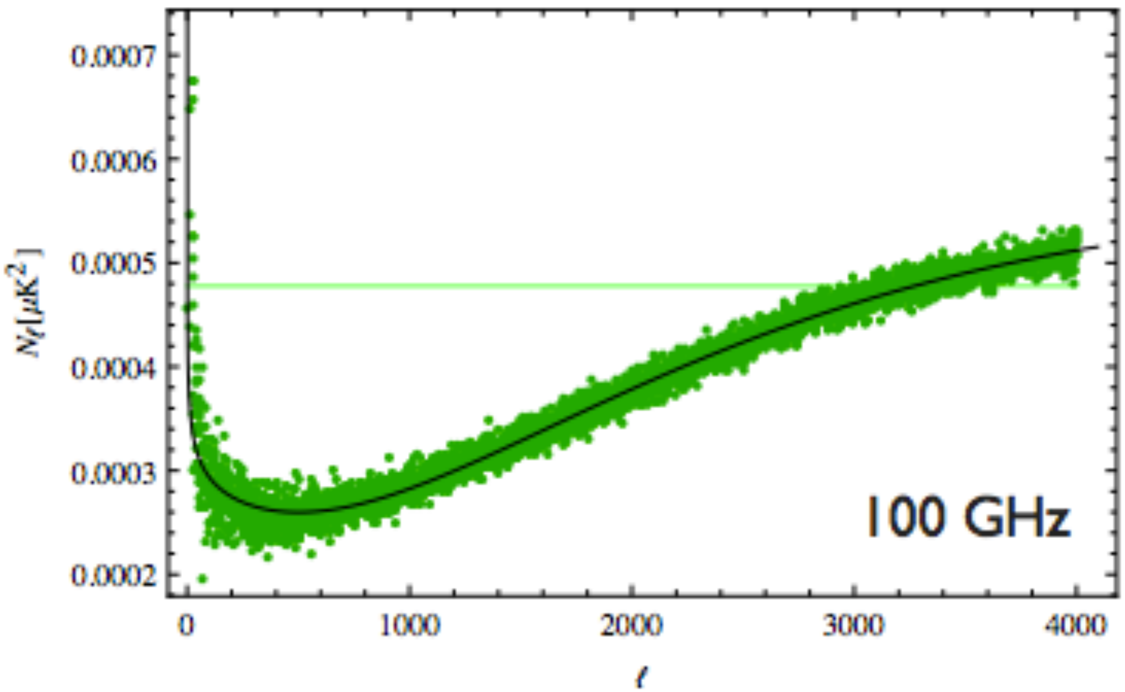
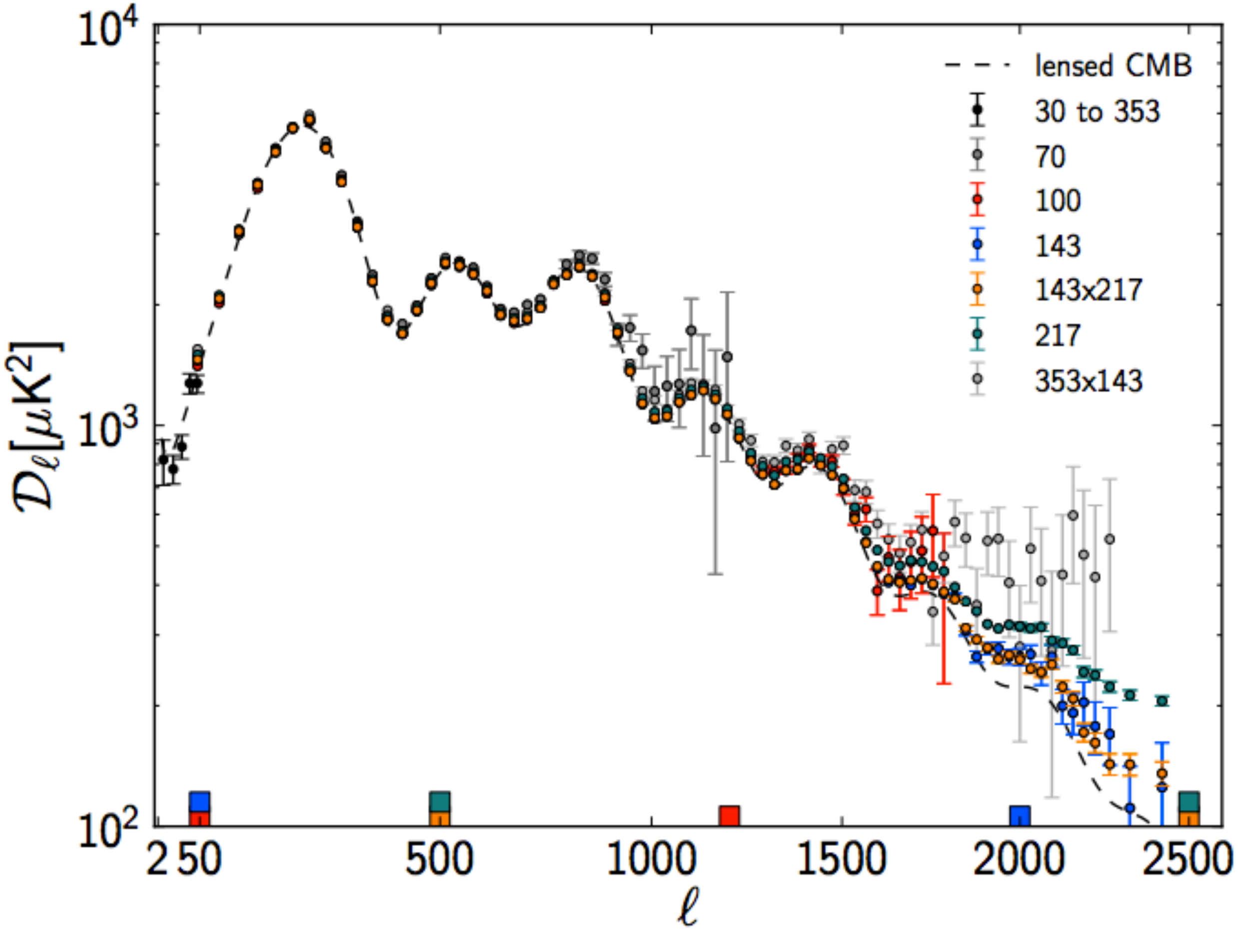


Image credit: Raphael Flauger

- Compute power spectrum
- Fit model to your

100x100
143x143
143x217
217x217

data



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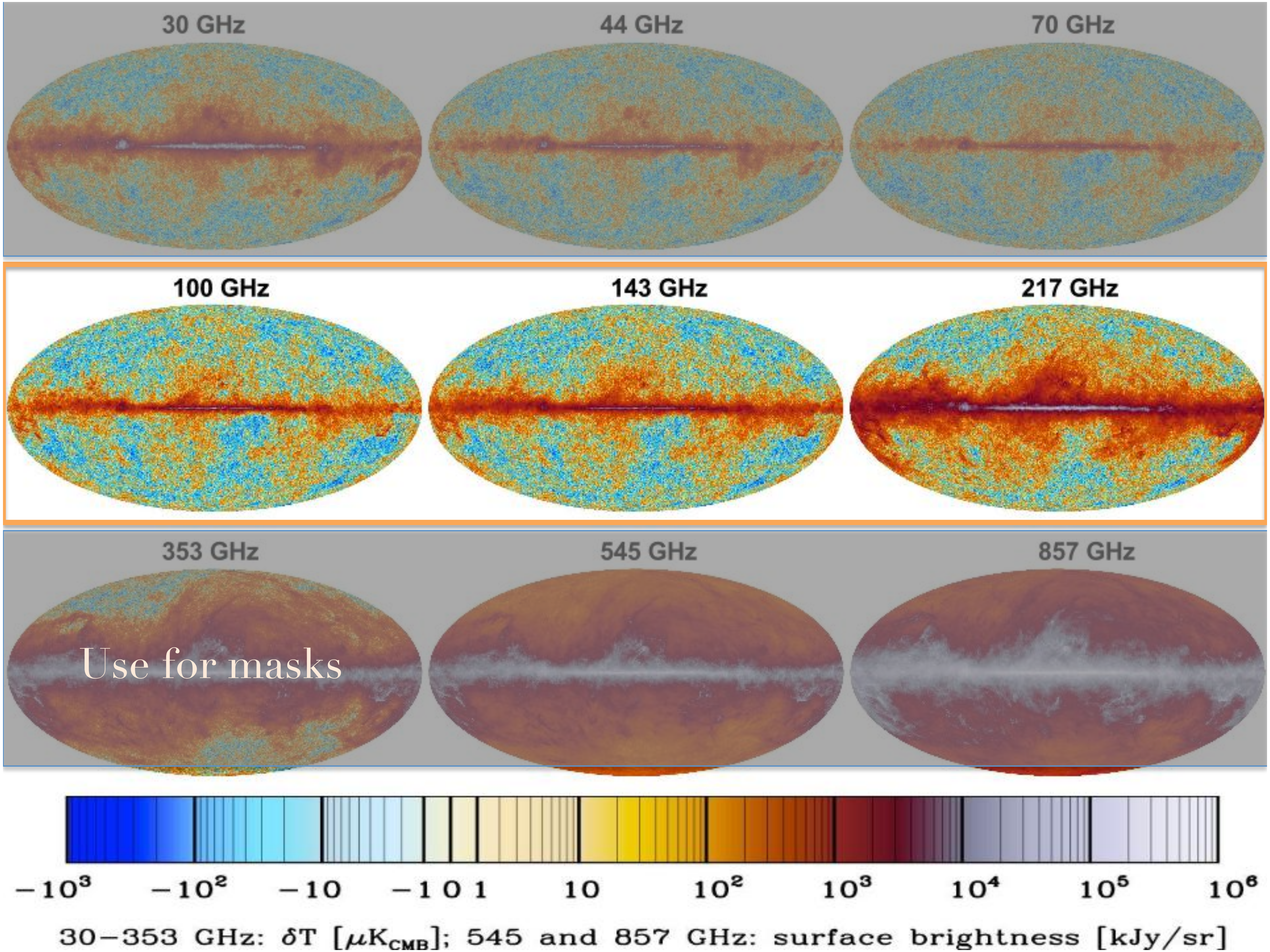
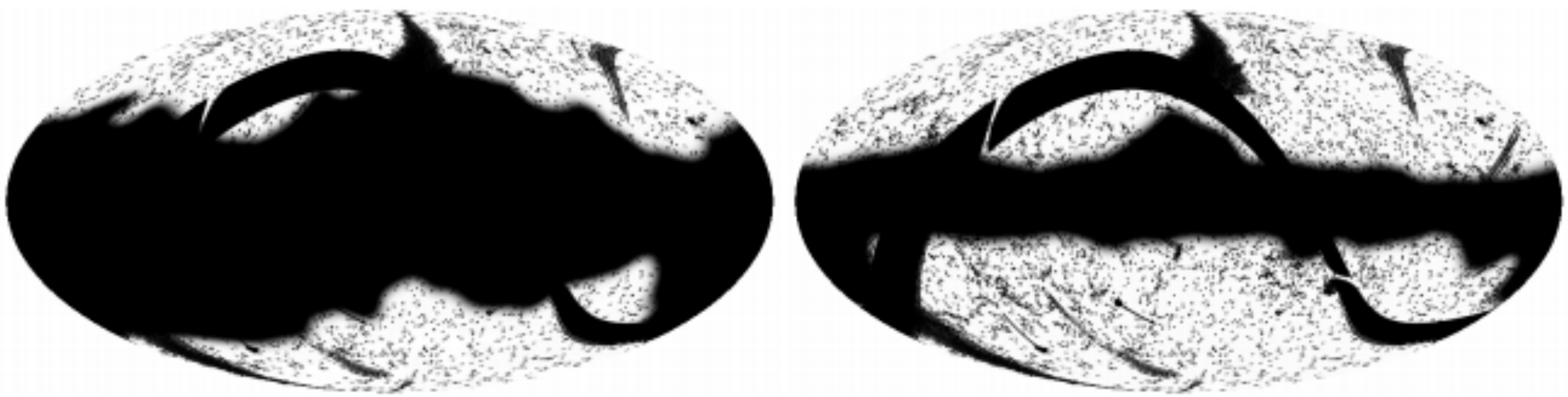
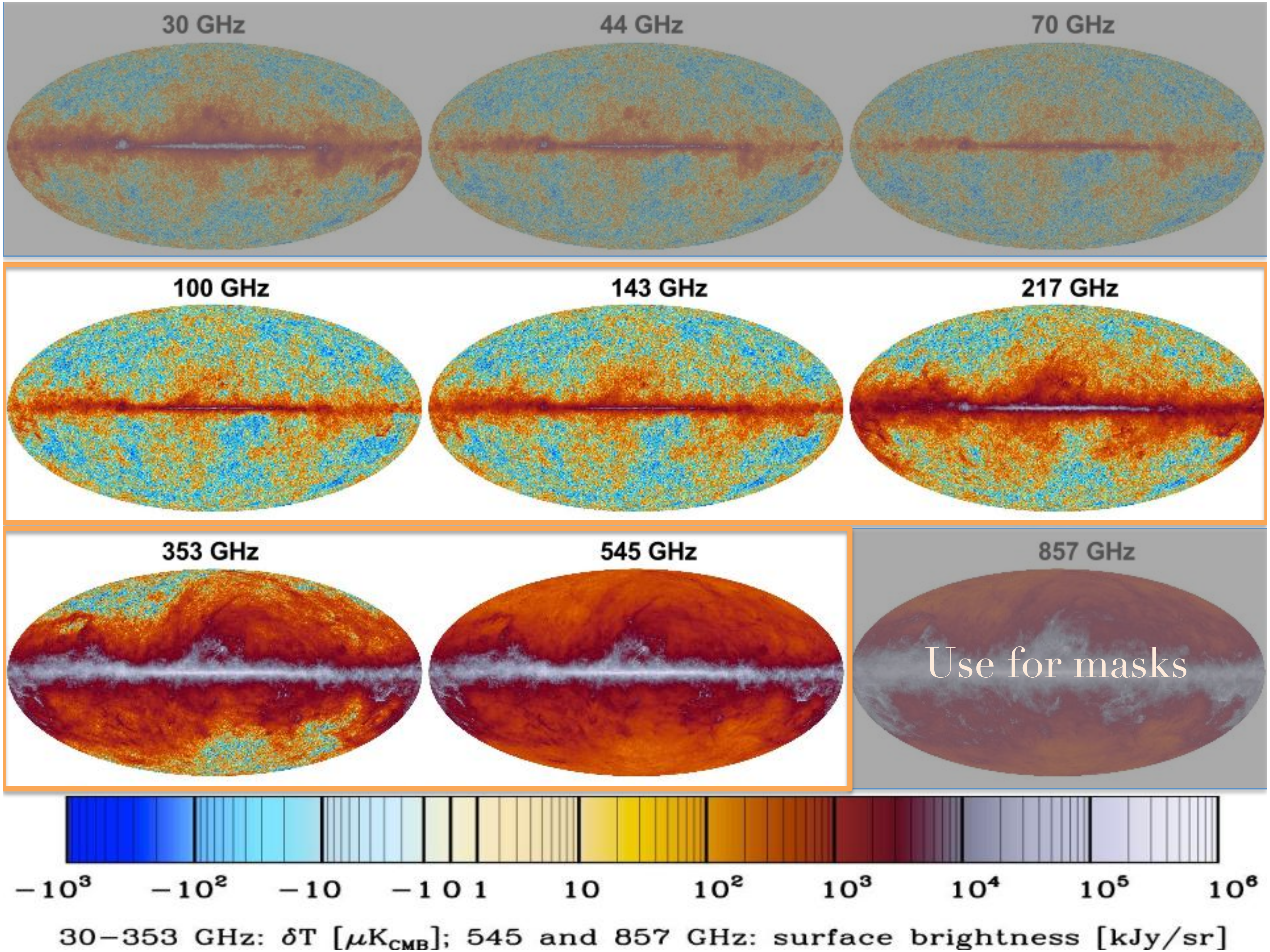

30 GHz
44 GHz
70 GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
857 GHz
Use for masks
−10³ −10² −10 −1 0 1 10 10² 10³ 10⁴ 10⁵ 10⁶
30−353 GHz: δT [μK_CMB]; 545 and 857 GHz: surface brightness [kJy/sr]

With additional cleaning...



$$T_i^{clean} = (1 + \alpha_{ij})T_i - \alpha_{ij}T_j$$


30 GHz
44 GHz
70 GHz
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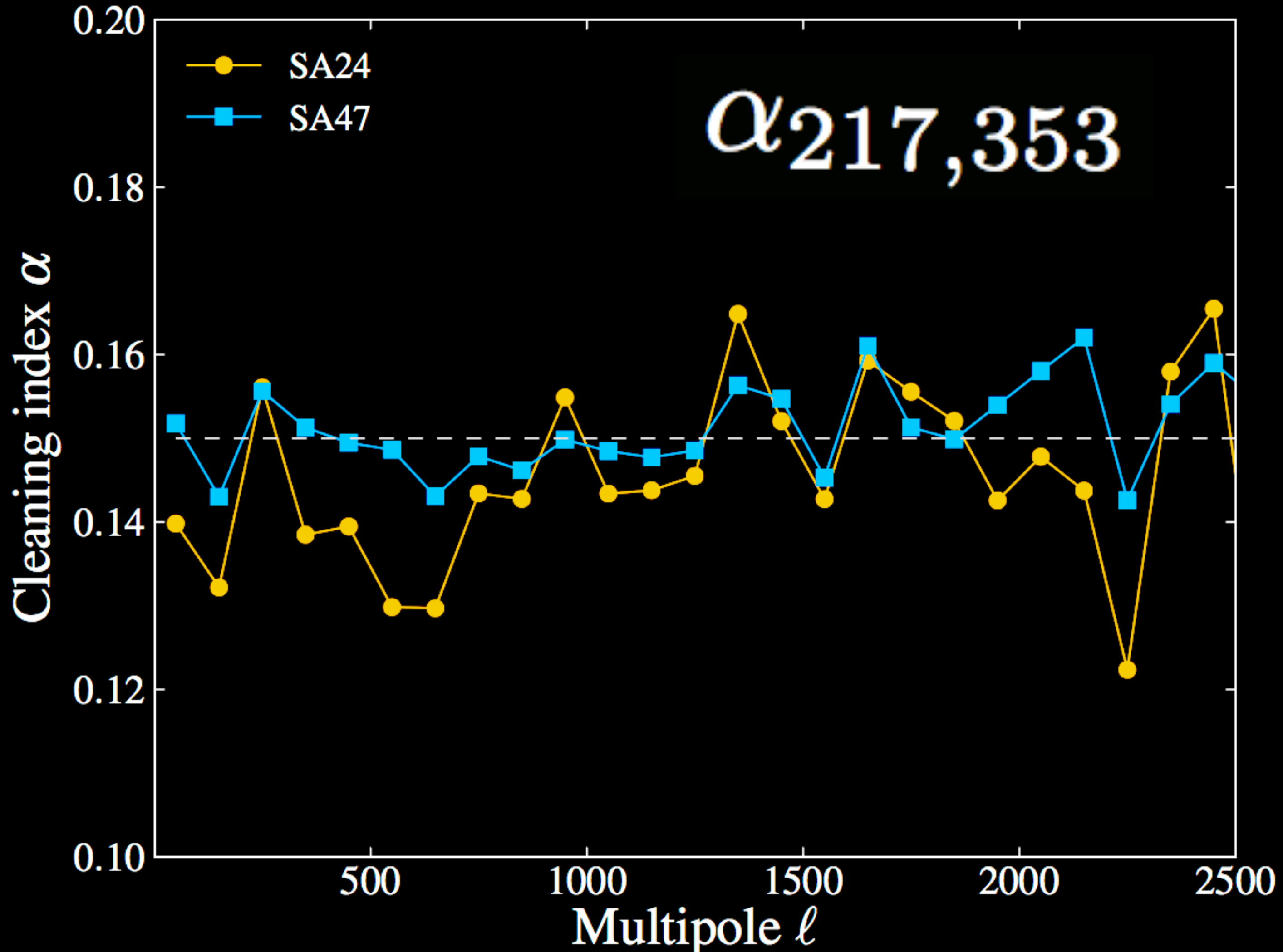
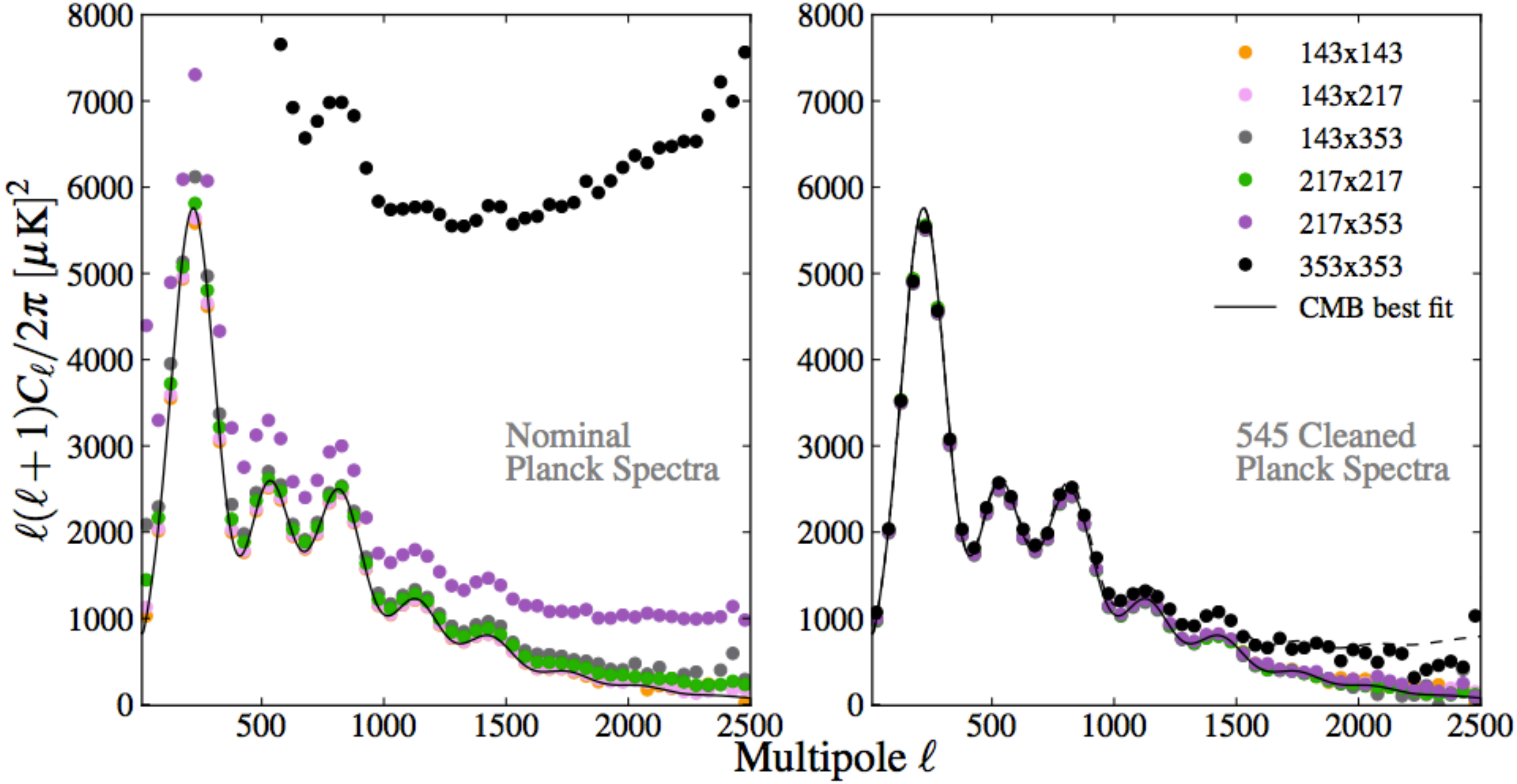
353 GHz
545 GHz
857 GHz
Use for masks
−10³ −10² −10 −1 0 1 10 10² 10³ 10⁴ 10⁵ 10⁶
30−353 GHz: δT [μK_CMB]; 545 and 857 GHz: surface brightness [kJy/sr]

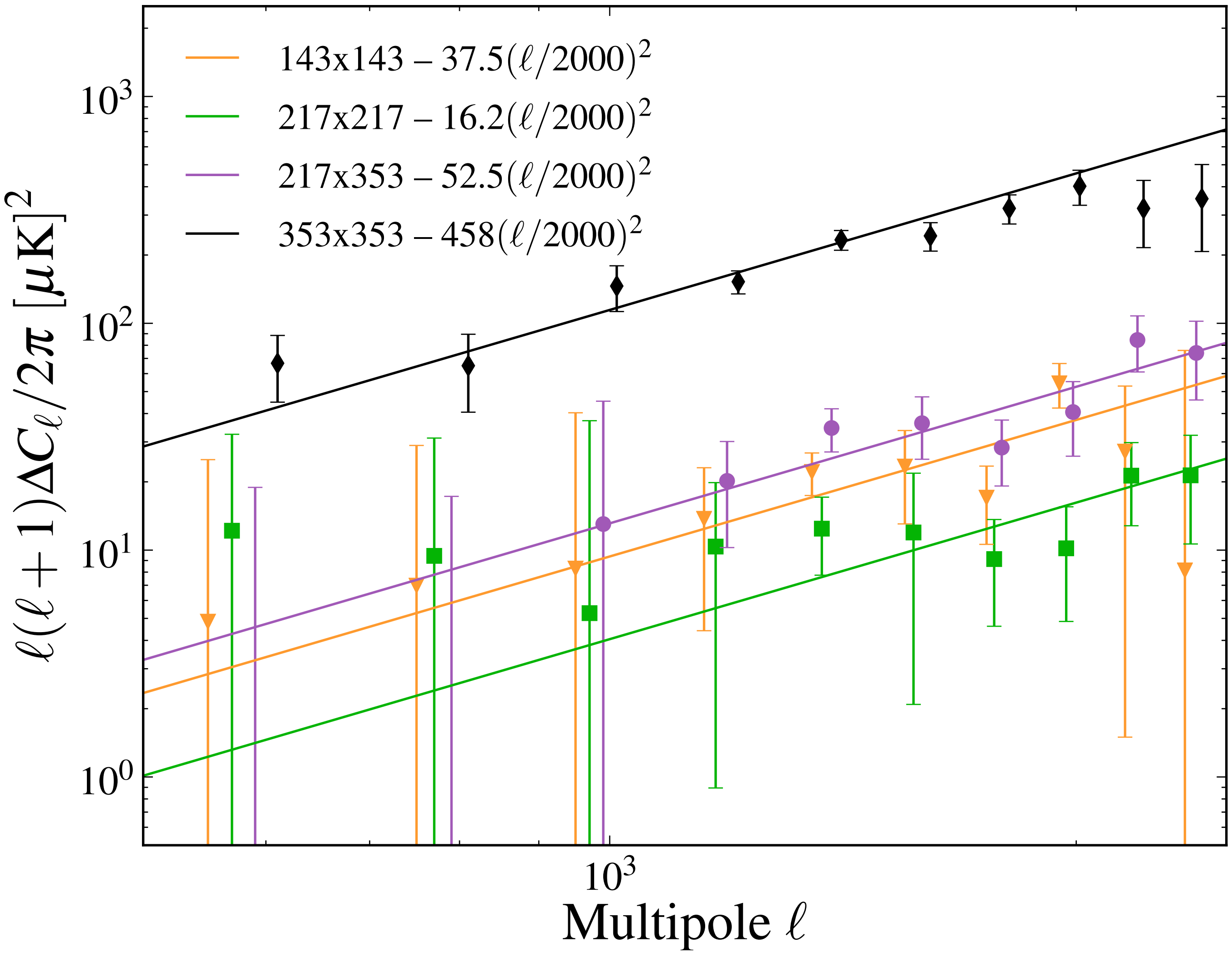
Cleaning coefficient



What does extra cleaning do?

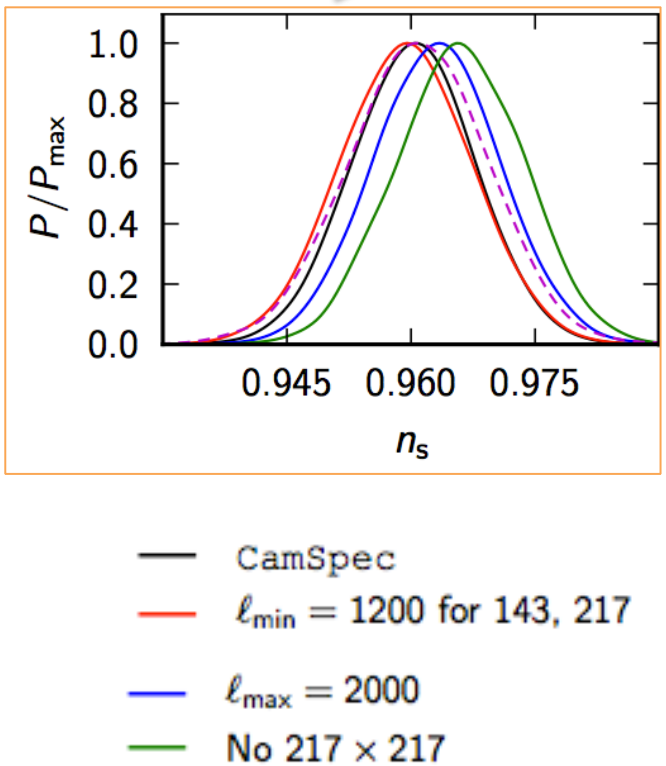


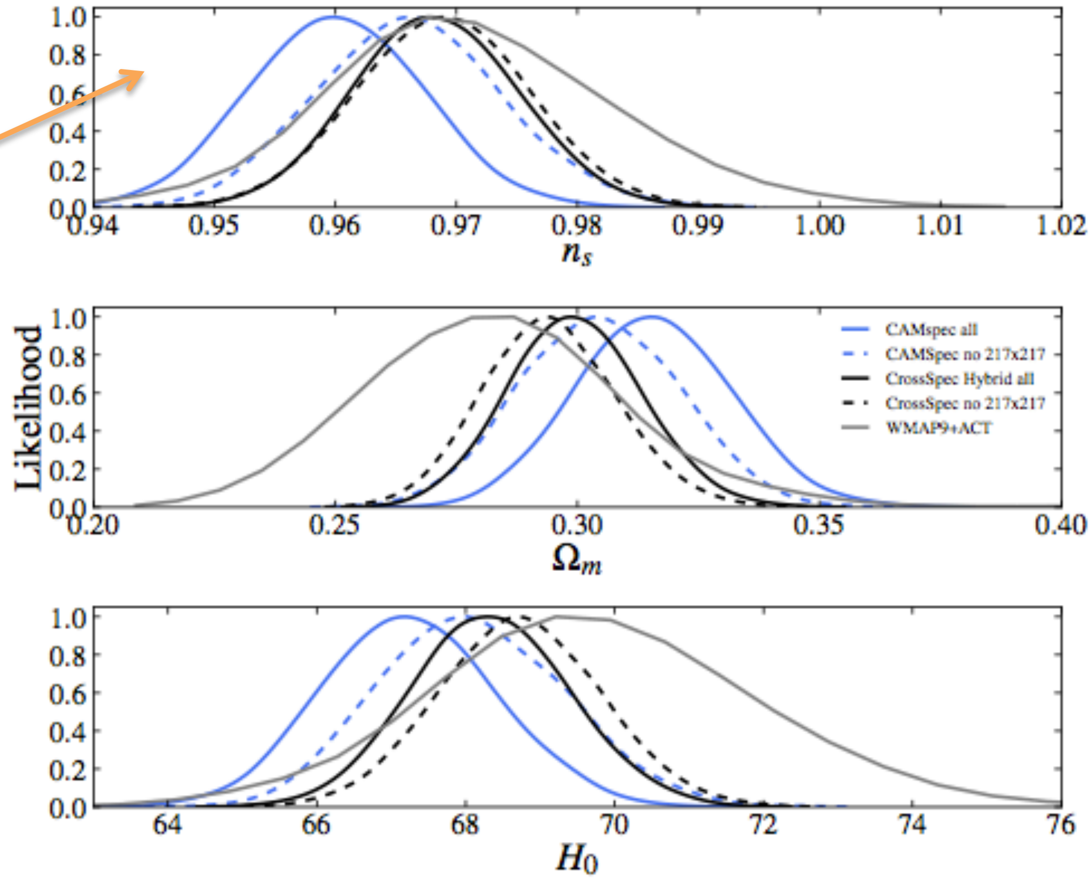
Residual dusty emission



$$C_\ell^{dust,217\times353} = (C_\ell^{dust,217\times217} C_\ell^{dust,353\times353})^{1/2}$$

Parameter shifts

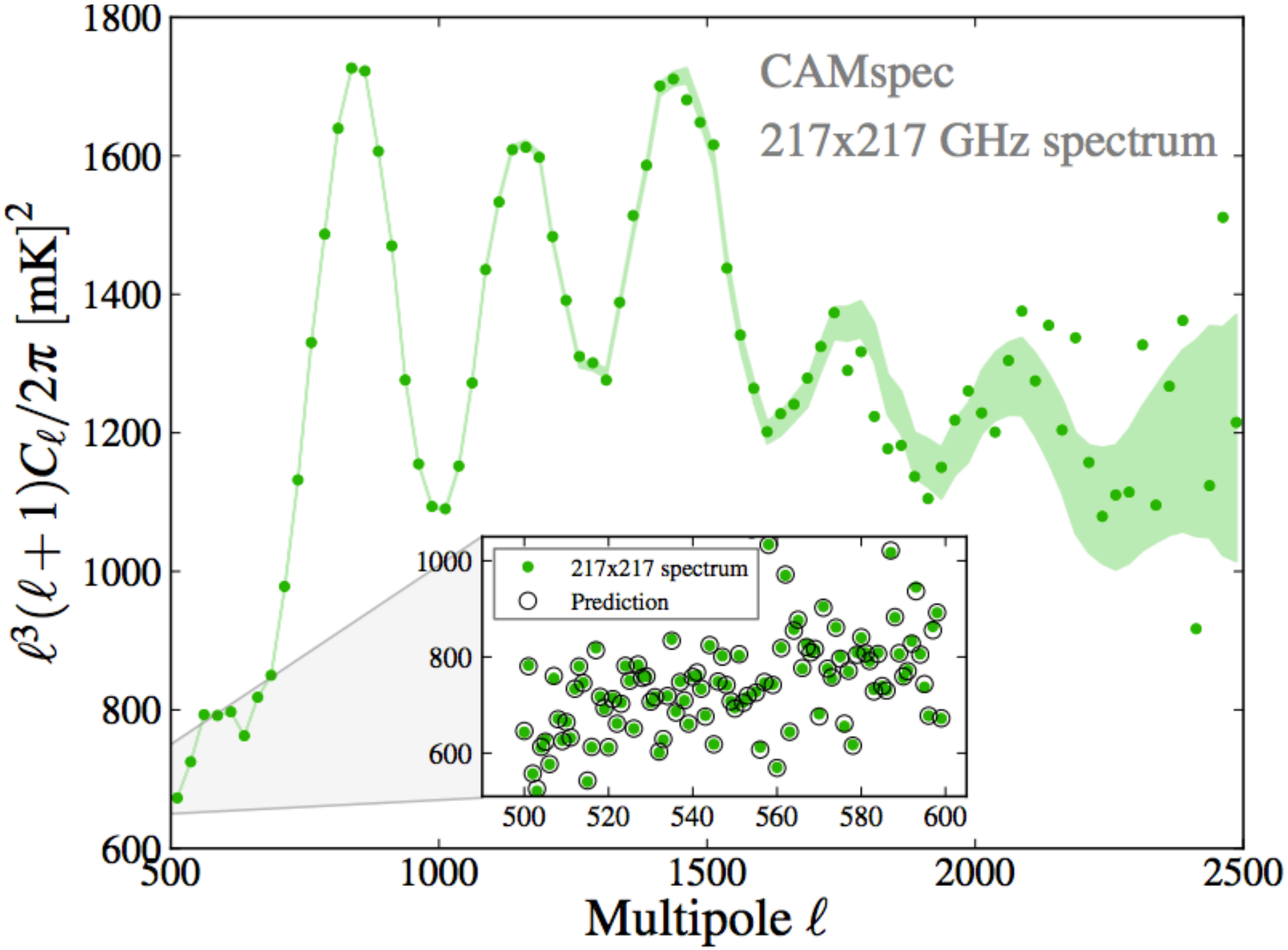




Why didn't Planck do this removal?

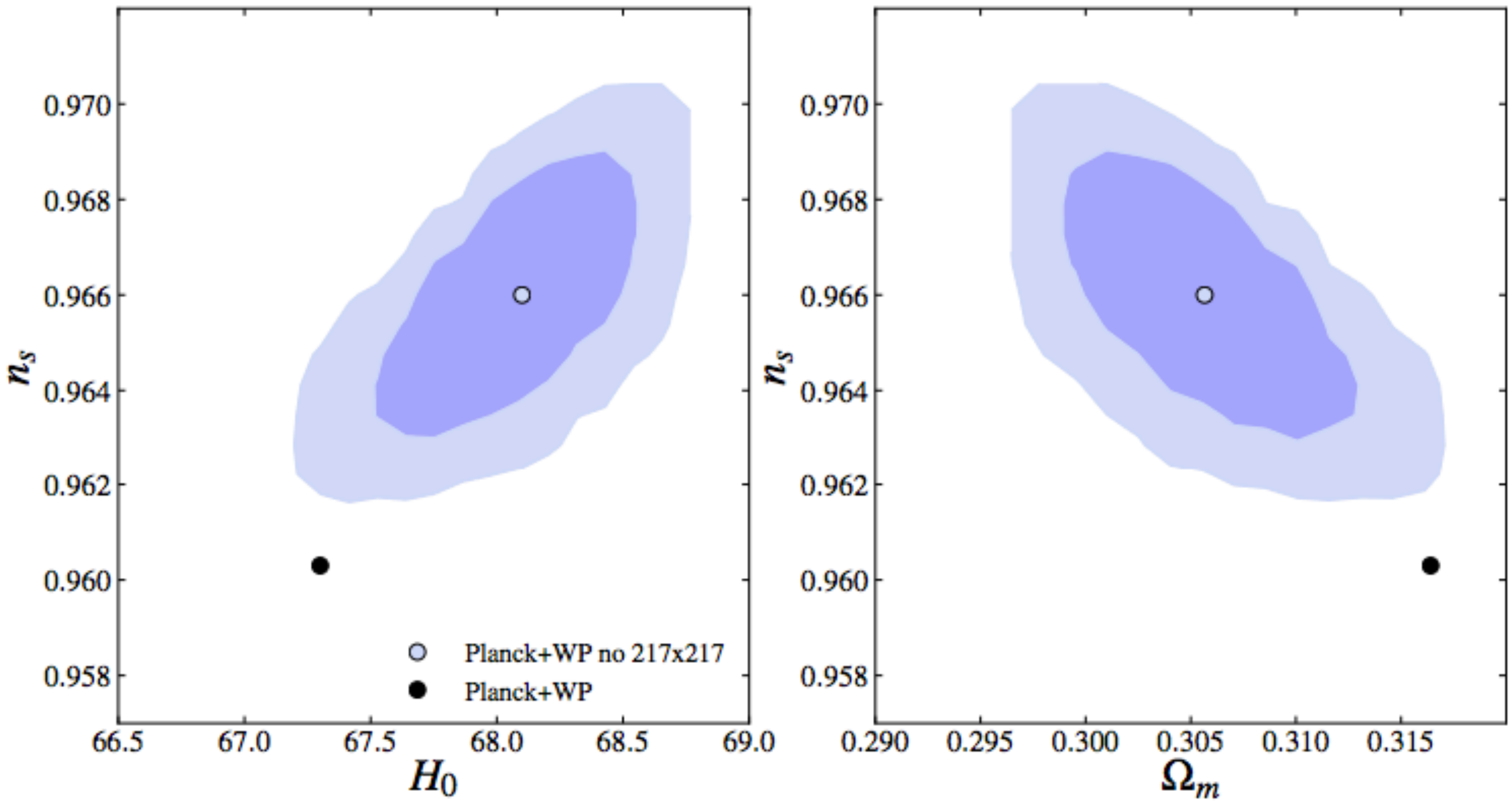
- Dusty galaxy emission either subtracted, or modelled
- Planck model is sufficient to handle the dust
- Doing extra high-frequency cleaning gives you more of the sky
- Shifts we see aren't due to improved cleaning...

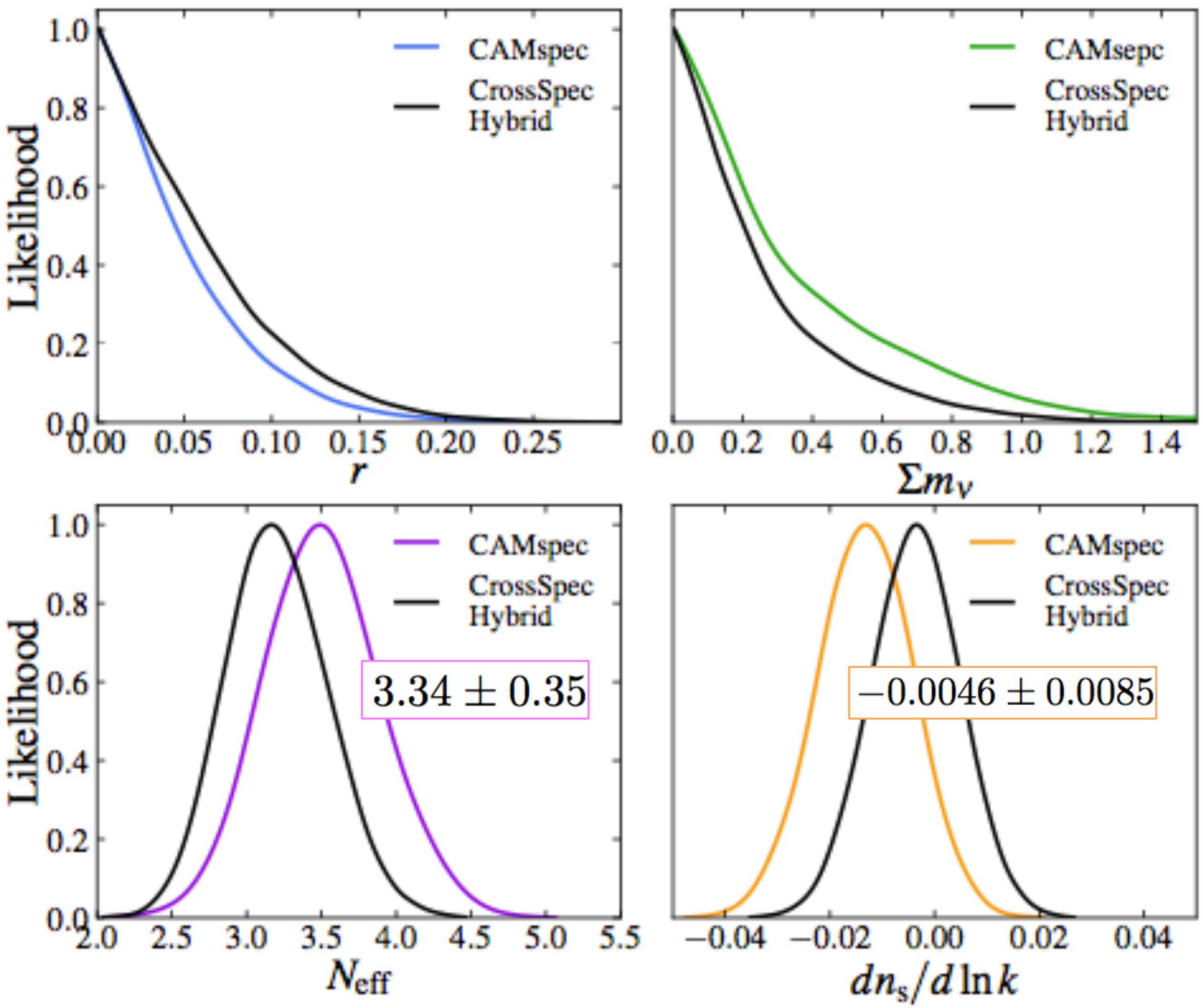
Where do the shifts come from?



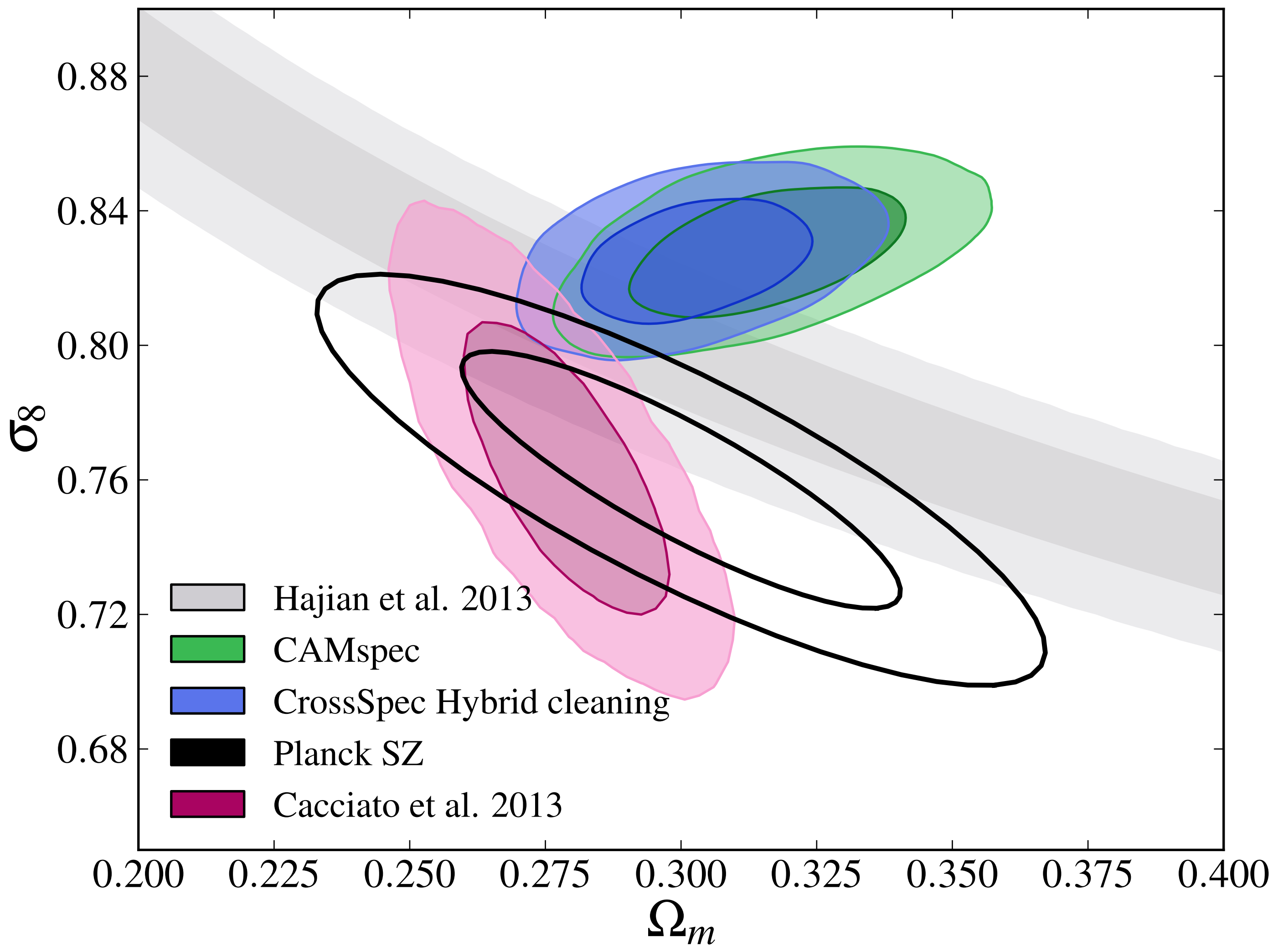
$$p(Y_\alpha|Y_j) = \sqrt{\det\left(\frac{\mathcal{D}_{\alpha\beta}}{2\pi}\right)} \times \exp\left[-\frac{1}{2}(Y_\alpha - \langle Y_\alpha\rangle)\mathcal{D}_{\alpha\beta}(Y_\beta - \langle Y_\beta\rangle)\right] \quad \text{with} \quad \langle Y_\alpha\rangle = -\mathcal{D}^{-1}_{\alpha\beta}\mathcal{D}_{\beta_j}Y_j$$

Shifts in simulations





Likelihood
CAMspec
CrossSpec Hybrid
r
CAMsepc
CrossSpec Hybrid
Σm_ν
Likelihood
CAMspec
CrossSpec Hybrid
3.34 ± 0.35
N_eff
CAMspec
CrossSpec Hybrid
−0.0046 ± 0.0085
dn_s/d ln k



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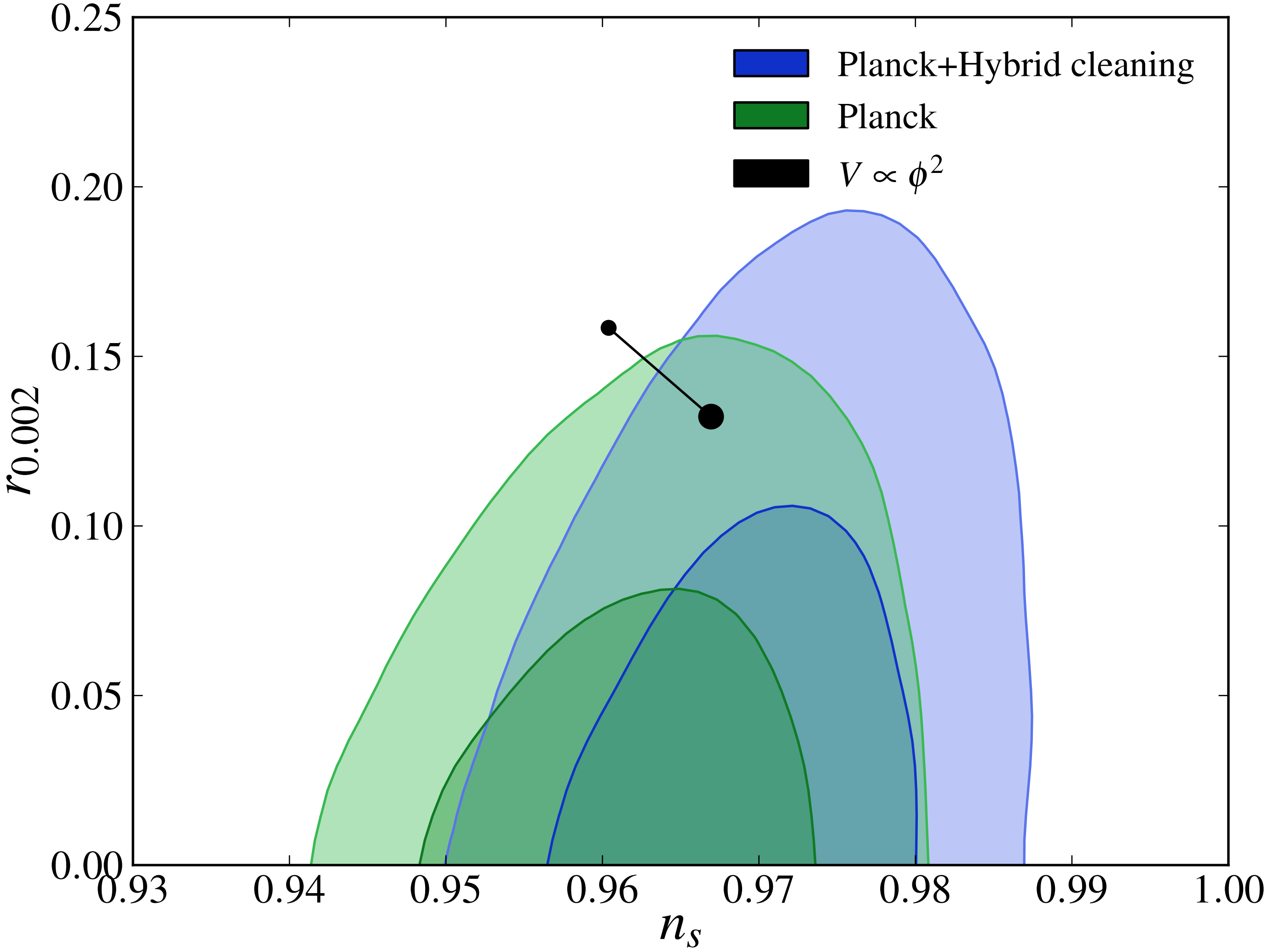
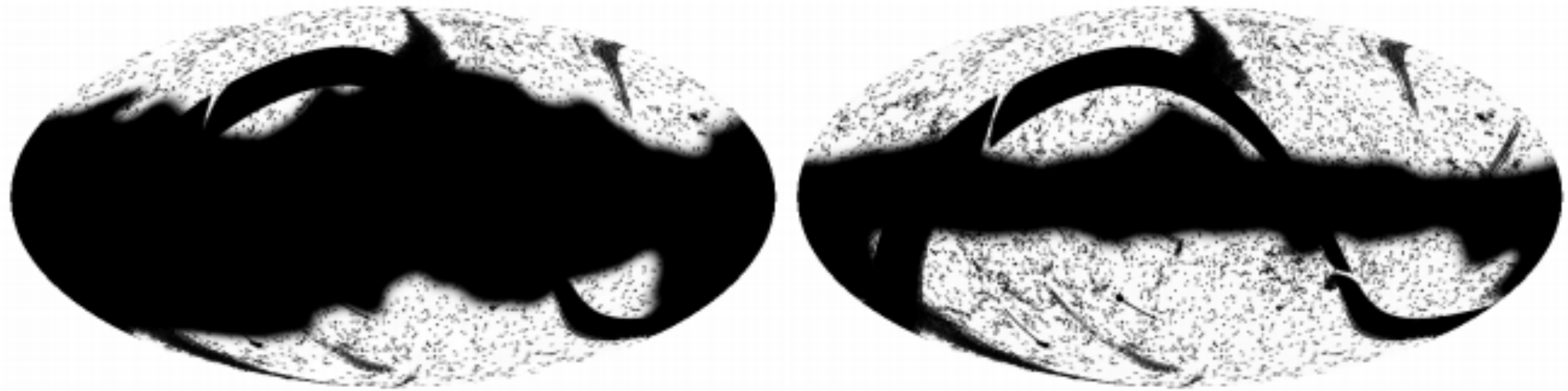


Planck+Hybrid cleaning
Planck
$V \propto \phi^2$
0.25
0.20
0.15
0.10
0.05
0.00
$r_{0.002}$
0.93
0.94
0.95
0.96
0.97
0.98
0.99
1.00
n_s

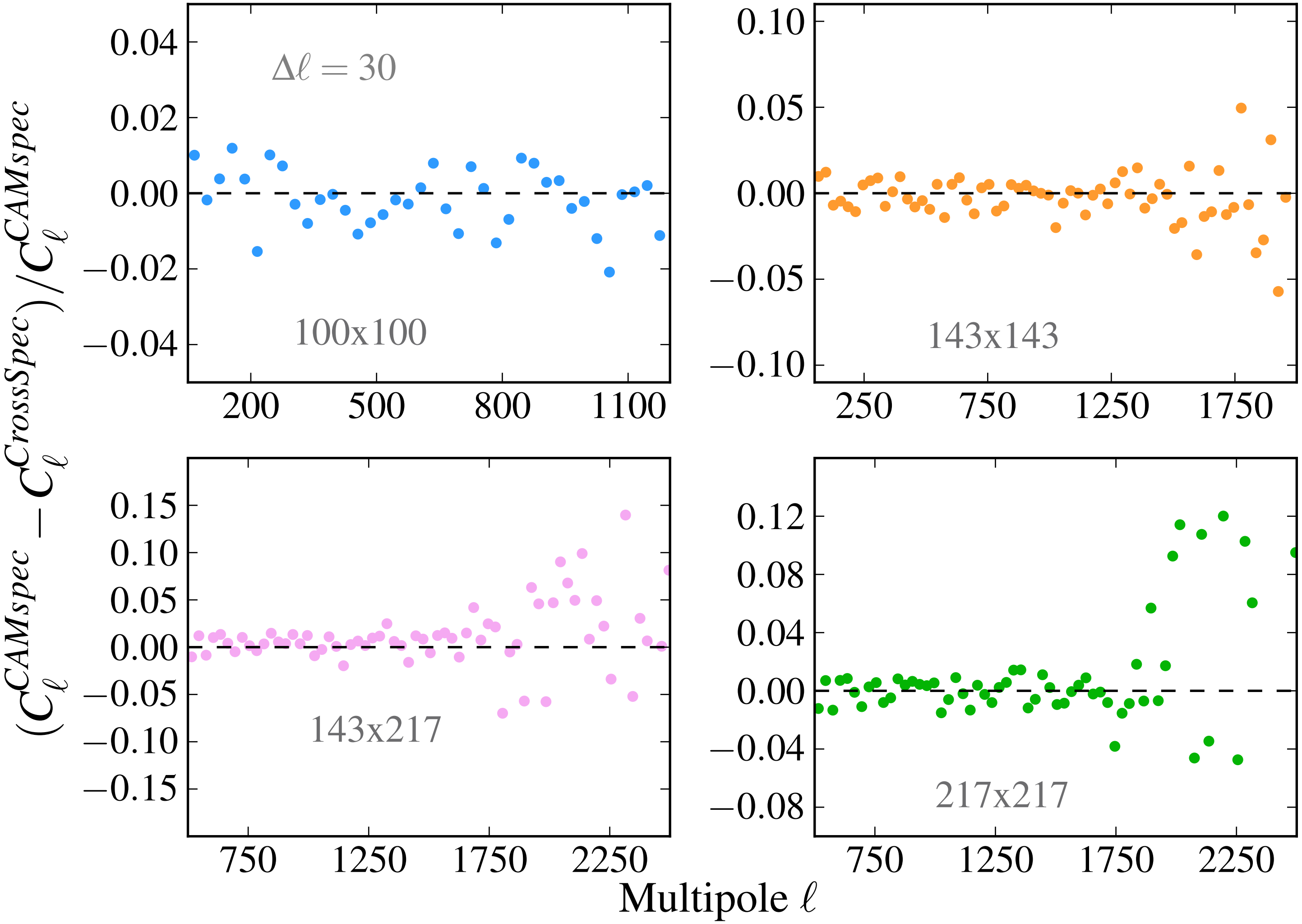
$r < 0.14$

Where are the shifts coming from?



We don't have the same maps as the Planck team uses.

survey vs detector set spectra



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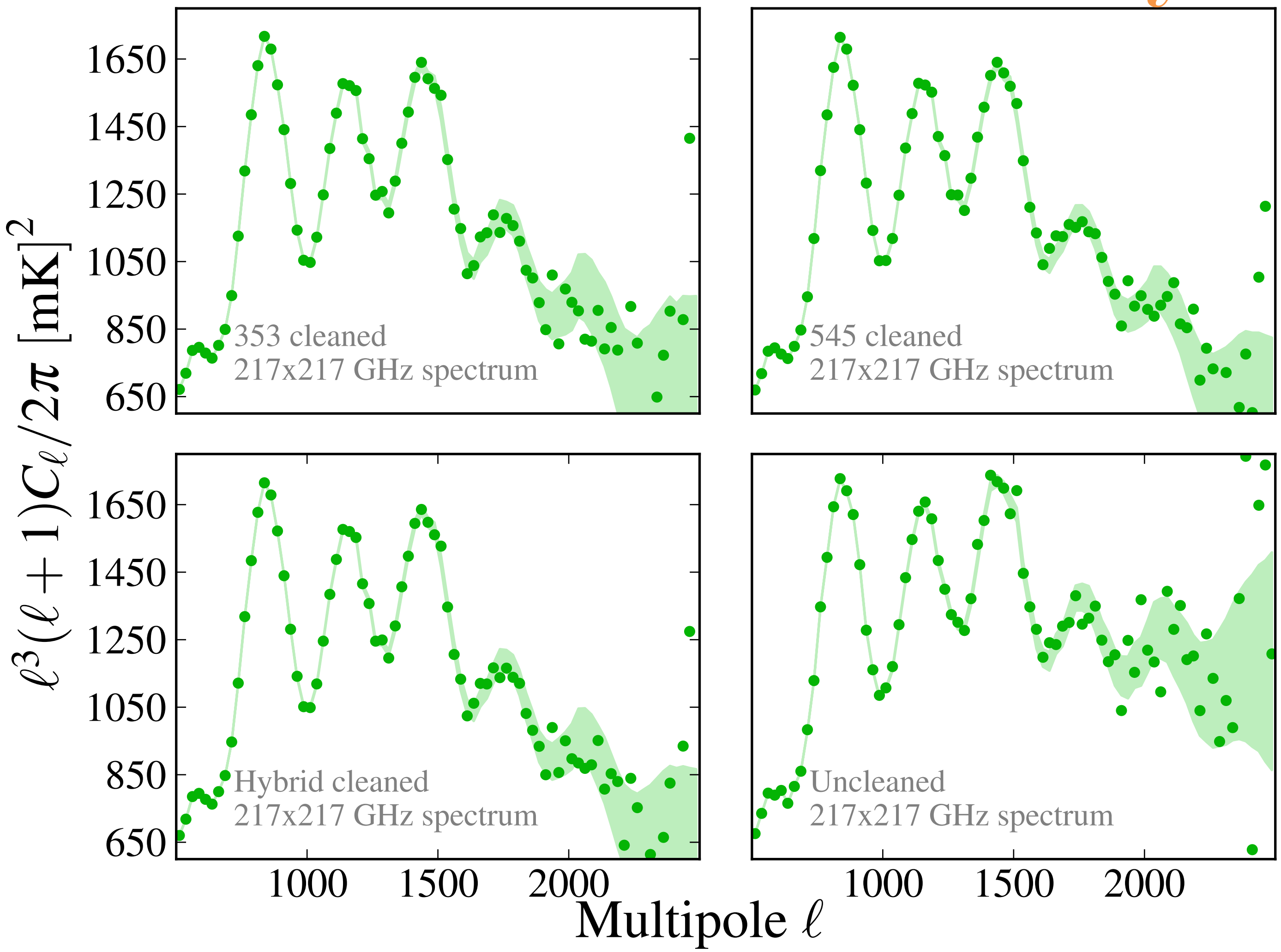
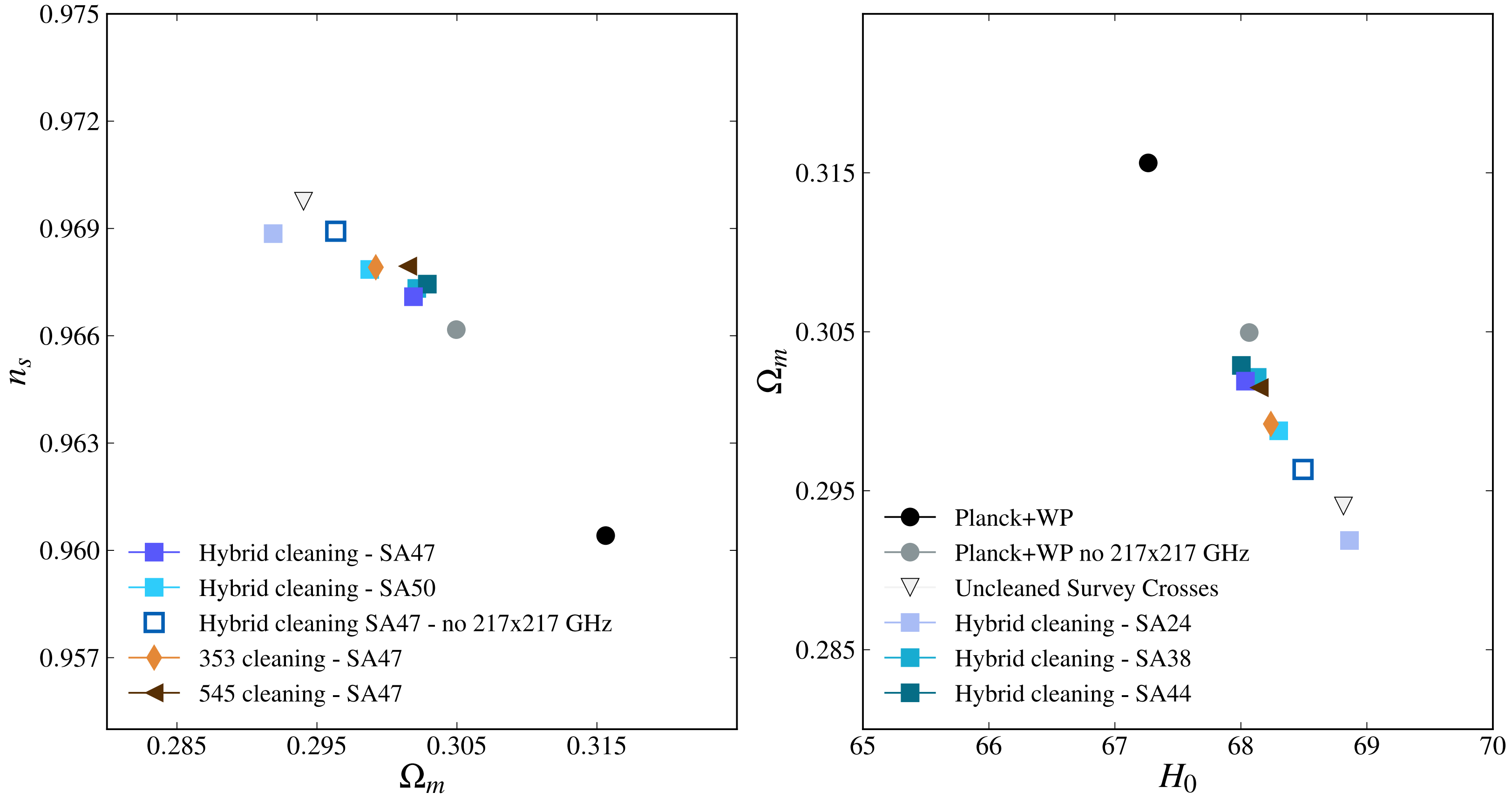
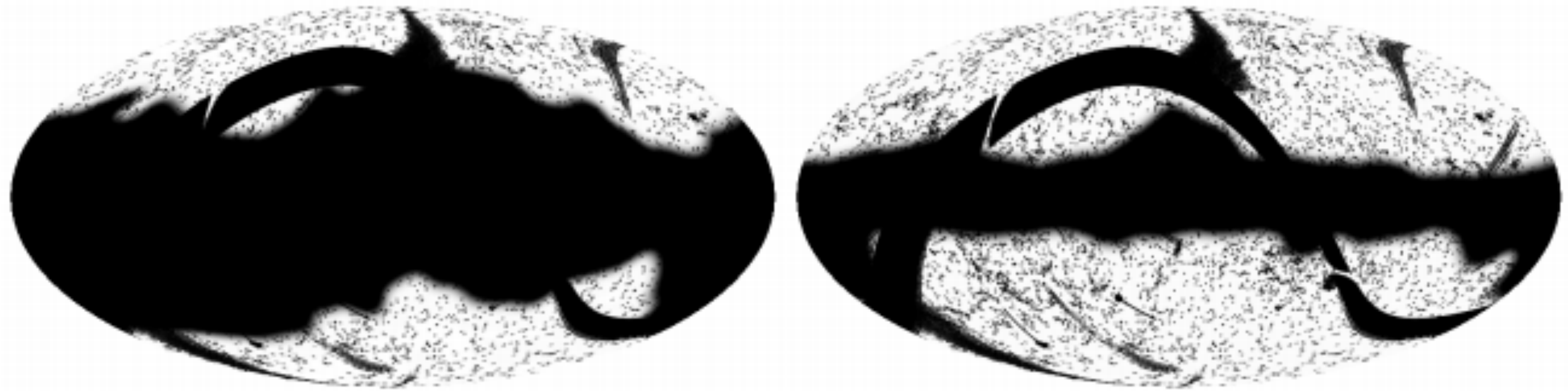
Internal consistency



Different cleaning prescriptions



Sky coverage



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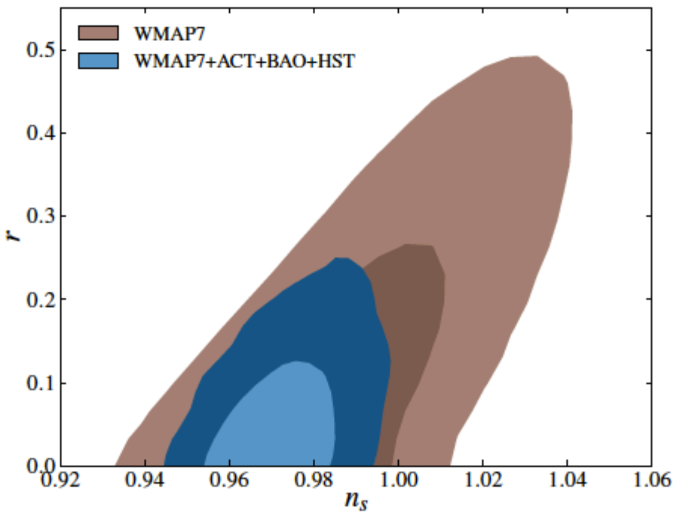
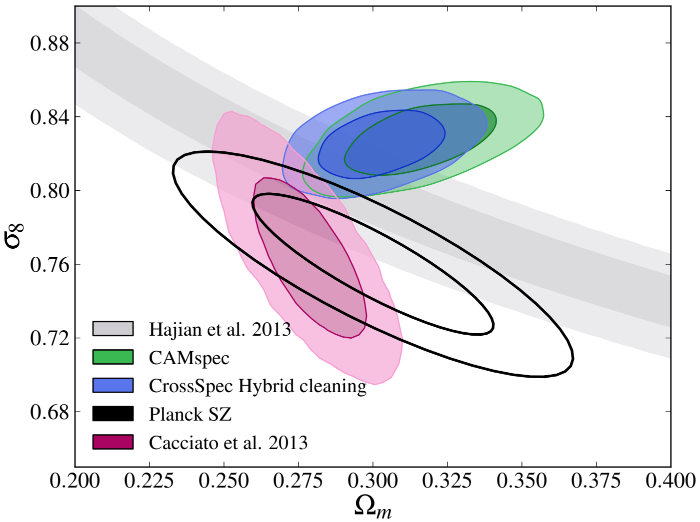
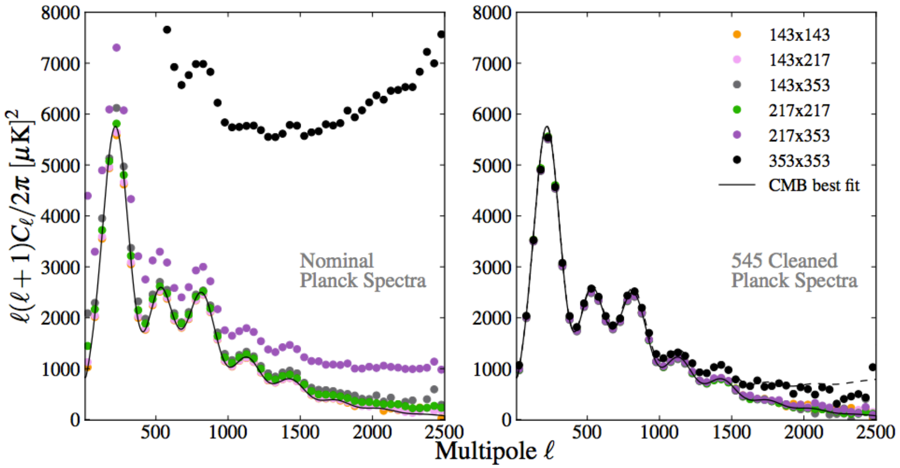
Shifts not due to f_{sky}

	$f_{sky} = 0.38$	$f_{sky} = 0.44$	$f_{sky} = 0.47$	$f_{sky} = 0.50$
$\Omega_c h^2$	0.1174	0.1172	0.1169	0.1165
n_s	0.9673	0.9674	0.9671	0.9679
h	0.681	0.680	0.680	0.683
$100\ \Omega_b h^2$	2.199	2.199	2.197	2.206
$\log(10^{10} A_s)$	3.086	3.082	3.080	3.082
τ	0.091	0.089	0.089	0.091
$-2 \ln \mathcal{L}_{\mathrm{CAMspec}}$	7543.95	7546.05	7555.72	7640.30
$-2 \ln \mathcal{L}_{\mathrm{Commander}}$	-8.06	-8.03	-8.10	-8.02
$-2 \ln \mathcal{L}_{\mathrm{lowlike}}$	2014.58	2014.64	2014.72	2014.64

Summary


WMAP7
WMAP7+ACT+BAO+HST
r
n_s
0.0
0.1
0.2
0.3
0.4
0.5
0.92
0.94
0.96
0.98
1.00
1.02
1.04
1.06


Hajian et al. 2013
CAMspec
CrossSpec Hybrid cleaning
Planck SZ
Cacciato et al. 2013
σ_8
Ω_m
0.68
0.72
0.76
0.80
0.84
0.88
0.200
0.225
0.250
0.275
0.300
0.325
0.350
0.375
0.400


$\ell(\ell+1)C_\ell/2\pi$ [μK]^2
Nominal
Planck Spectra
545 Cleaned
Planck Spectra
143x143
143x217
143x353
217x217
217x353
353x353
CMB best fit
Multipole ℓ
0
1000
2000
3000
4000
5000
6000
7000
8000
500
1000
1500
2000
2500