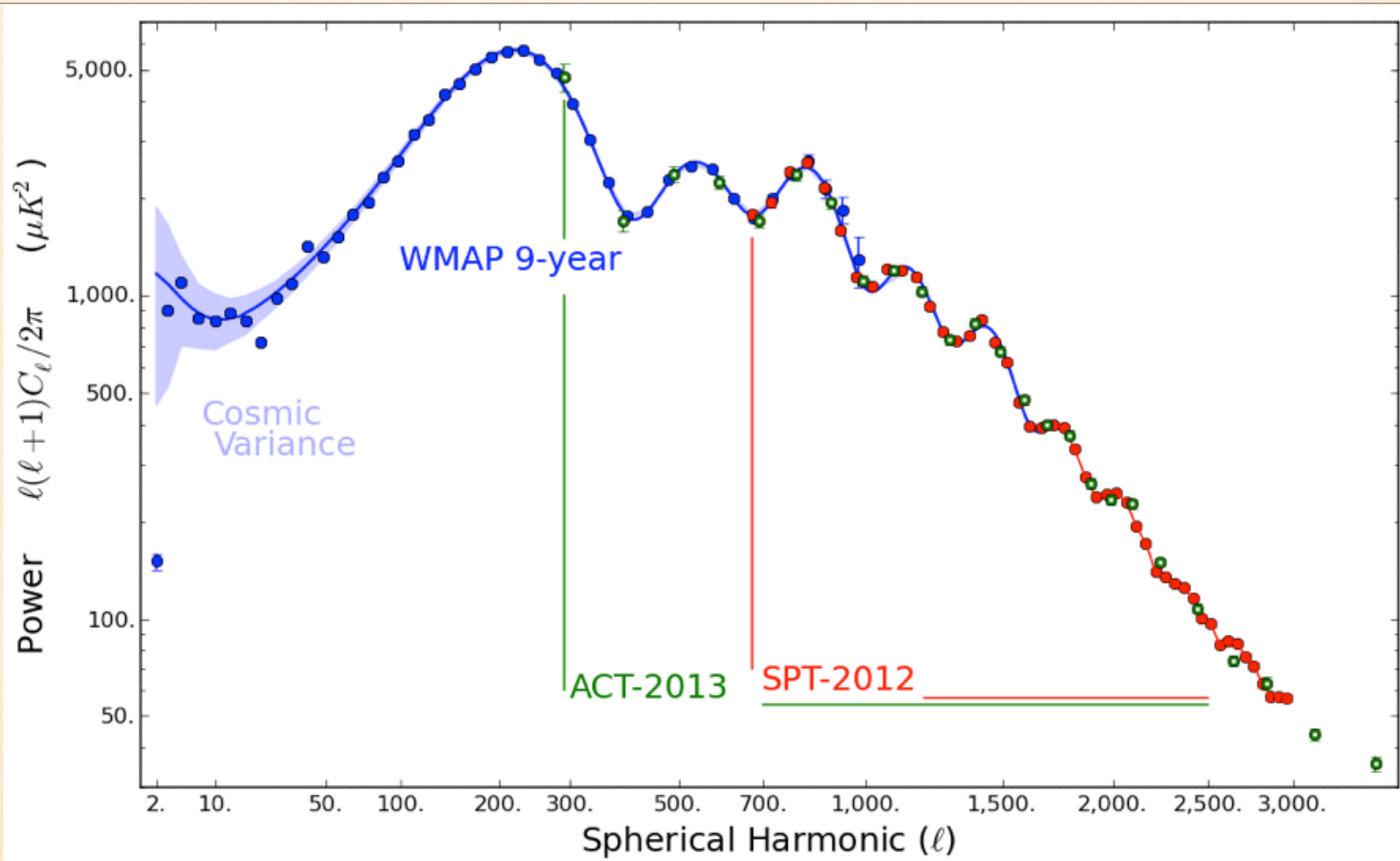
BEYOND CMB:
CROSS CORRELATIONS

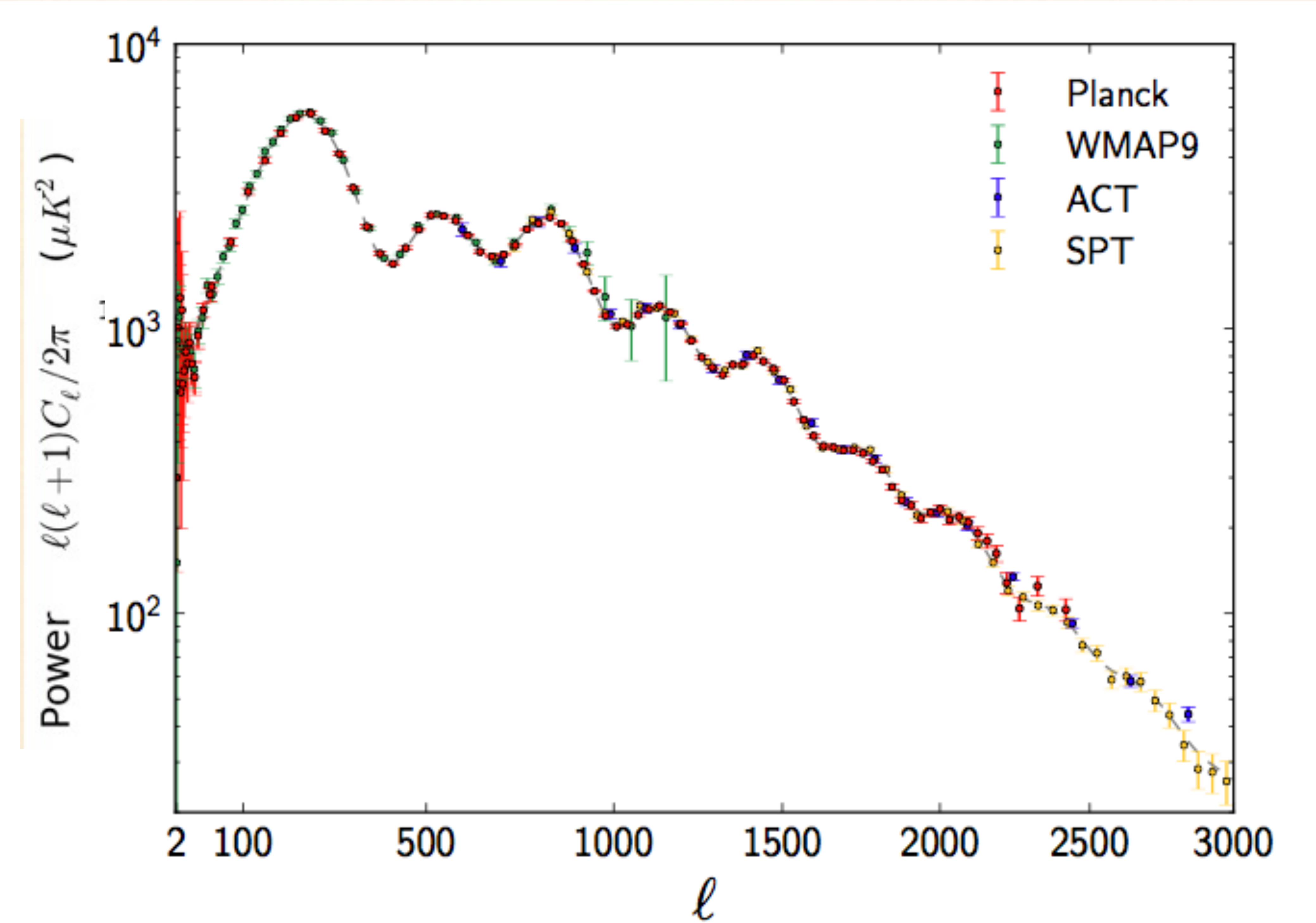
Amir Hajian

LBNL, Berkeley
December 13, 2013

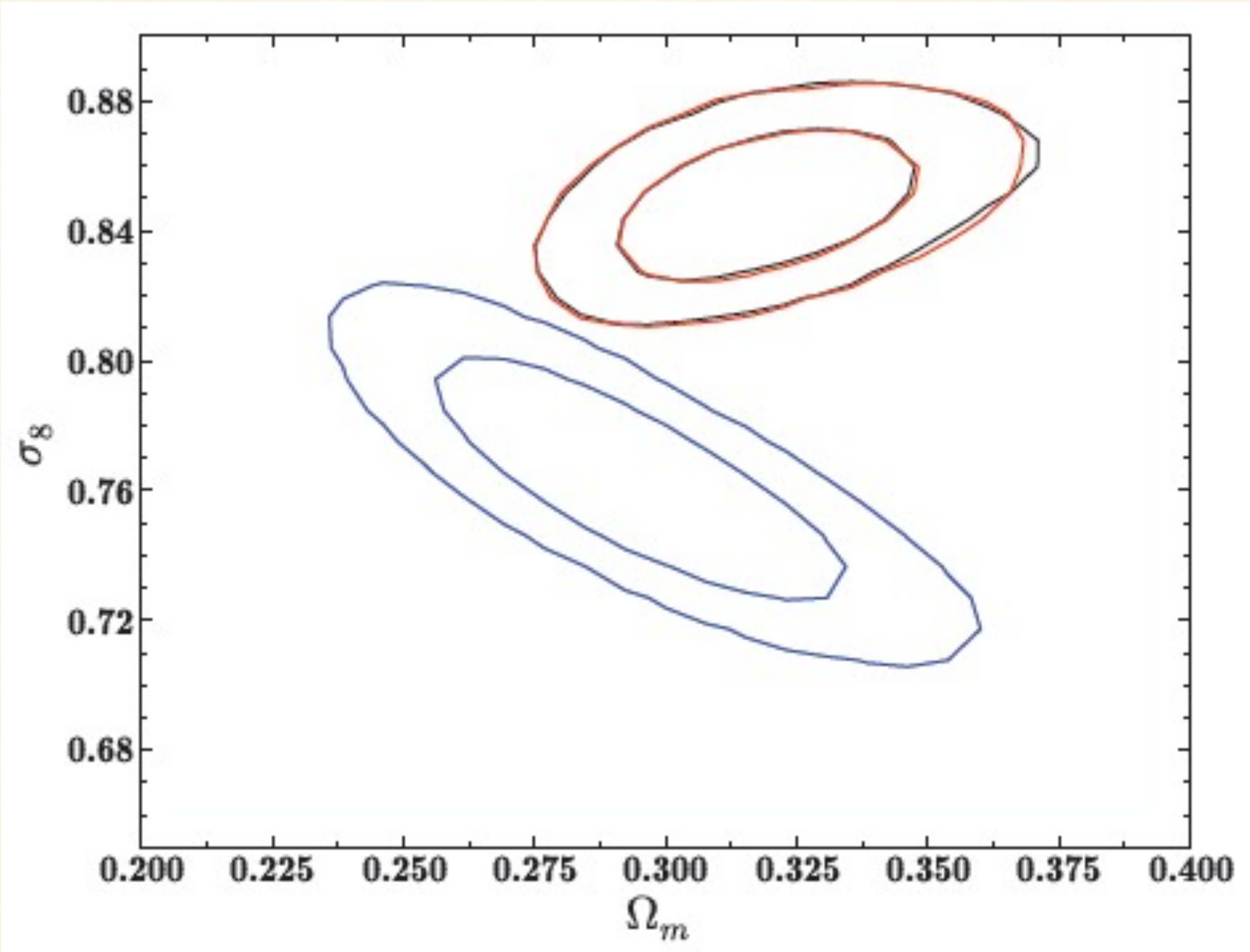
MEASURED CMB POWER SPECTRUM ...



CMB POWER SPECTRUM: COSMOLOGY FITS

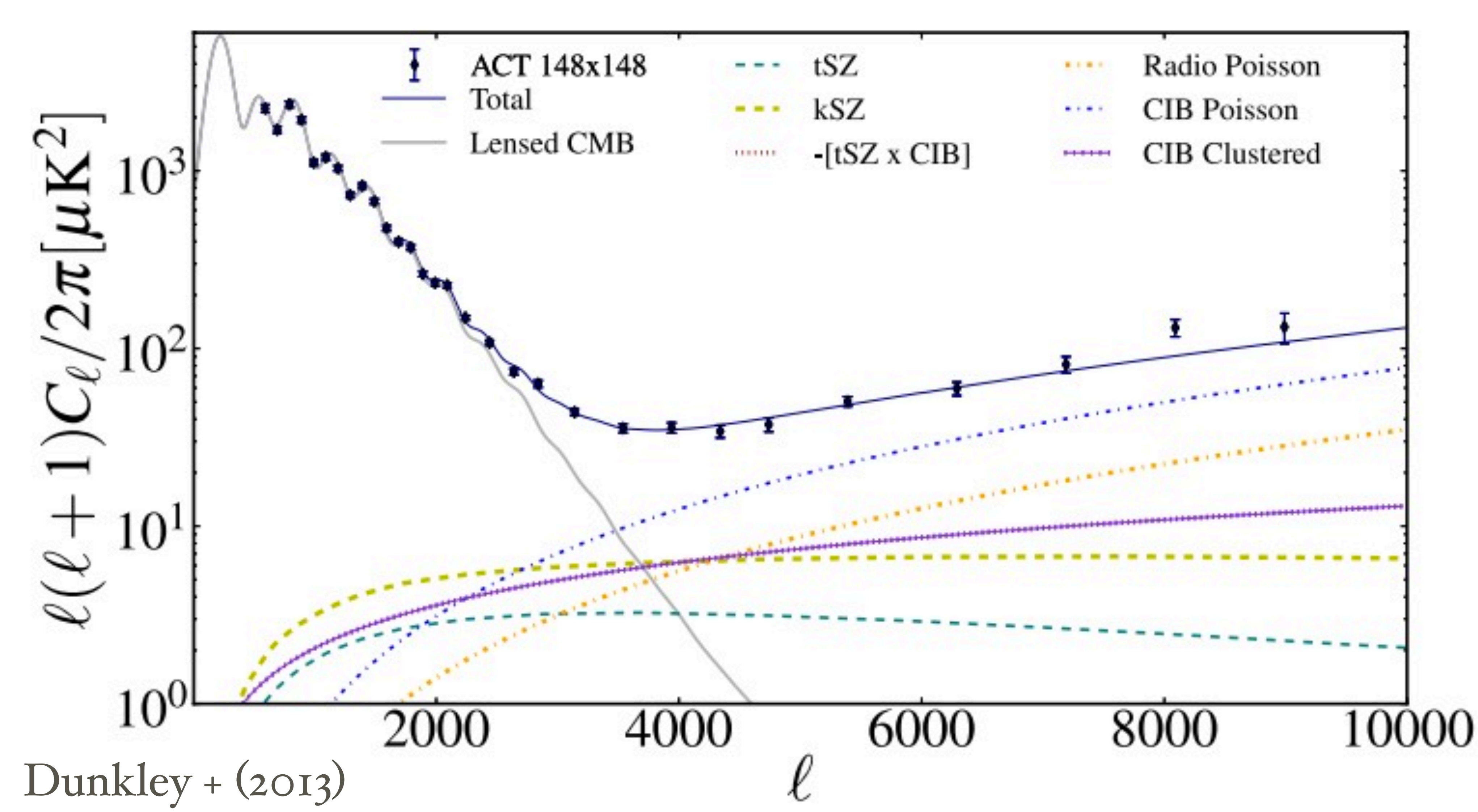


... ALMOST FITS

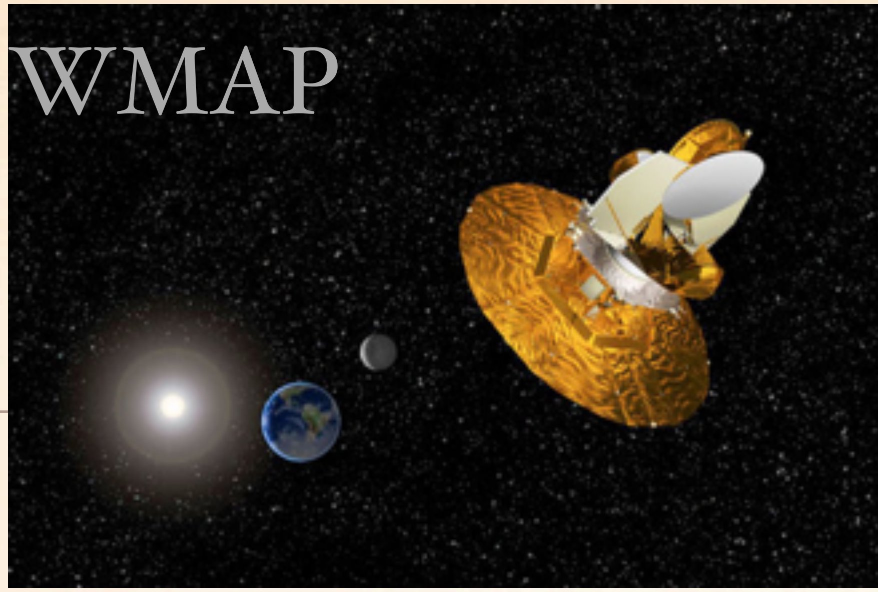


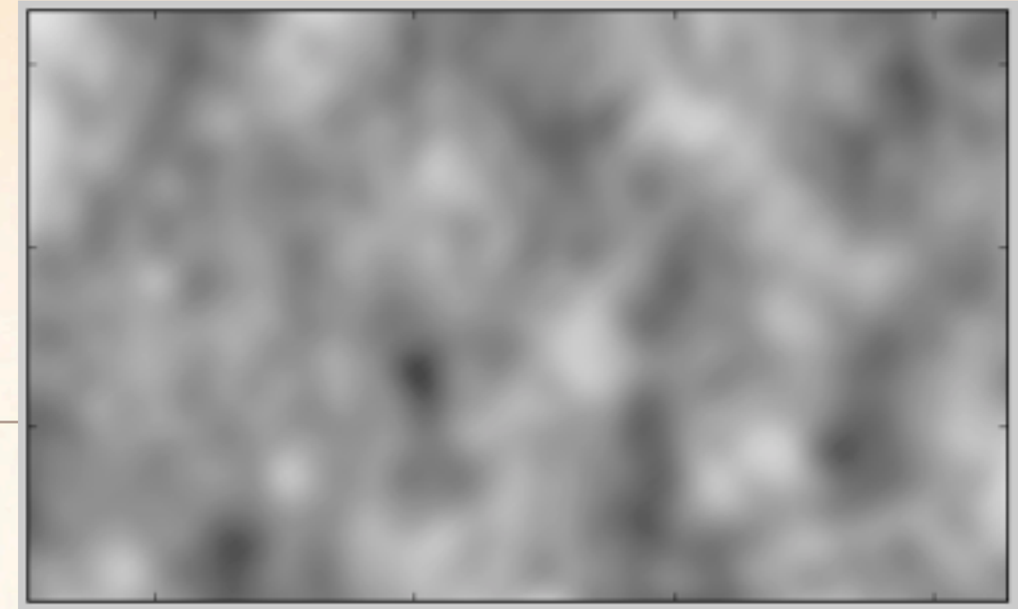
Planck Collaboration XX

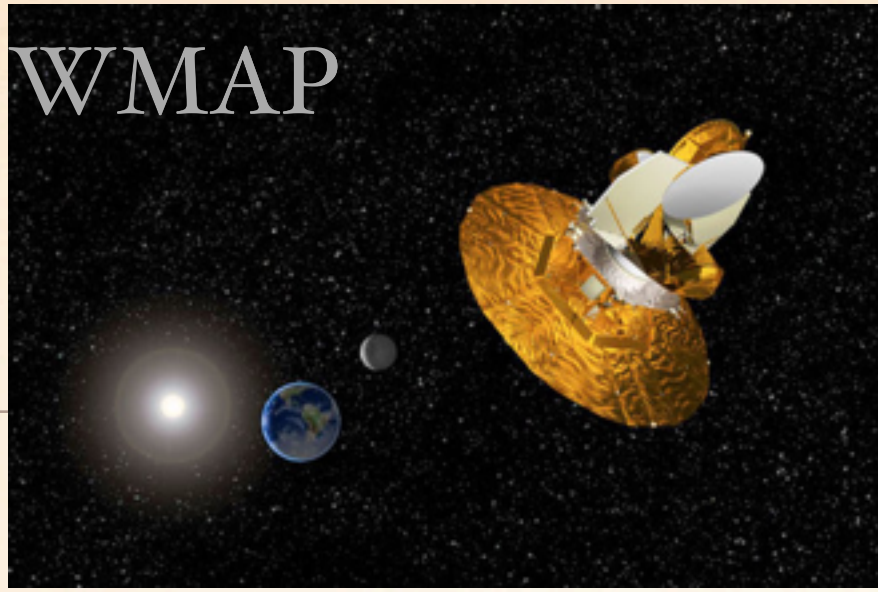
FULL CMB POWER SPECTRUM



Dunkley + (2013)


WMAP

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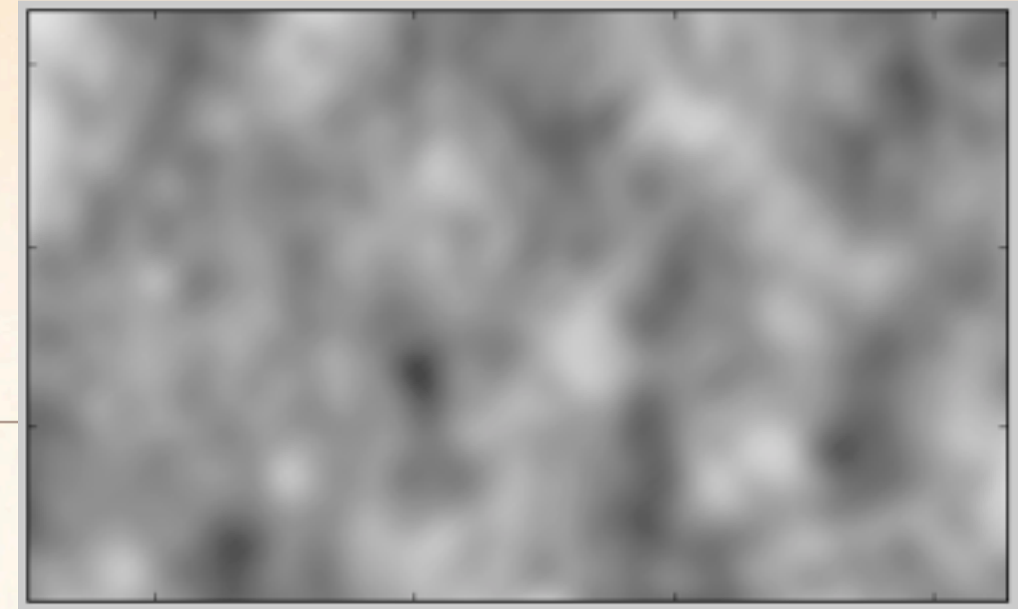
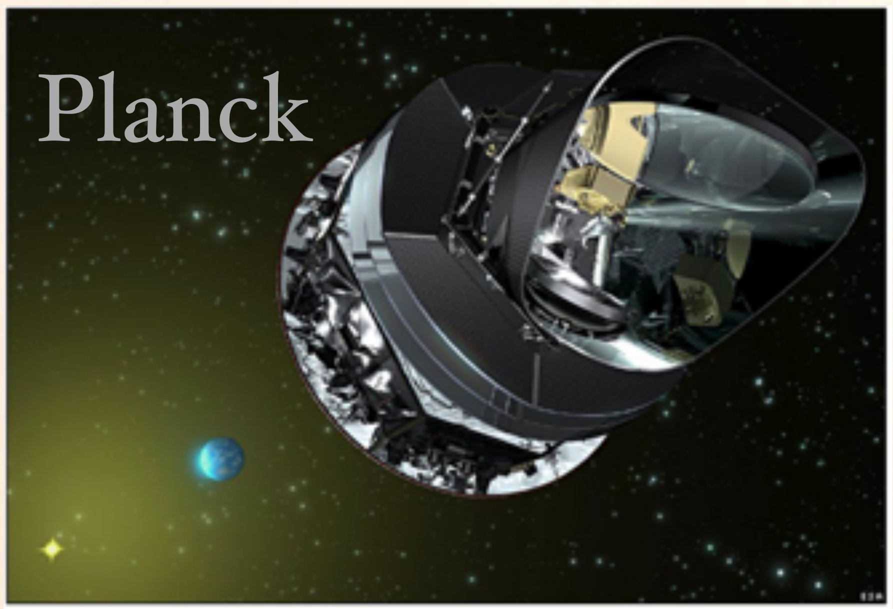
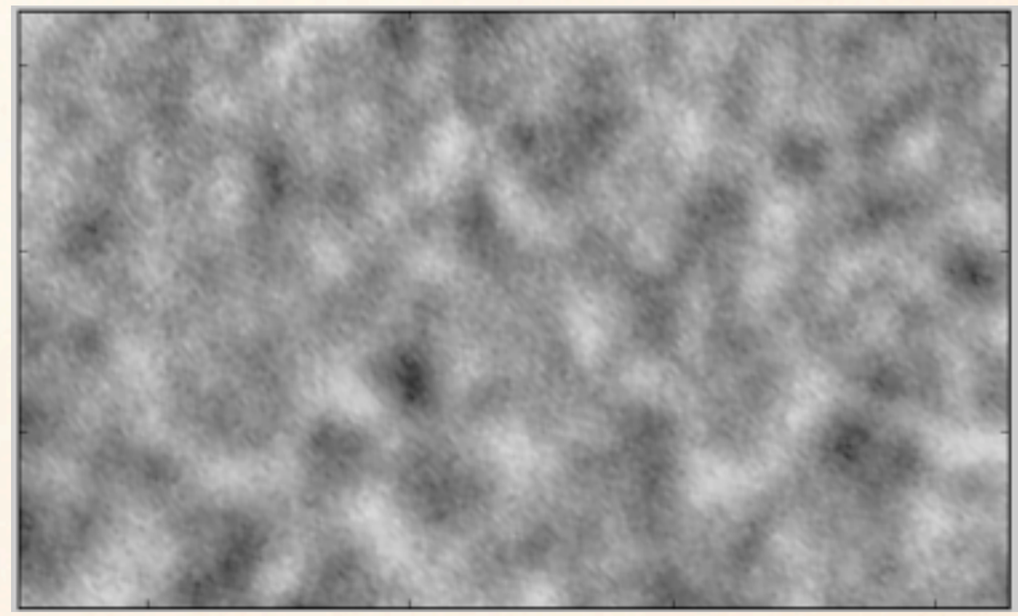
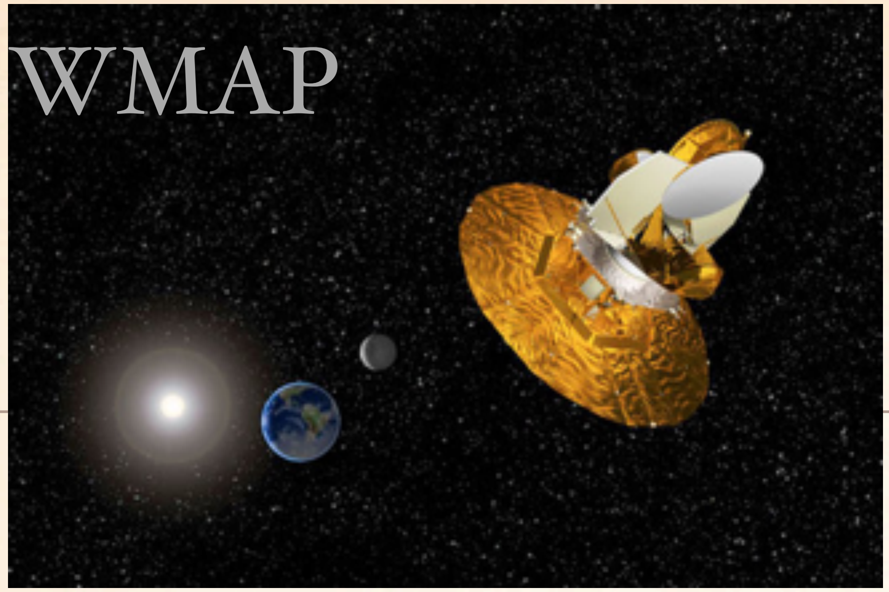
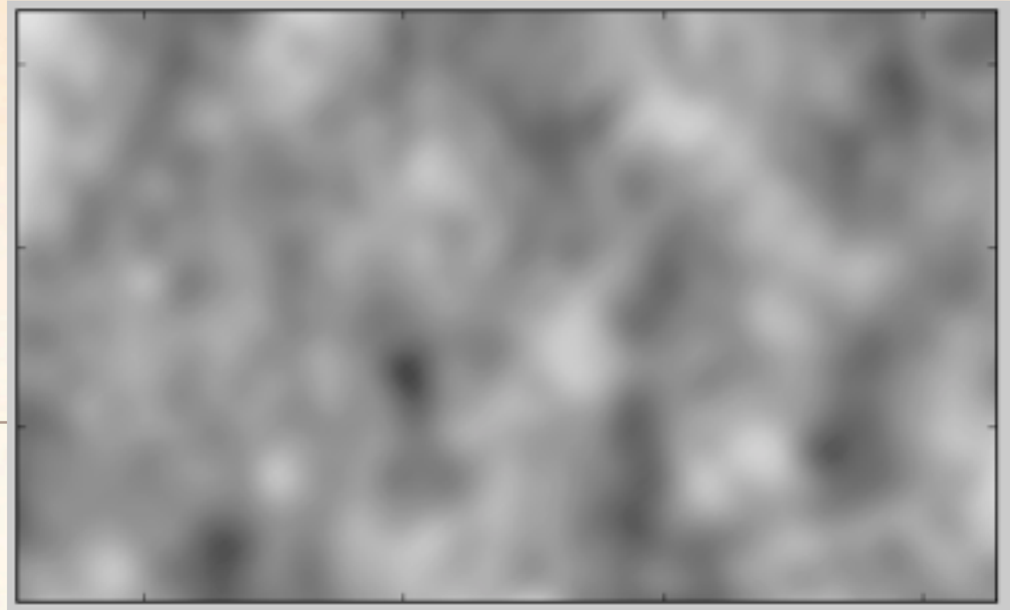
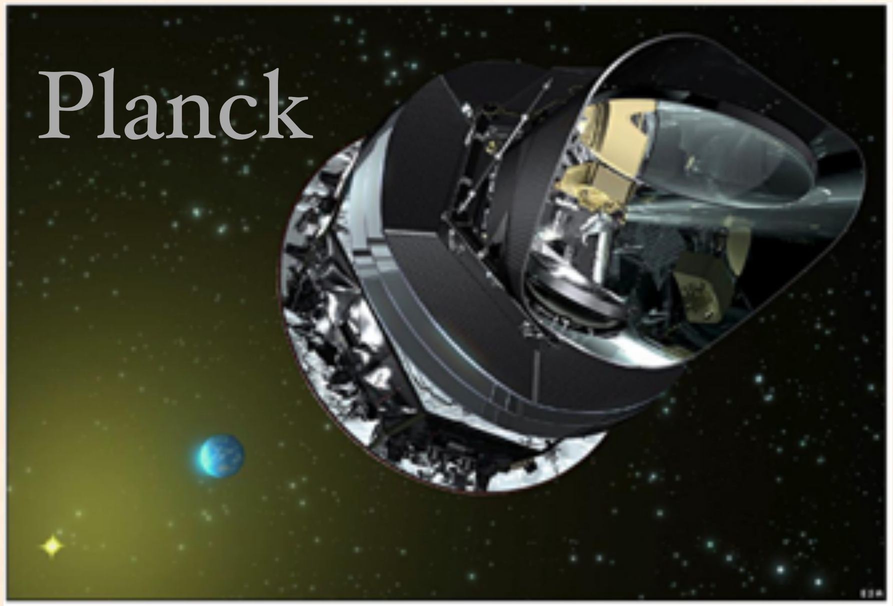



Planck




WMAP

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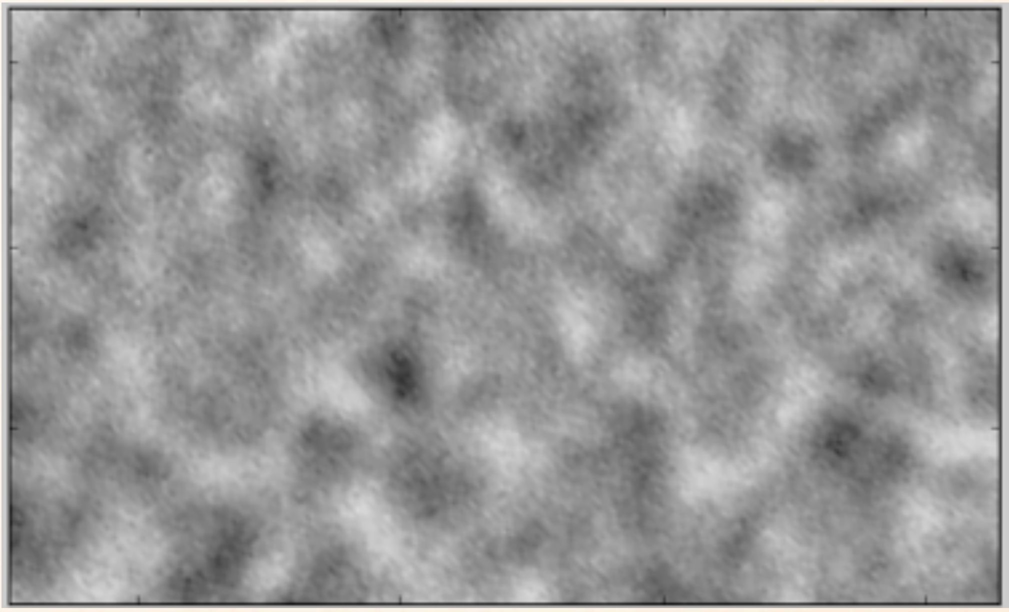
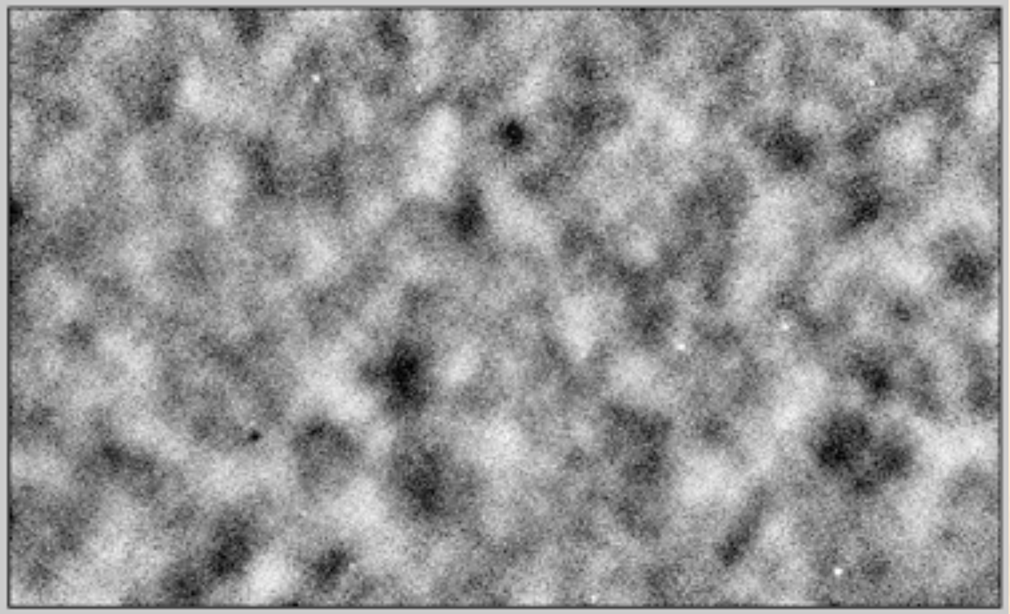
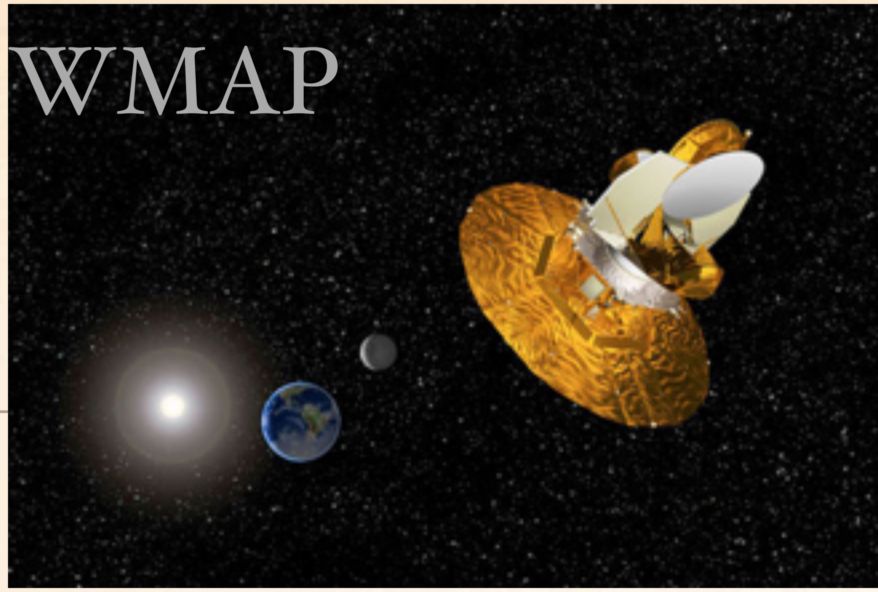
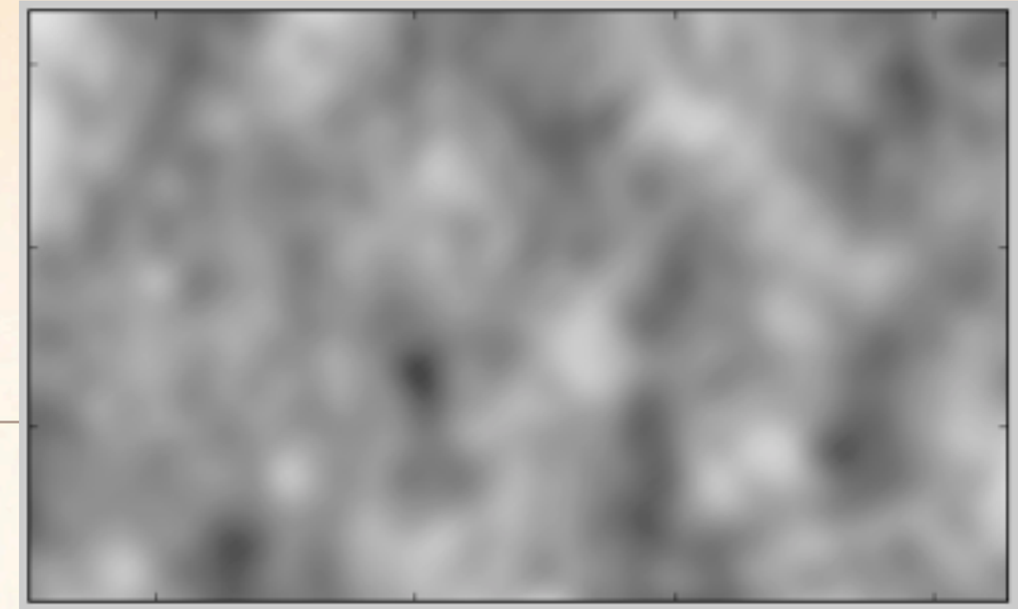
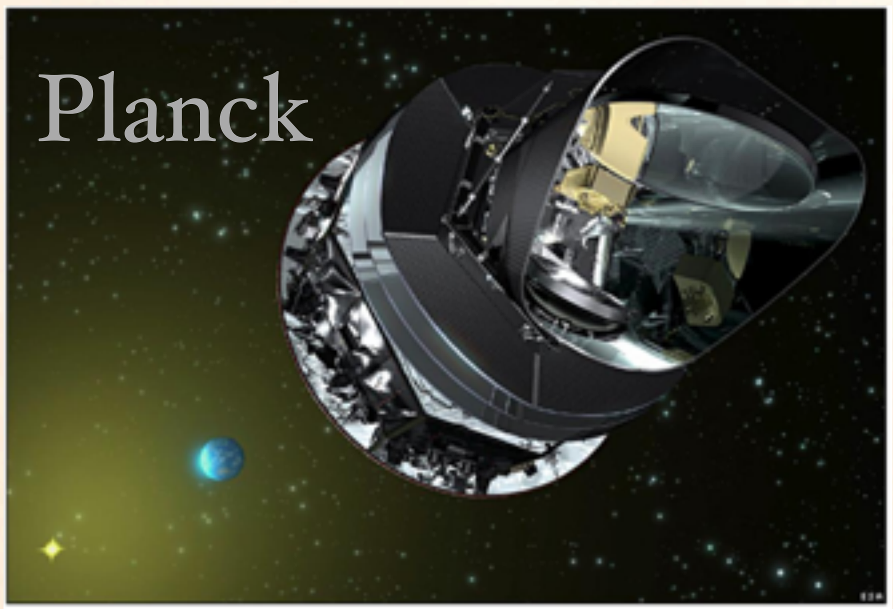



ACT




WMAP

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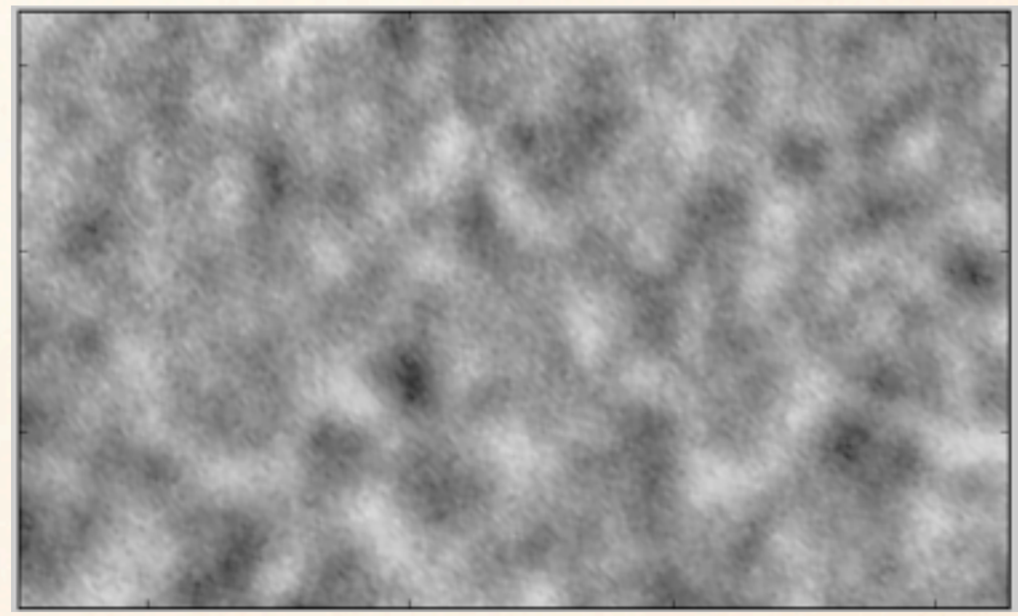
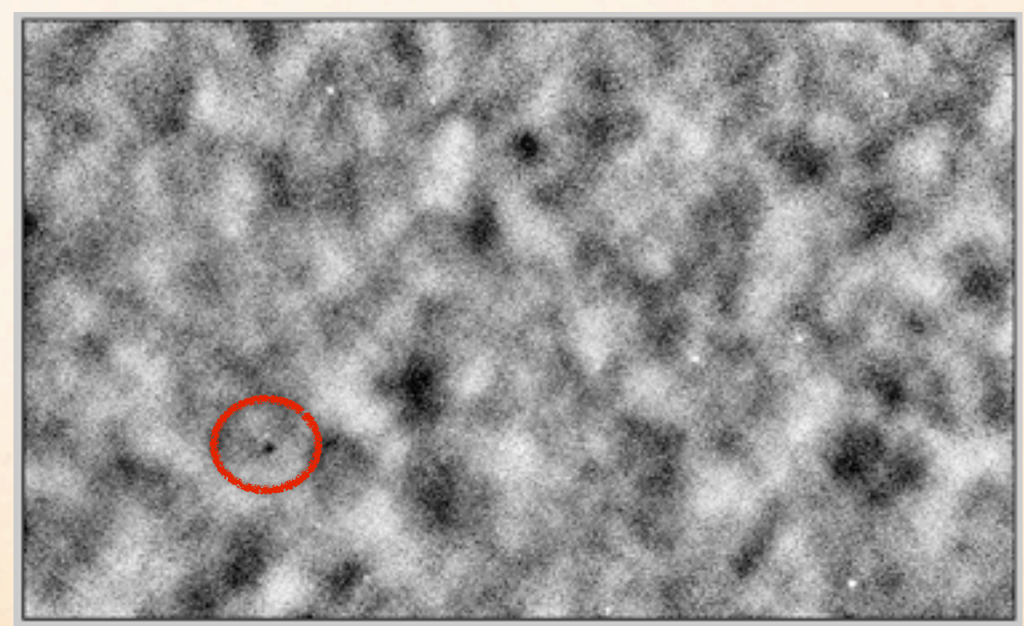
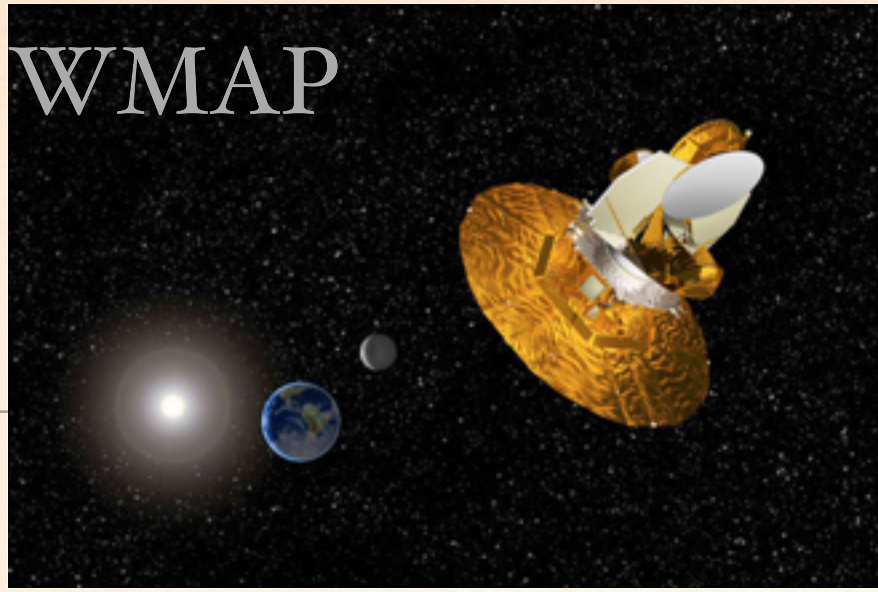
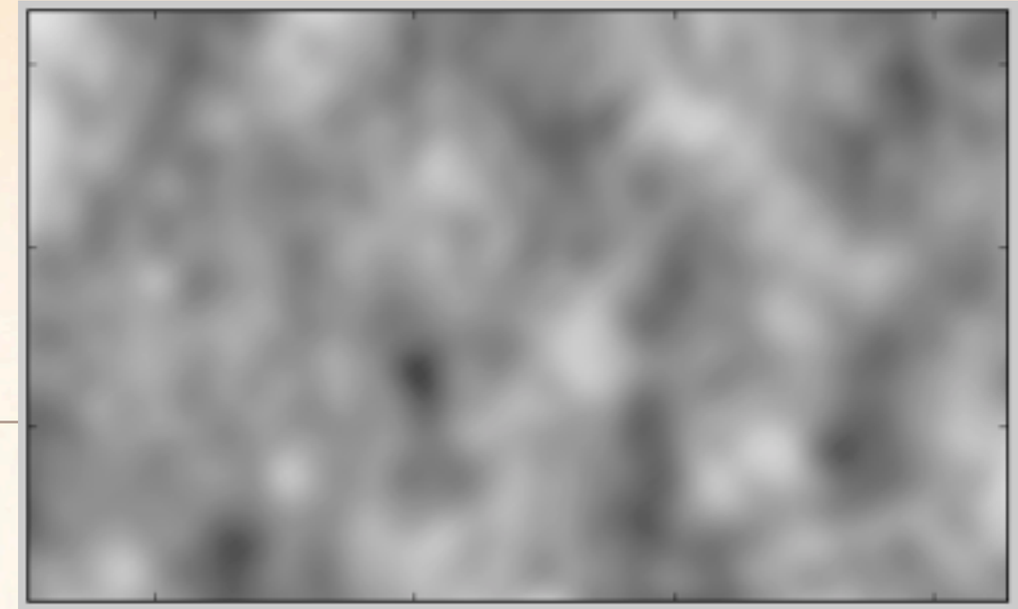
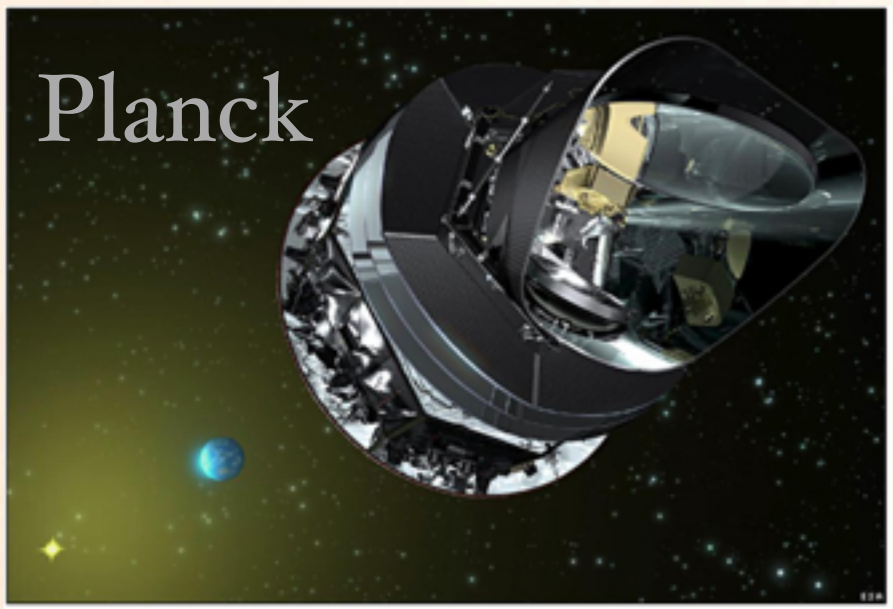



ACT




WMAP

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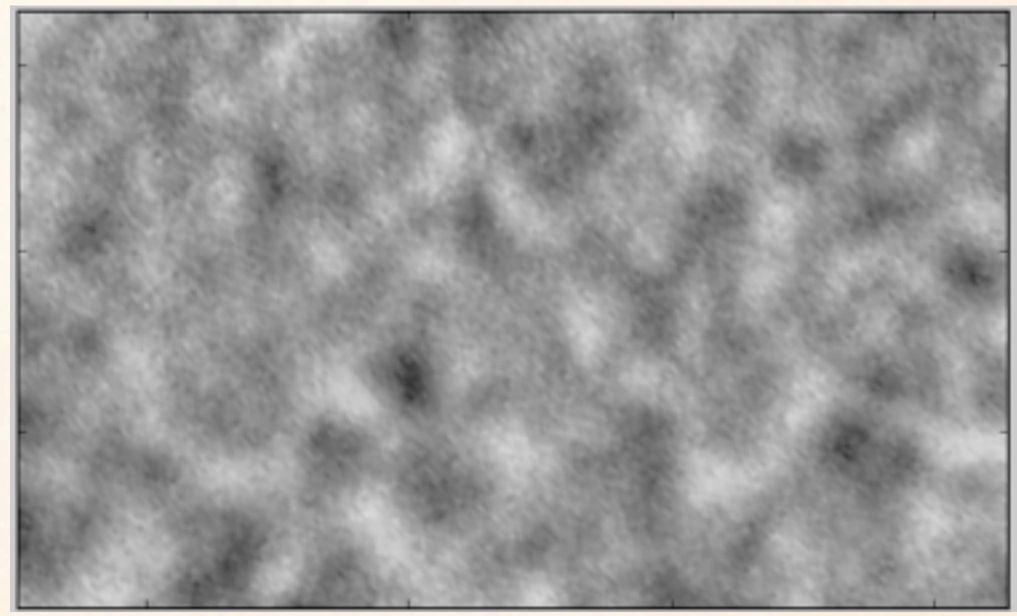
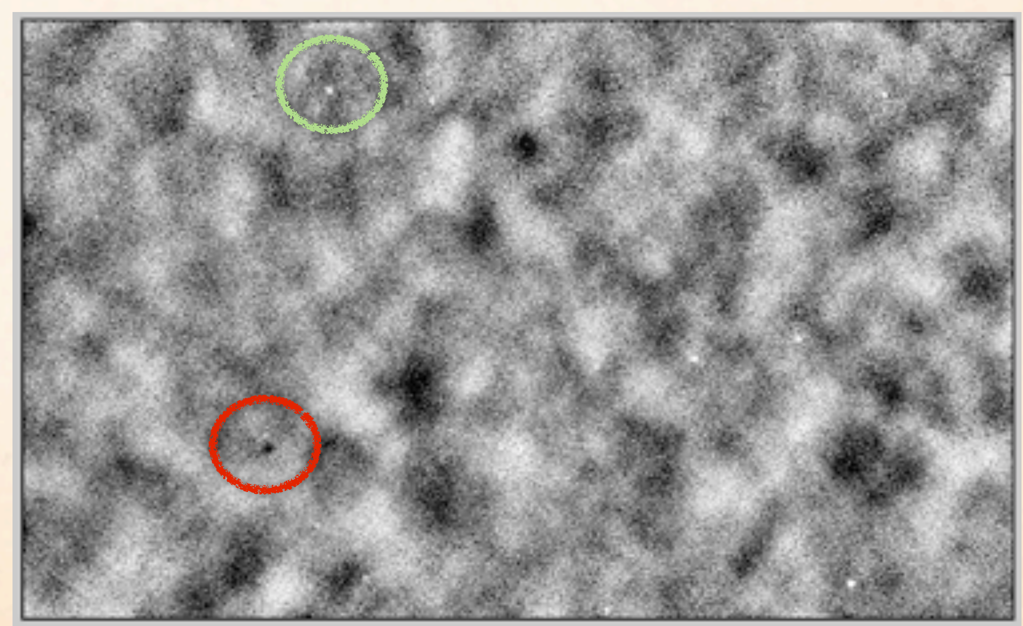
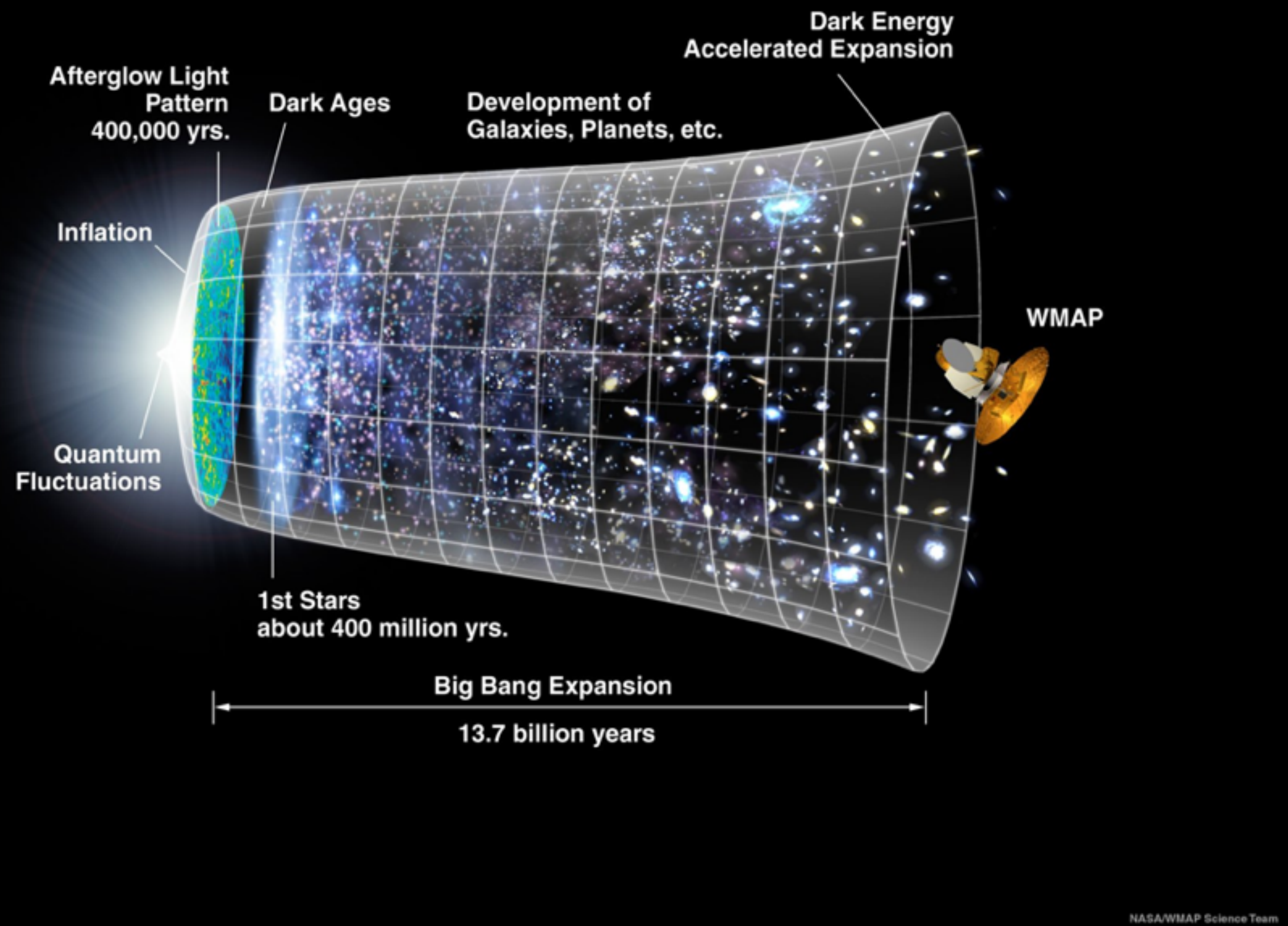


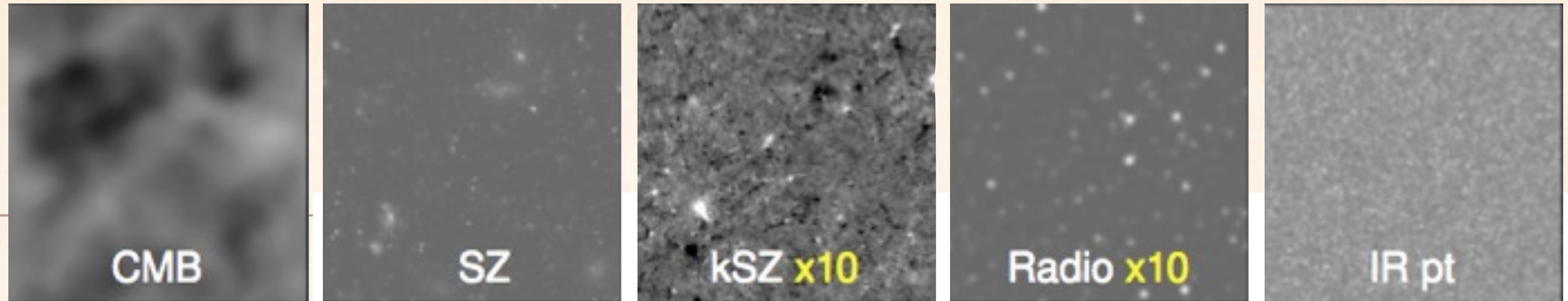

ACT



THE OBSERVED SKY

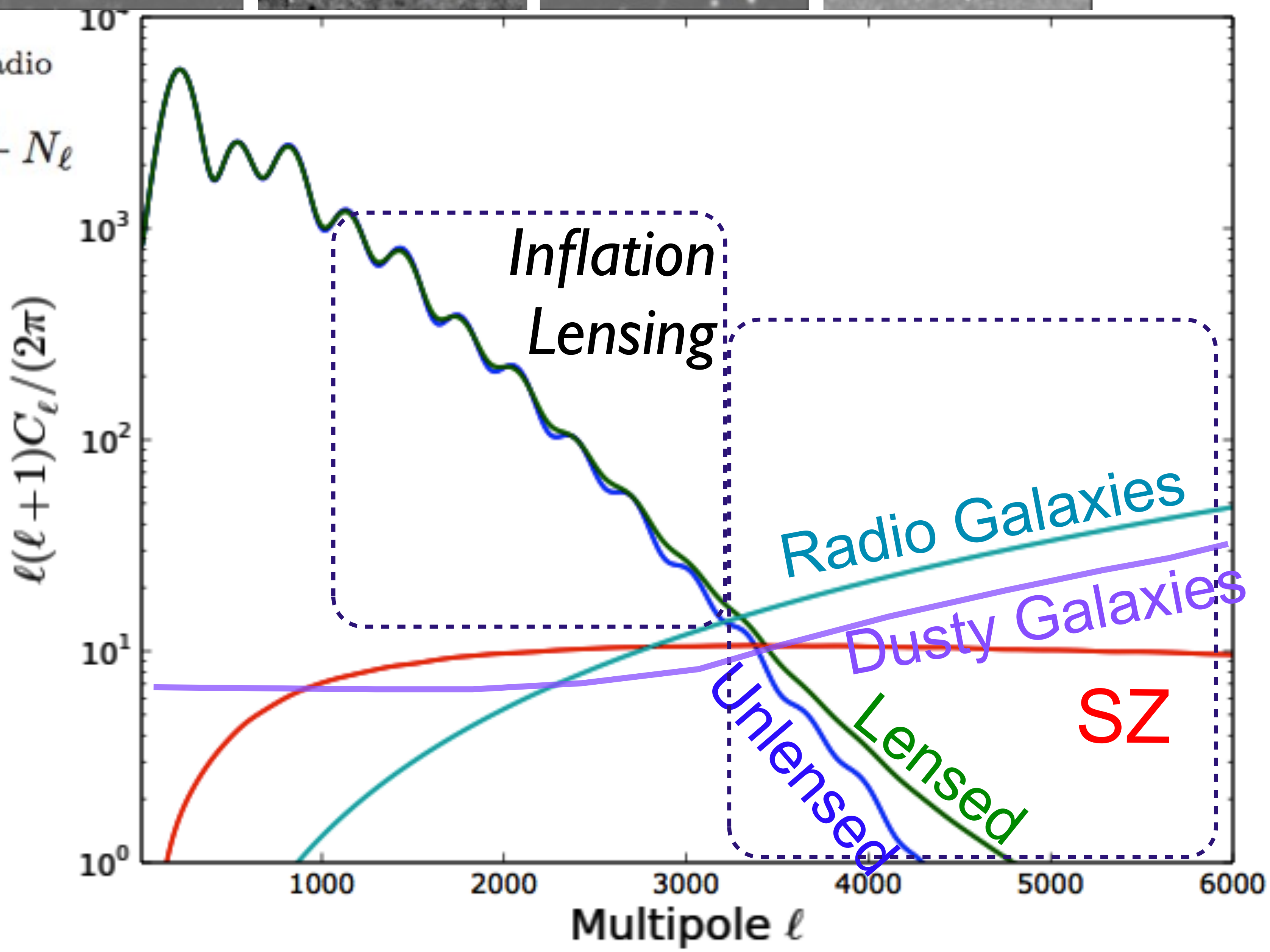


THE COMPONENTS



$$C_\ell^{\rm sky} = C_\ell^{\rm cirrus} + C_\ell^{\rm CMB} + C_\ell^{\rm radio} + C_\ell^{\rm DSFG} + C_\ell^{\rm SZ} + C_\ell^{\rm ff} + N_\ell$$

+ cross terms



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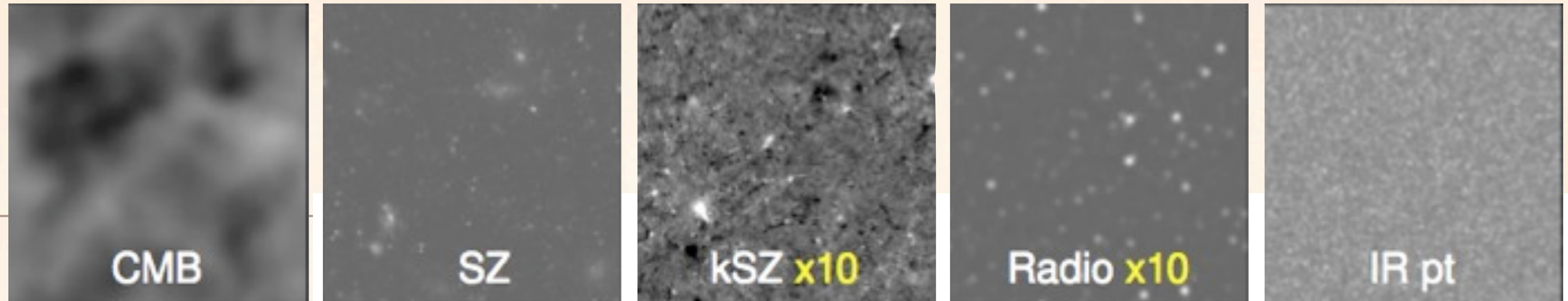

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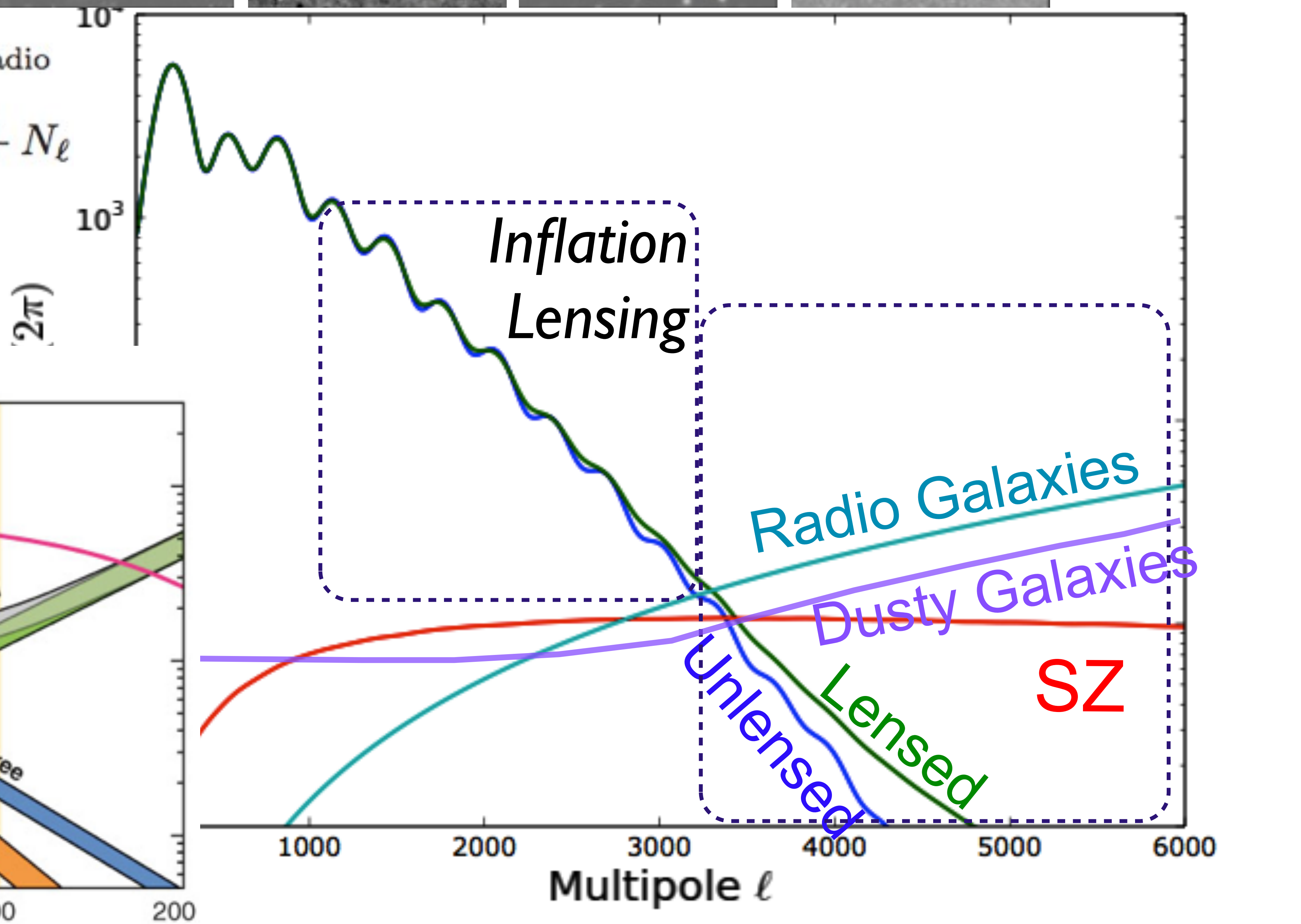
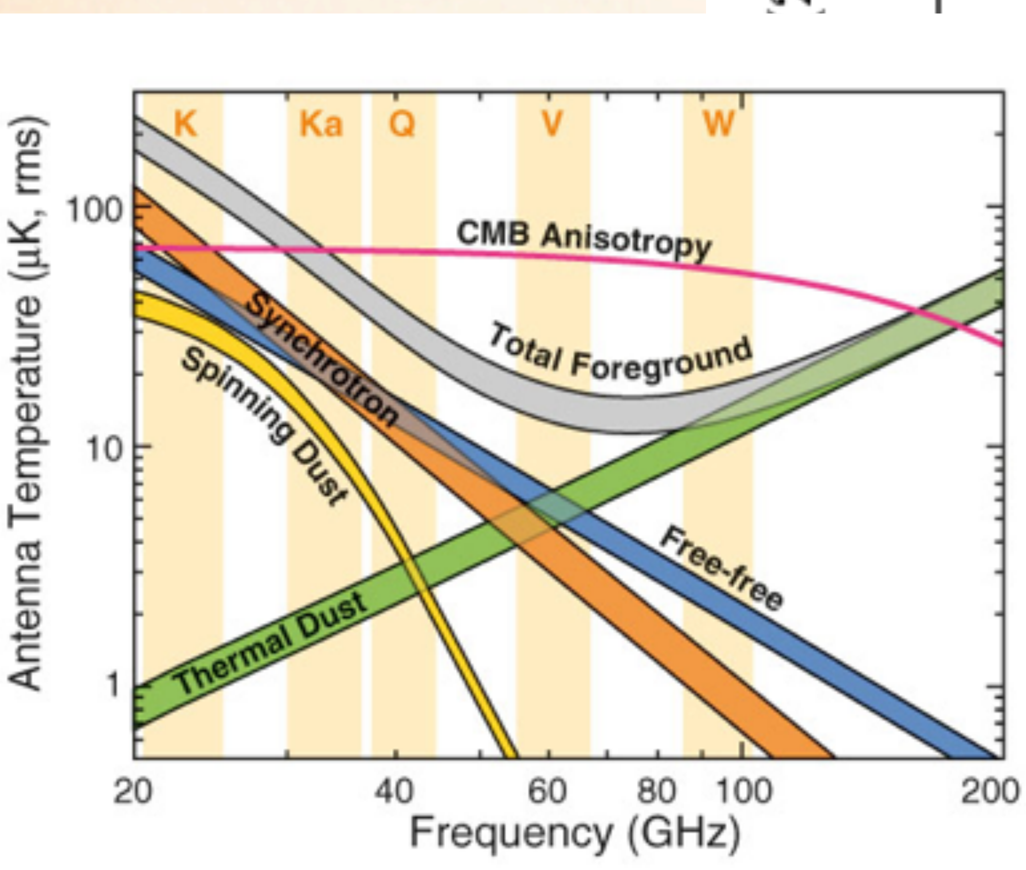
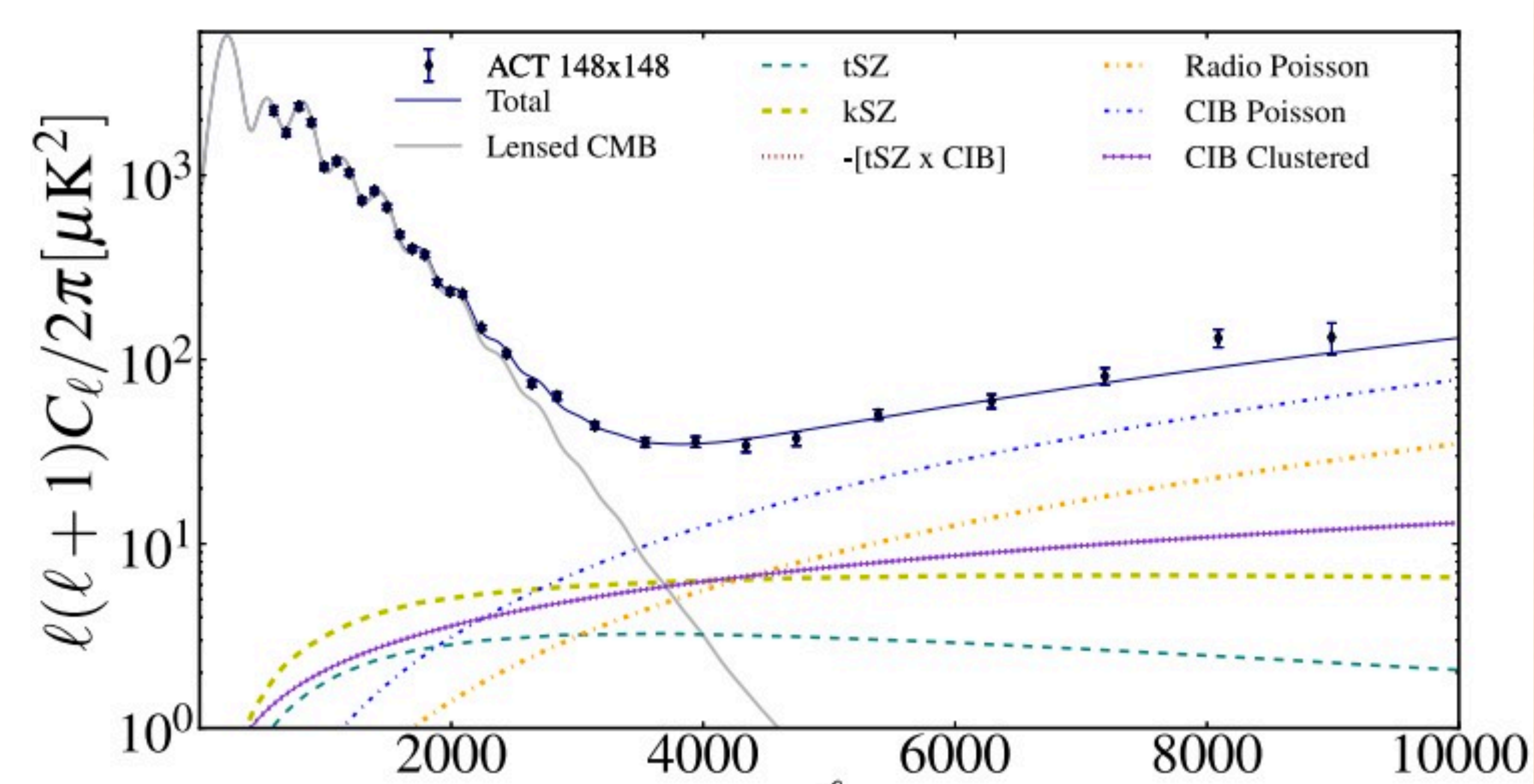


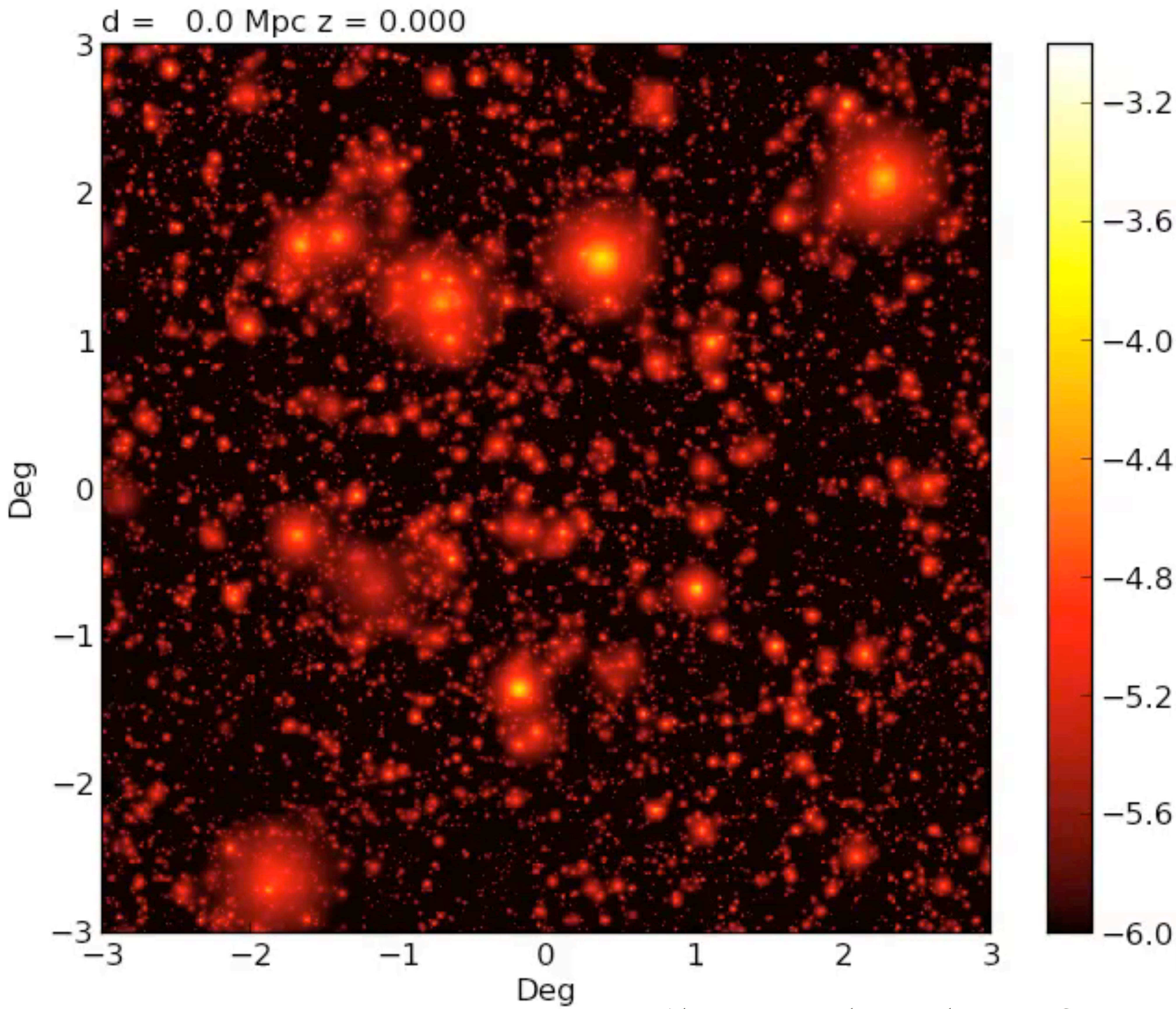


FULL POWER SPECTRA

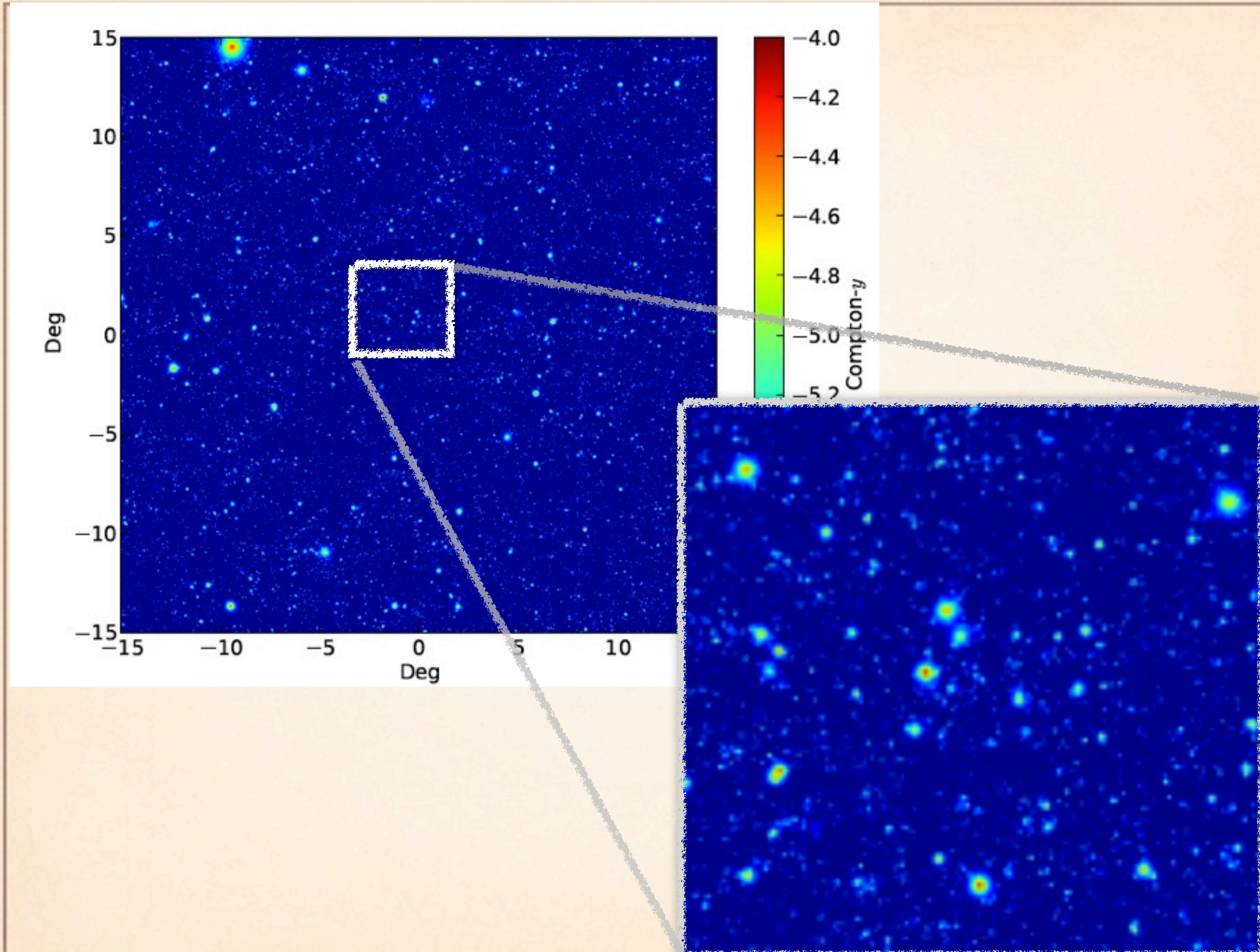


Dunkley + (2013)

Clusters



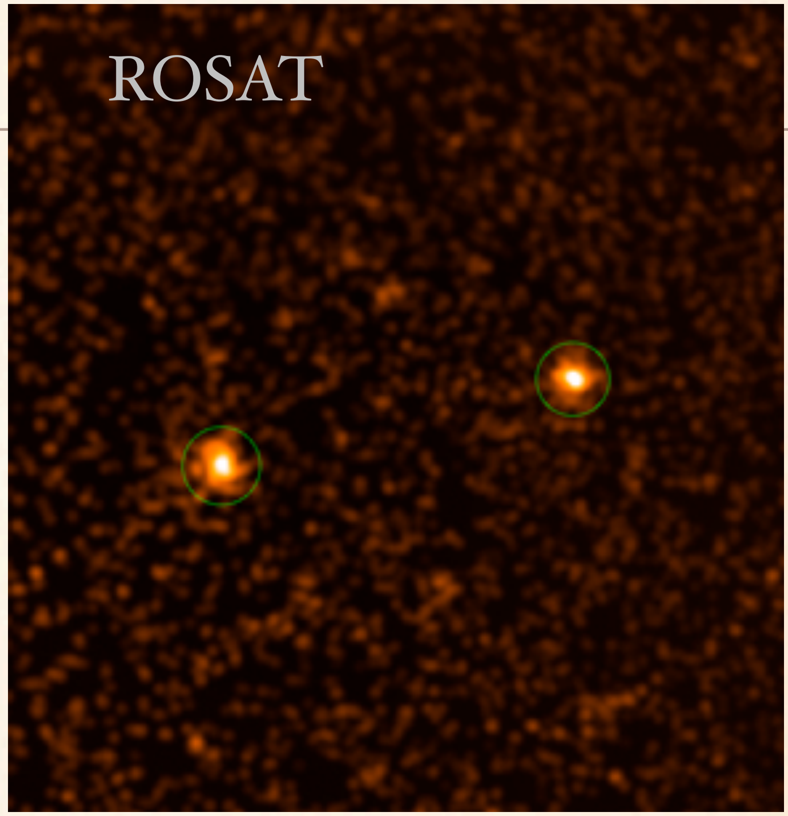
Alvarez, Battaglia, Bond, Hajian, Stein, Emberson (in prep)

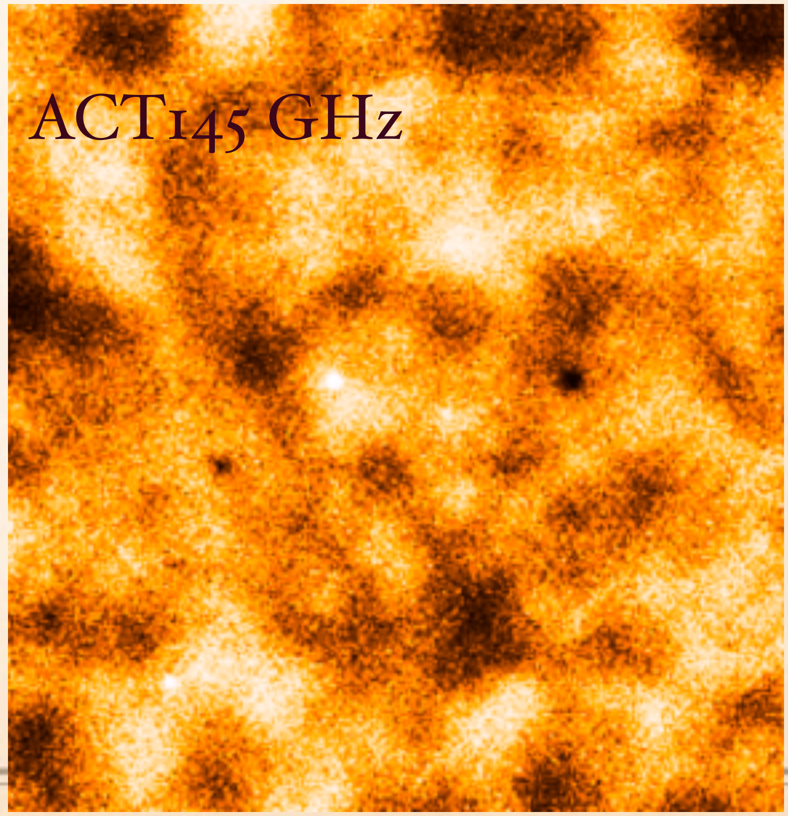


Alvarez, Battaglia, Bond, Hajian, Stein, Emberson (in prep)

XRAY X CMB:MOTIVATION

- CMB observes distortions due to the SZ effect
- ROSAT observes X-ray emissions due to the same hot and dense plasma





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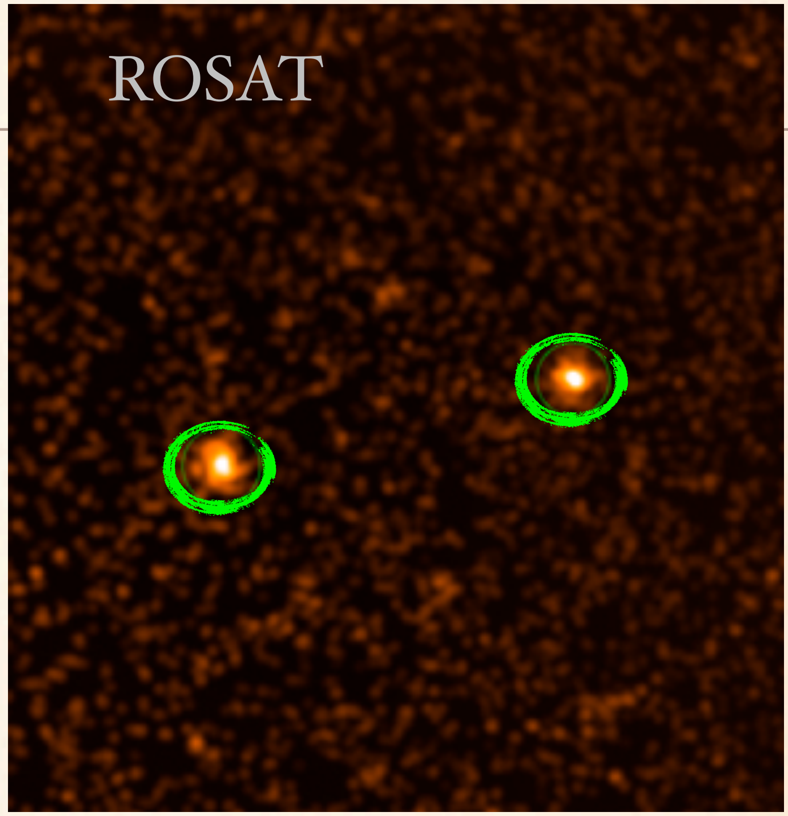
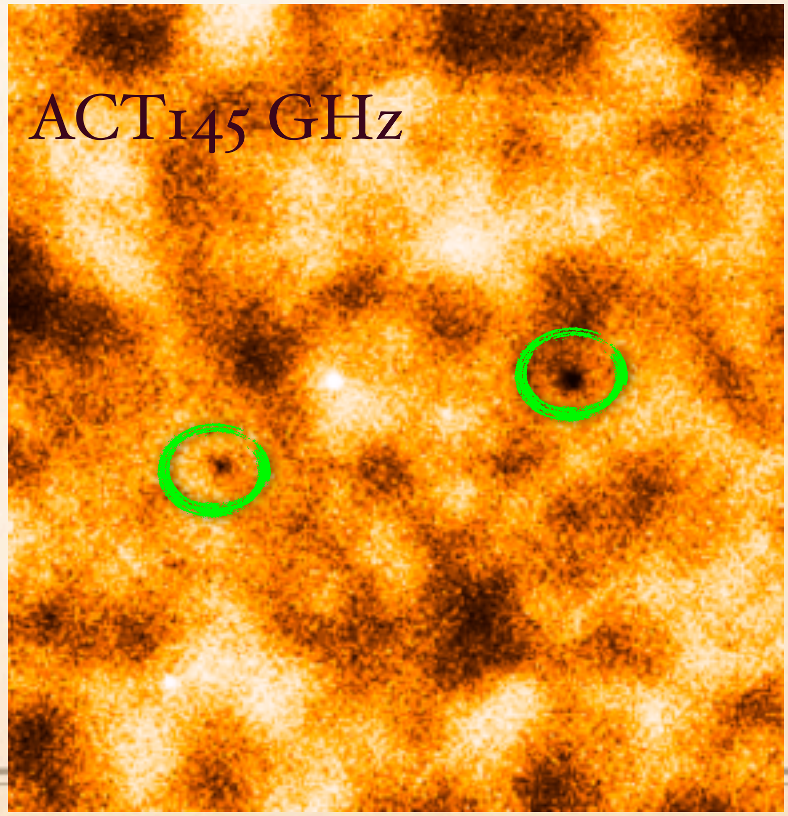
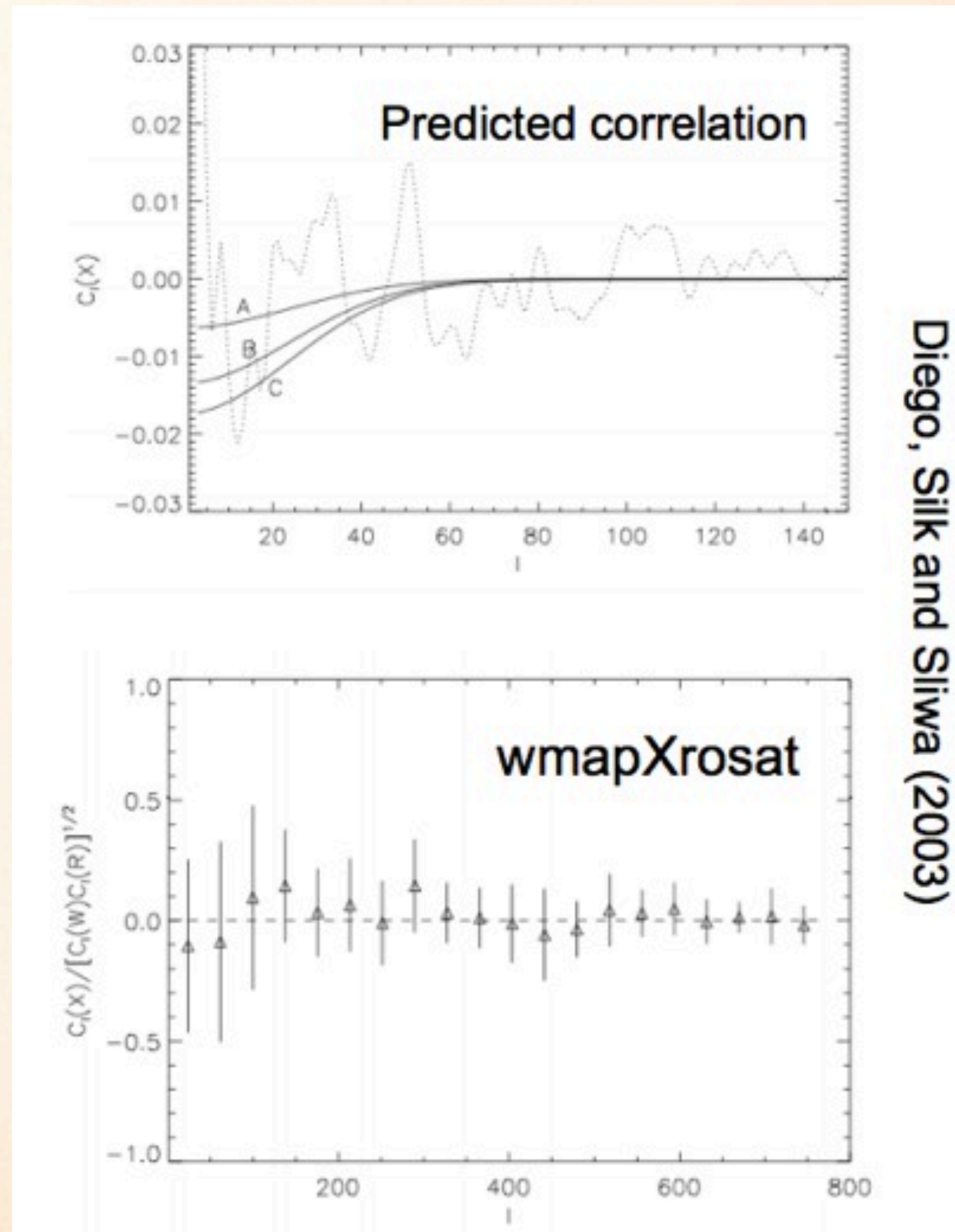




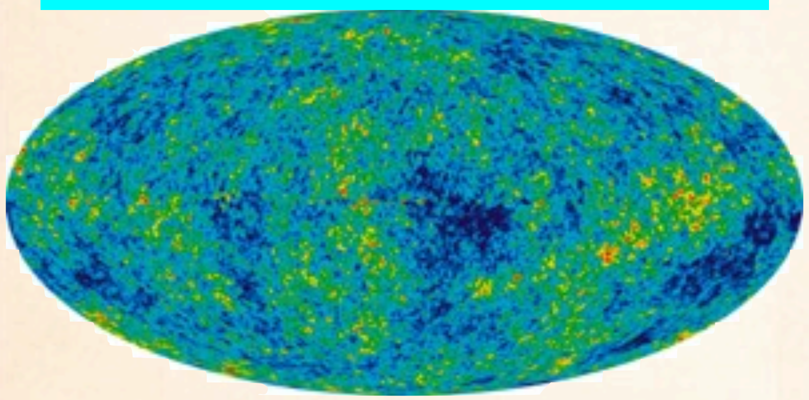
MOTIVATION

- CMB observes distortions due to the SZ effect
- ROSAT observes X-ray emissions due to the same hot and dense plasma
- The two maps should be correlated and at nu < 220 GHz, the correlation is negative in sign
- WMAP1xROSAT studied by Diego, Silk and Sliwa (2003) -> no detection on large scales ell < 800.



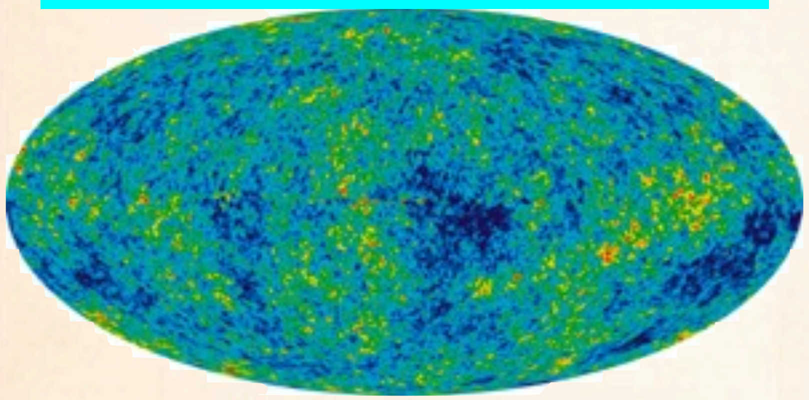
FROM MAPS TO PARAMETERS

$$\Delta T(\theta,\phi) = \sum_{l=2}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta,\phi)$$



FROM MAPS TO PARAMETERS

$$\Delta T(\theta,\phi) = \sum_{l=2}^{\infty}\sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta,\phi)$$



$$\int d\Omega_{\hat{n}} \Delta T(\hat{n}) Y^{*}_{lm}(\hat{n}) \longrightarrow a_{lm}$$

Spherical Harmonic Transform

FROM MAPS TO PARAMETERS

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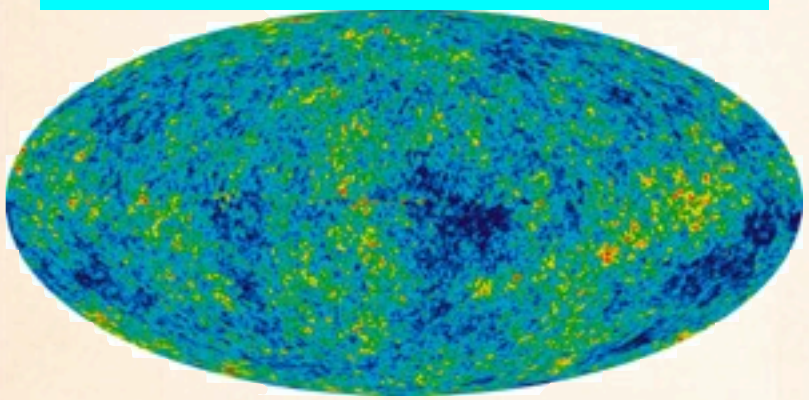
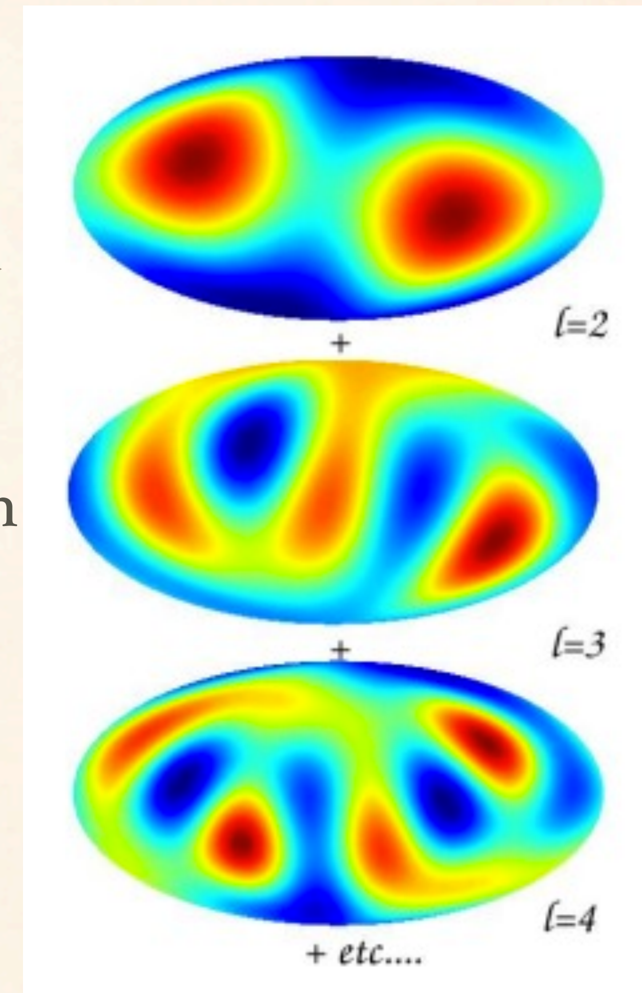


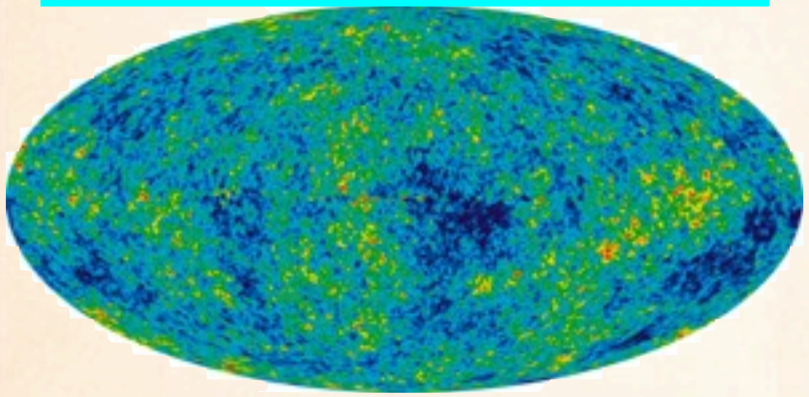
$$\int d\Omega_{\hat{n}} \Delta T(\hat{n}) Y^*_{lm}(\hat{n})$$

Spherical Harmonic Transform



ANGULAR POWER SPECTRUM

$$\Delta T(\theta,\phi) = \sum_{l=2}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta,\phi)$$



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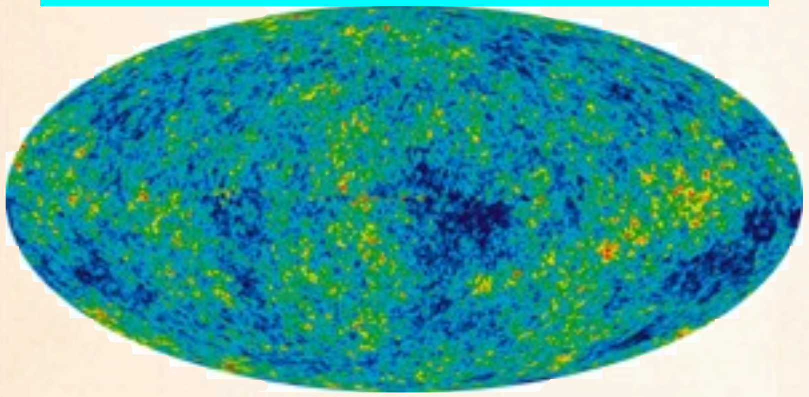
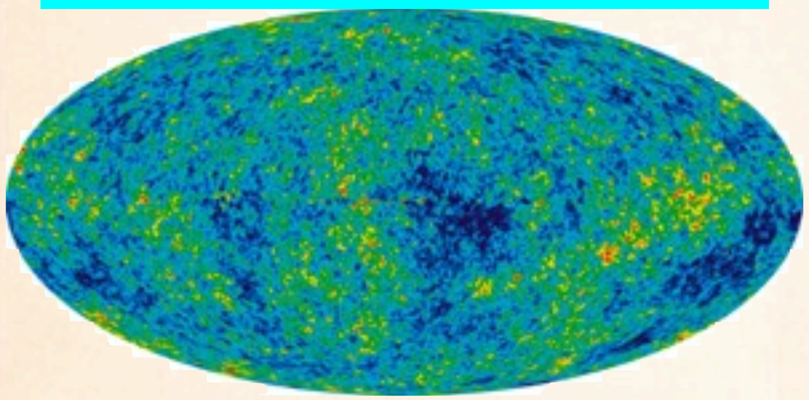


$$\int d\Omega_{\hat{n}} \Delta T(\hat{n}) Y^{*}_{lm}(\hat{n}) \longrightarrow a_{lm}$$

ANGULAR POWER SPECTRUM

$$\Delta T(\theta,\phi) = \sum_{l=2}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta,\phi)$$



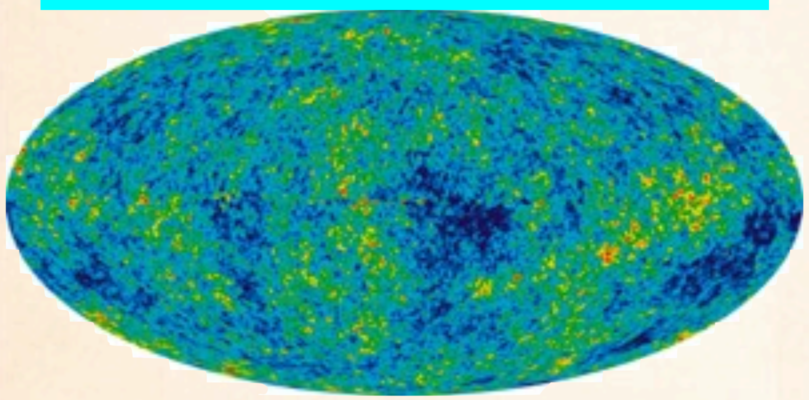
$$\int d\Omega_{\hat{n}} \Delta T(\hat{n}) Y^*_{lm}(\hat{n})$$

$$a_{lm}$$

$$\frac{1}{2l+1} \sum_{m=-l}^{l} |a_{lm}|^2$$

ANGULAR POWER SPECTRUM

$$\Delta T(\theta,\phi) = \sum_{l=2}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta,\phi)$$



$$\int d\Omega_{\hat{n}} \Delta T(\hat{n}) Y^*_{lm}(\hat{n})$$

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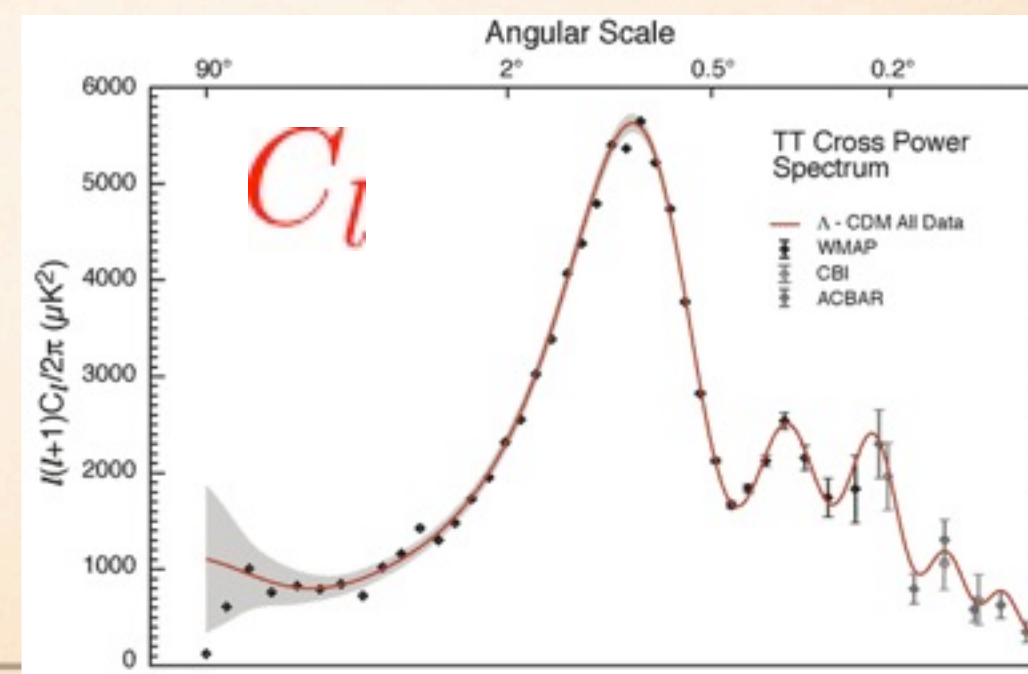
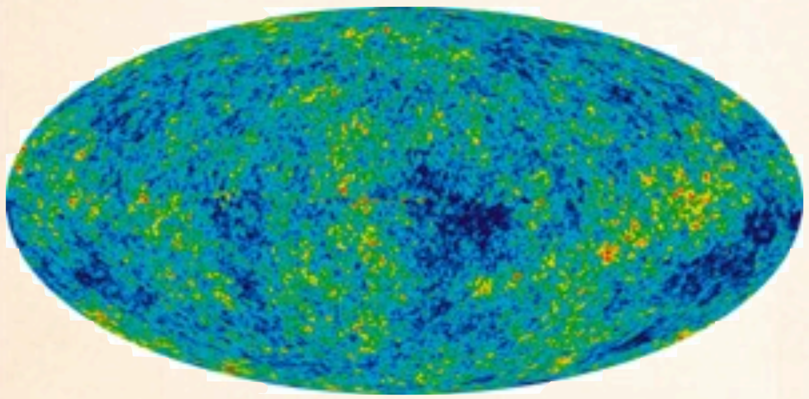


CROSS POWER SPECTRUM



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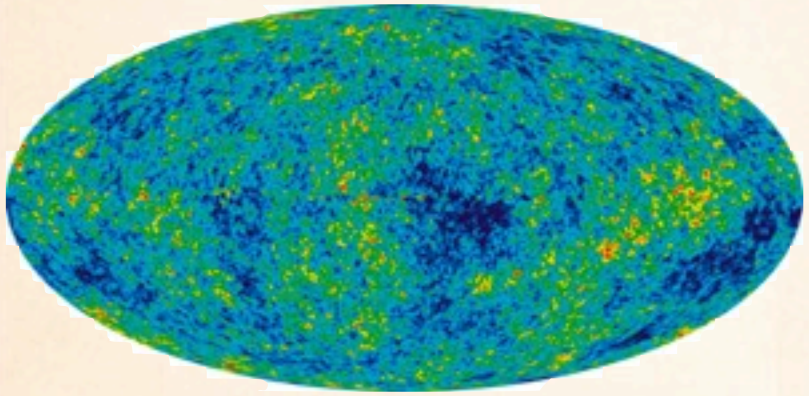
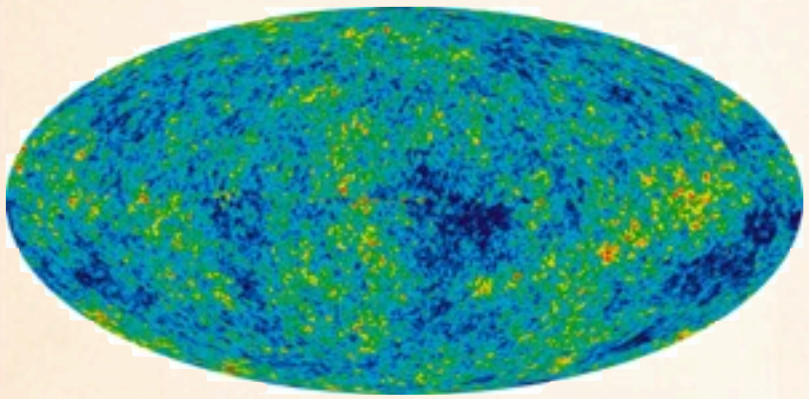
CROSS POWER SPECTRUM



$$\xrightarrow{\int d\Omega_{\hat{n}} \Delta T(\hat{n}) Y^*_{lm}(\hat{n})} a_{lm}$$

,

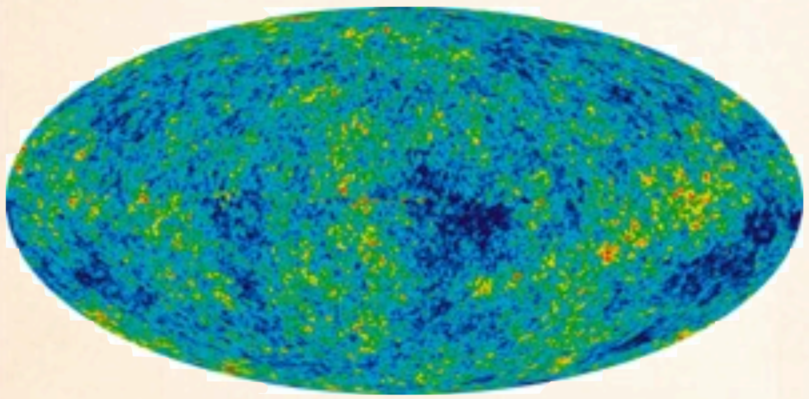
CROSS POWER SPECTRUM



$$\int d\Omega_{\hat{n}} \Delta T(\hat{n}) Y^*_{lm}(\hat{n}) \longrightarrow a_{lm}$$

$$\int d\Omega_{\hat{n}} \Delta T(\hat{n}) Y^*_{lm}(\hat{n}) \longrightarrow a'_{lm}$$

CROSS POWER SPECTRUM

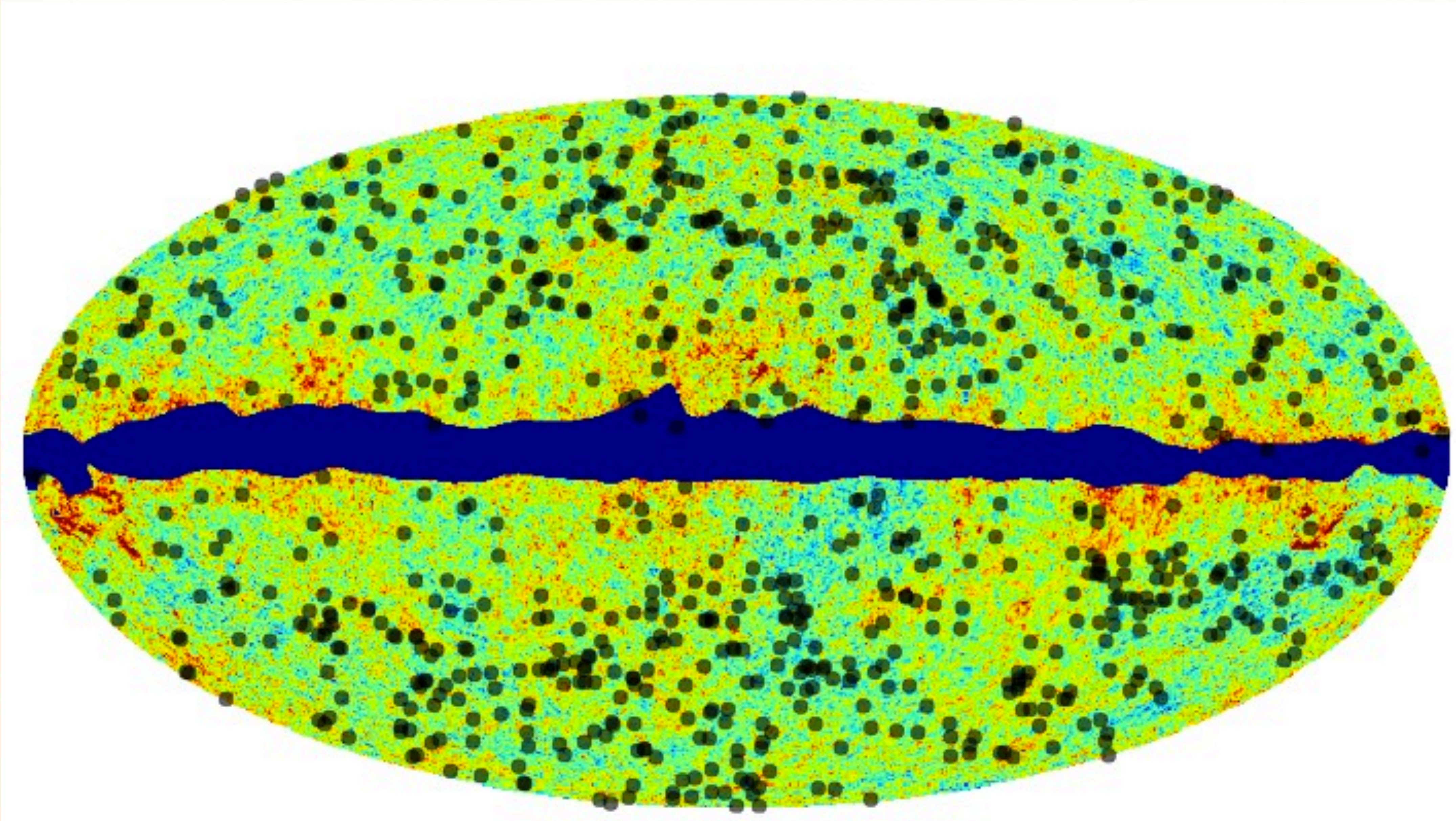


$$\int d\Omega_{\hat{n}} \Delta T(\hat{n}) Y^*_{lm}(\hat{n}) \longrightarrow a_{lm}$$

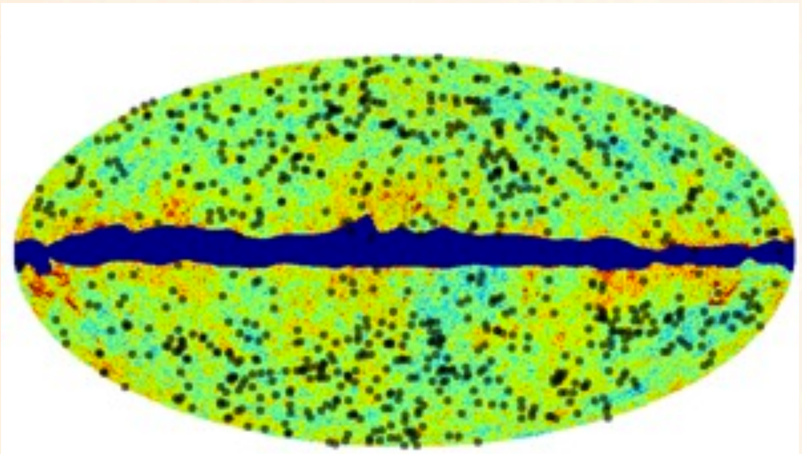
$$C_l$$

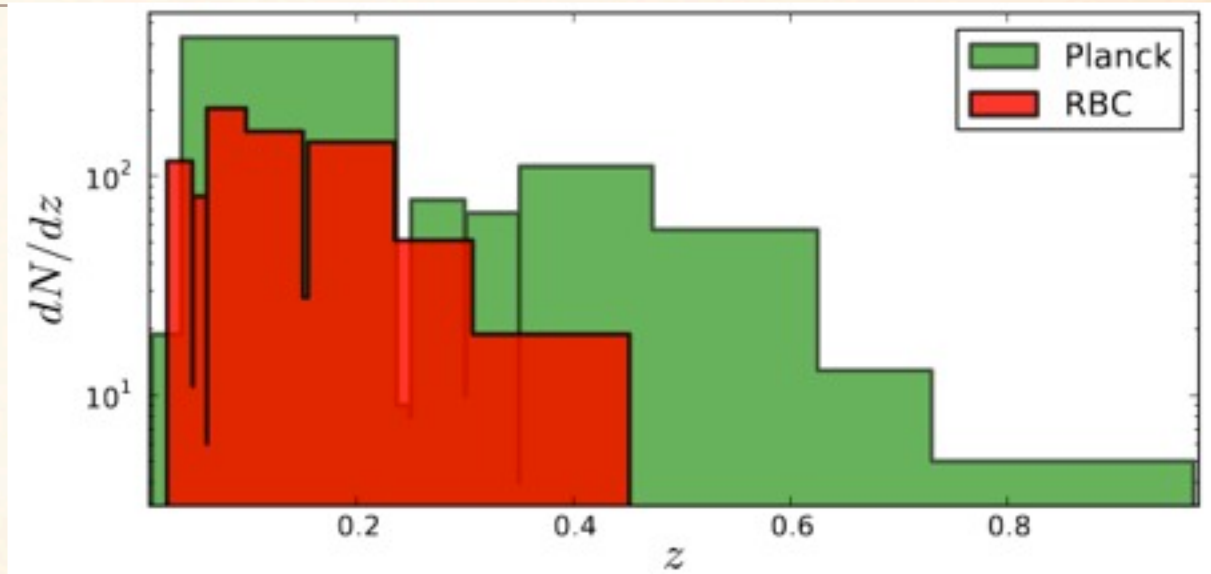
$$\int d\Omega_{\hat{n}} \Delta T(\hat{n}) Y^*_{lm}(\hat{n}) \longrightarrow a'_{lm}$$

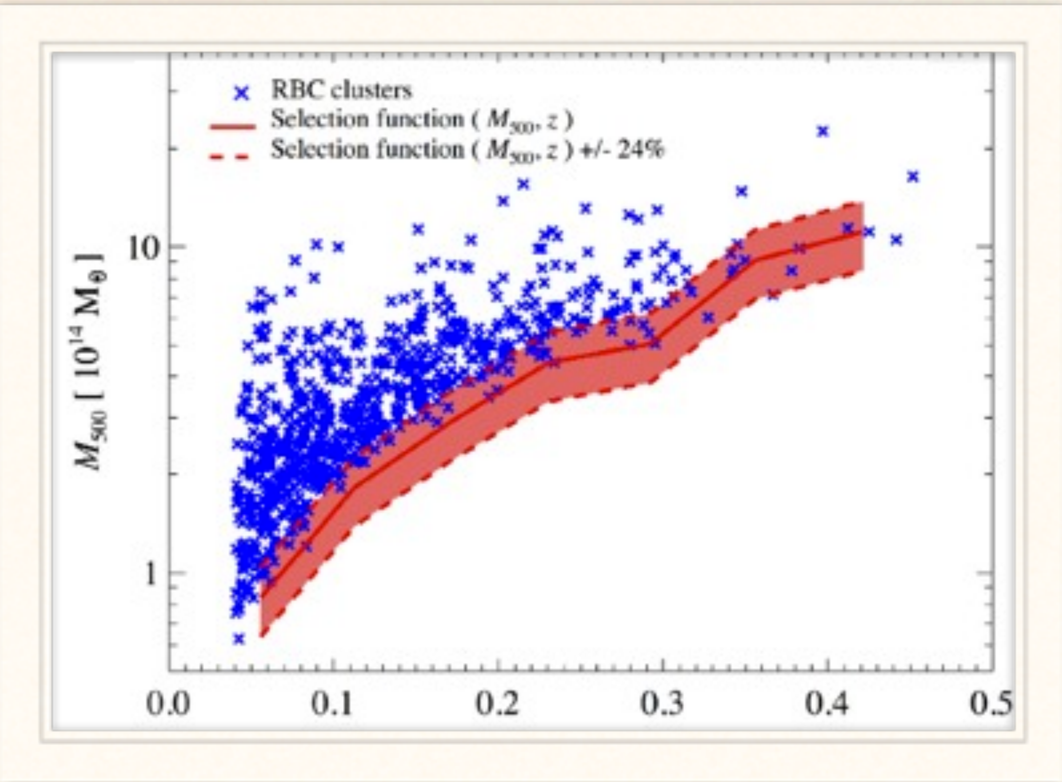
CATALOGS INSTEAD OF MAPS



CLUSTER SAMPLE





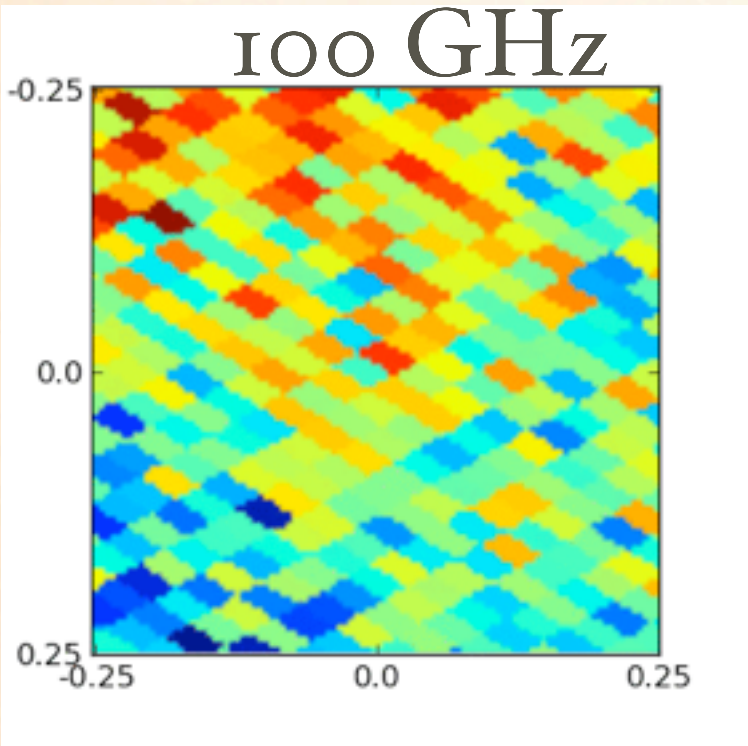


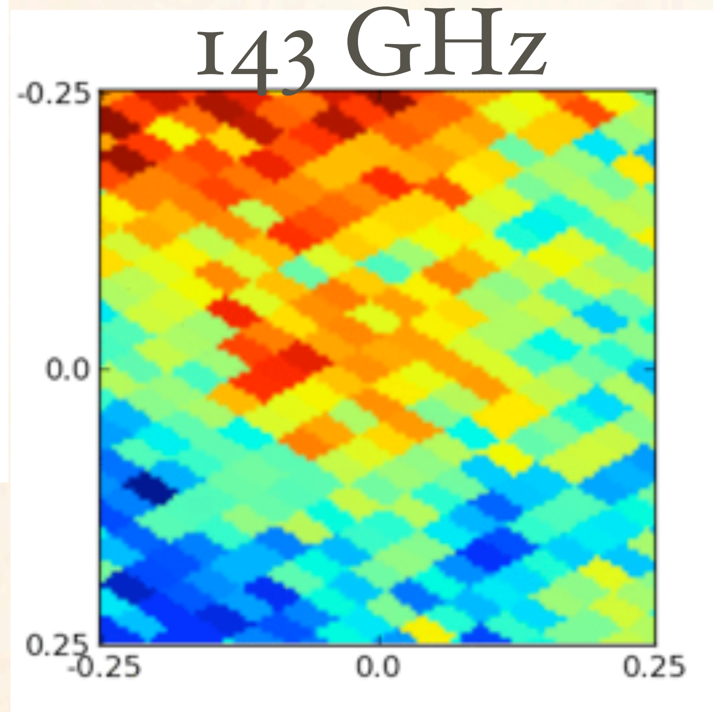
Subsamples of MCXC
(flux limited)

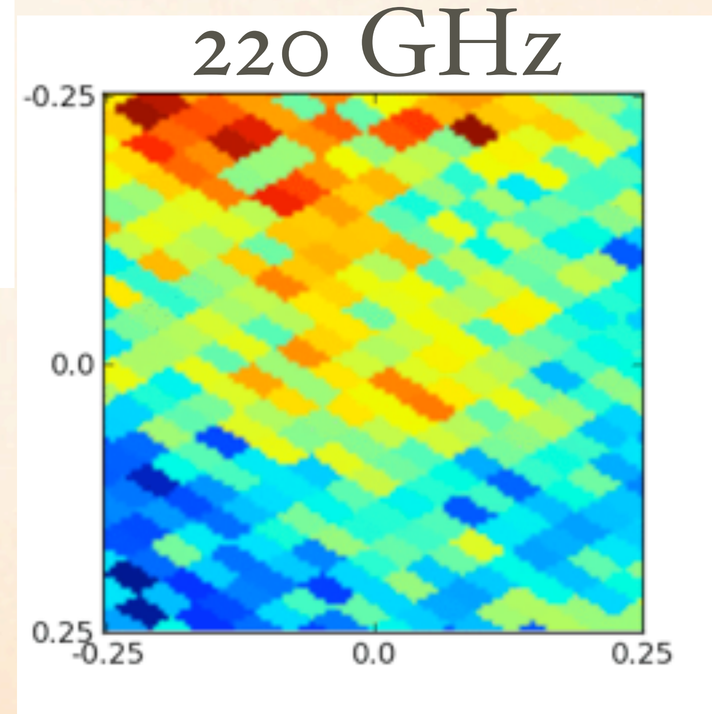
REFLEX
BCS
CIZA I&II

} RBC

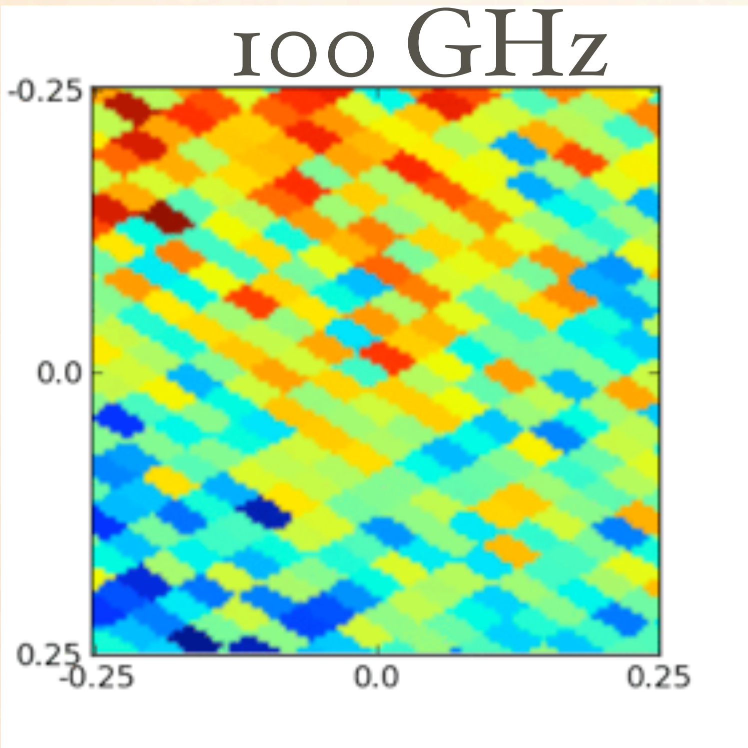
STACKED CLUSTERS

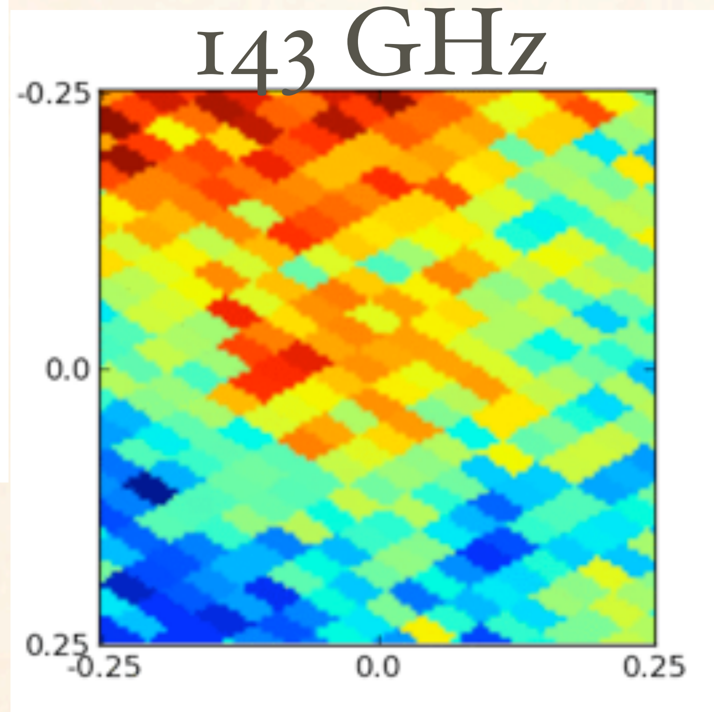


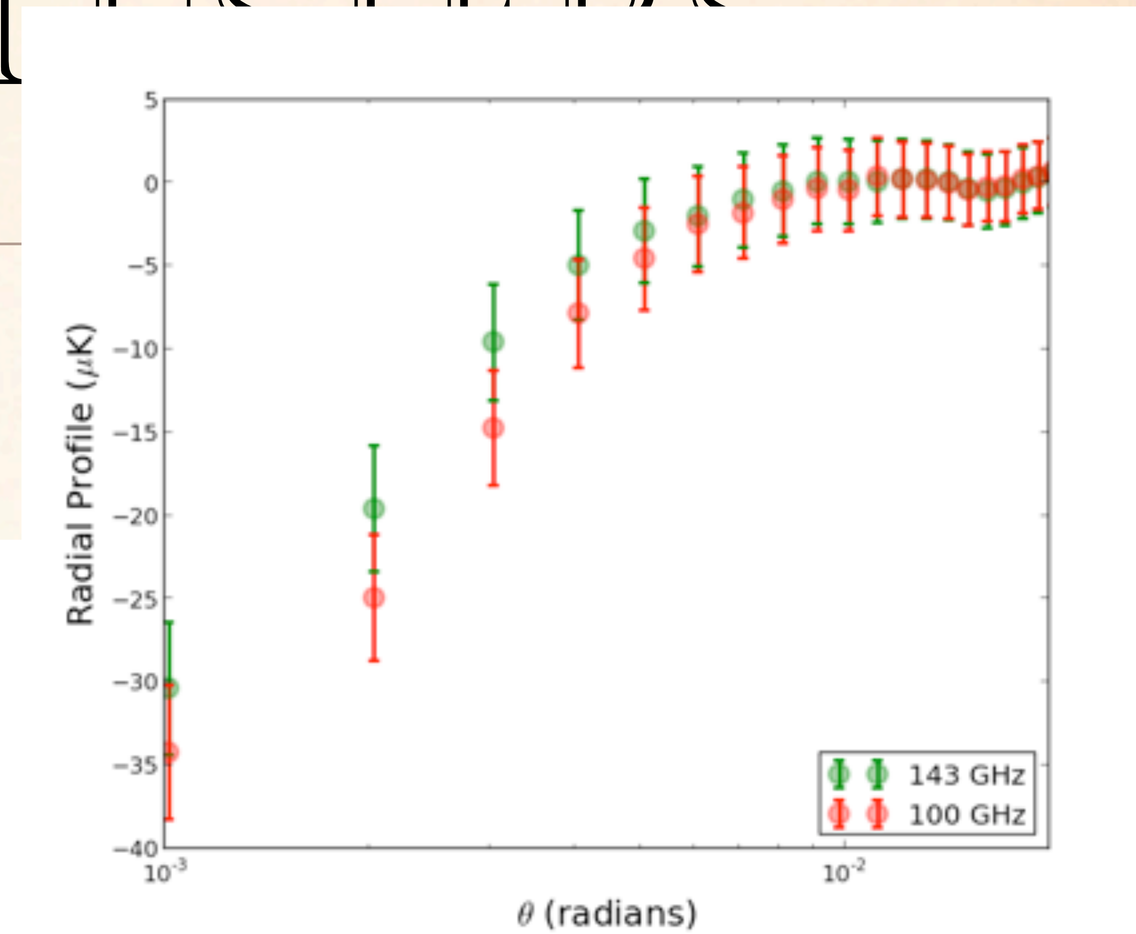


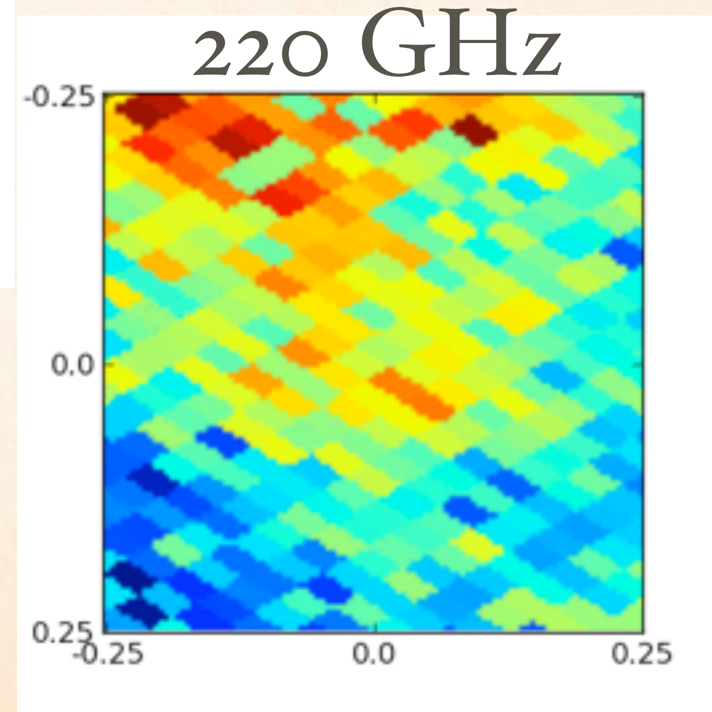


STACKED CL


100 GHz
-0.25
0.0
0.25
-0.25
0.0
0.25


143 GHz
-0.25
0.0
0.25
-0.25
0.0
0.25


Radial Profile (μK)
θ (radians)
143 GHz
100 GHz

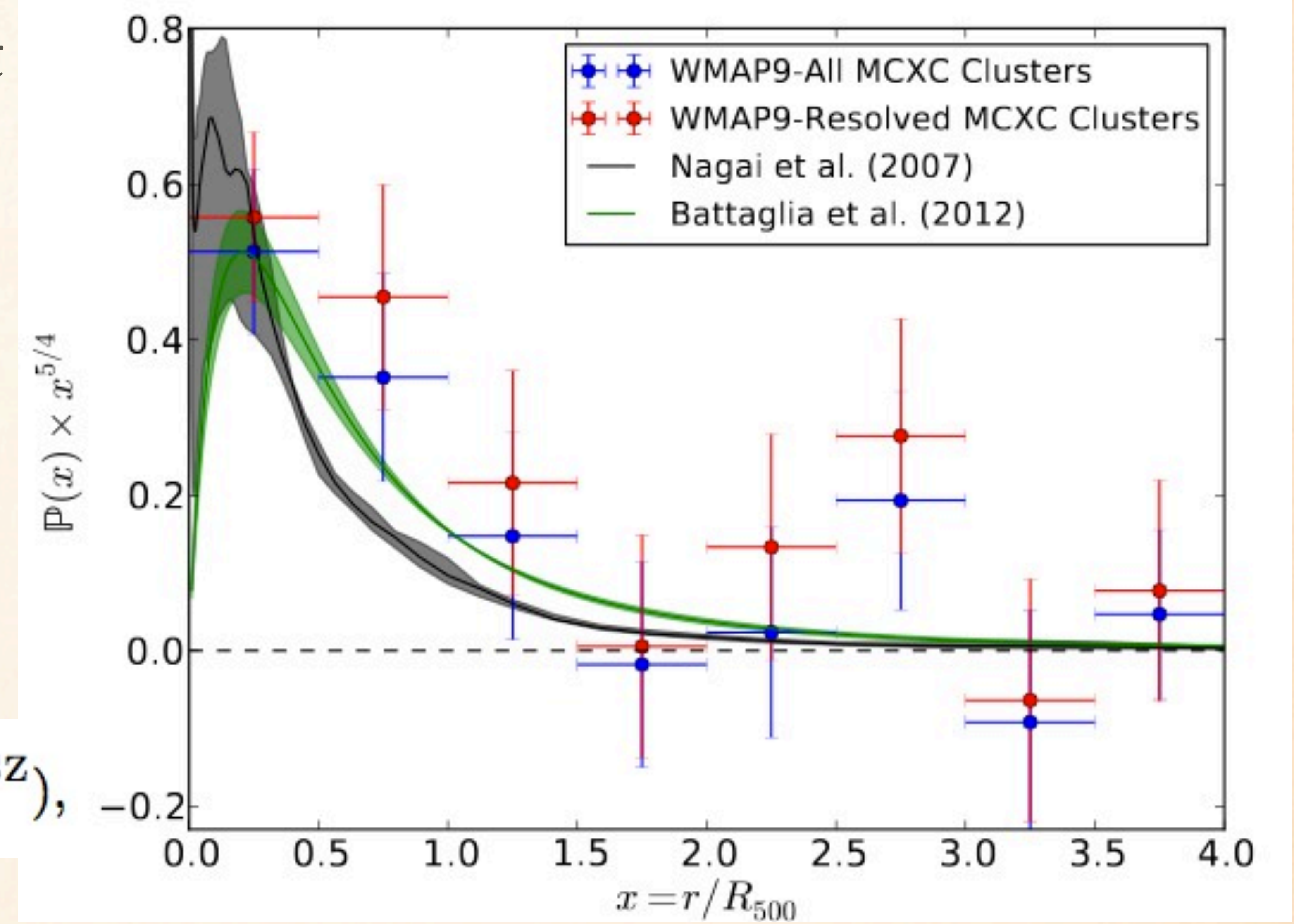

220 GHz
-0.25
0.0
0.25
-0.25
0.0
0.25

OPTIMAL "STACKING"

- Naive stacking does not take correlations in the map into account
- Optimal estimator uses the full covariance matrix of the data

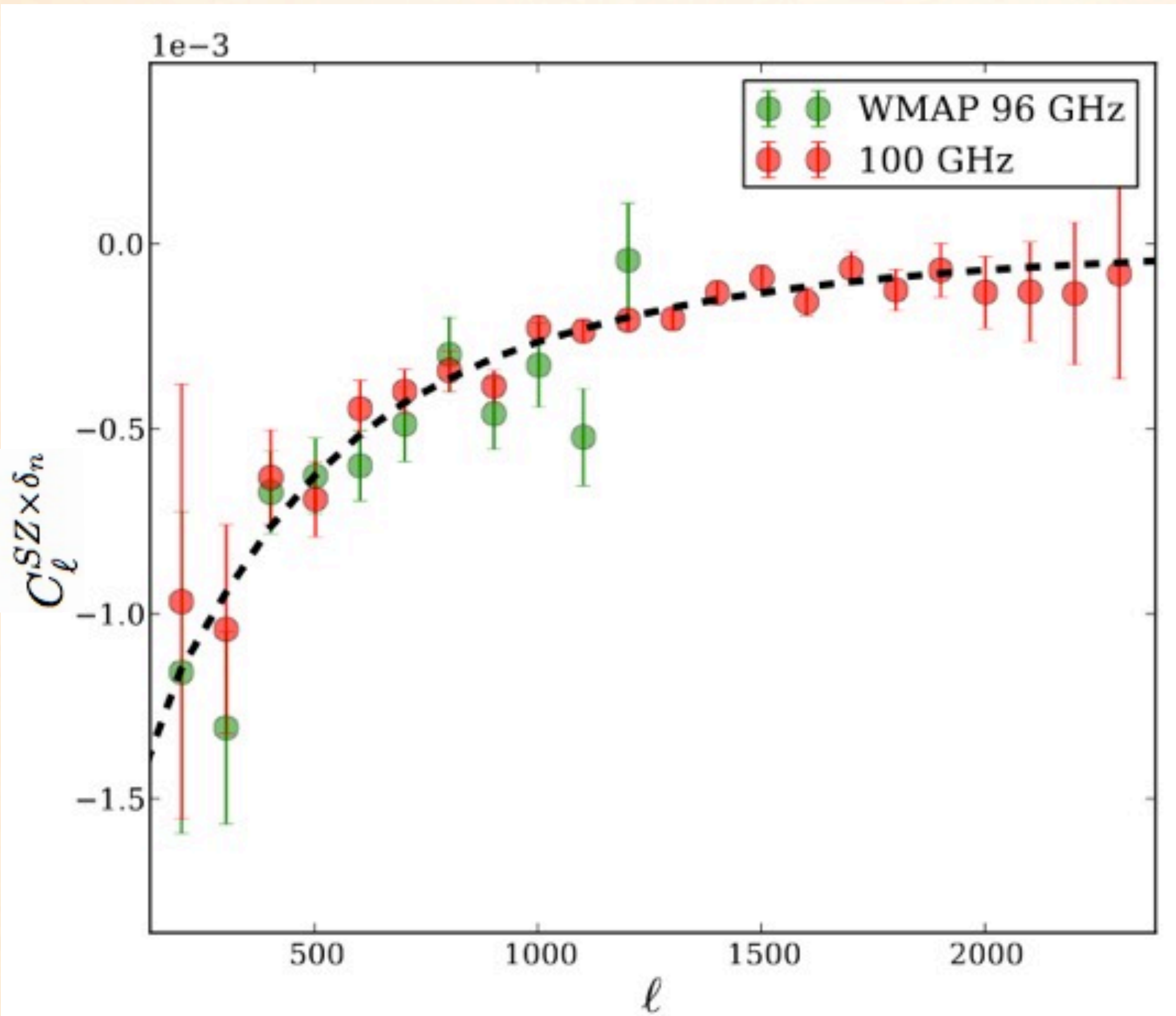
$$-\frac{1}{2}(\boldsymbol{\delta T}-\boldsymbol{\delta T}^{\mathrm{SZ}})^T\mathbf{C}^{-1}(\boldsymbol{\delta T}-\boldsymbol{\delta T}^{\mathrm{SZ}}),$$

$$\mathbf{C}=\mathbf{C_S}+\mathbf{C_N}.$$



Aslanbeigi, Lavaux, Hajian, Afshordi (2013)

ROSAT X W96, P100 GHZ

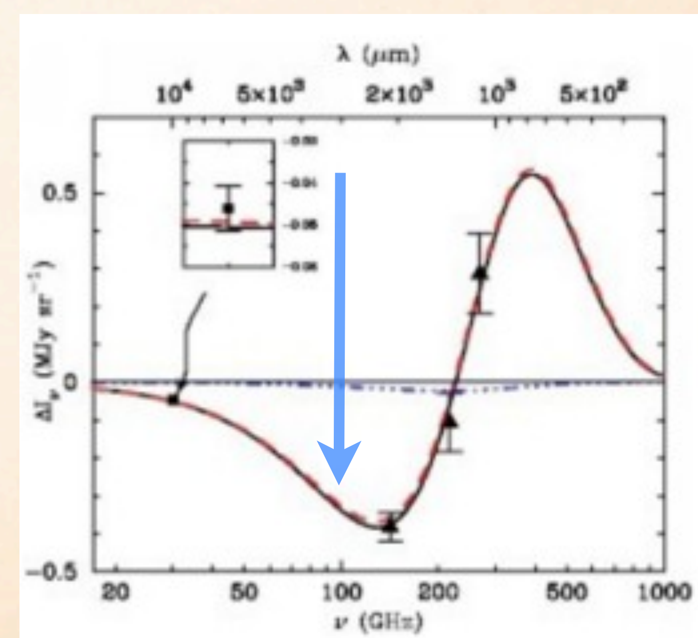


CMB map:

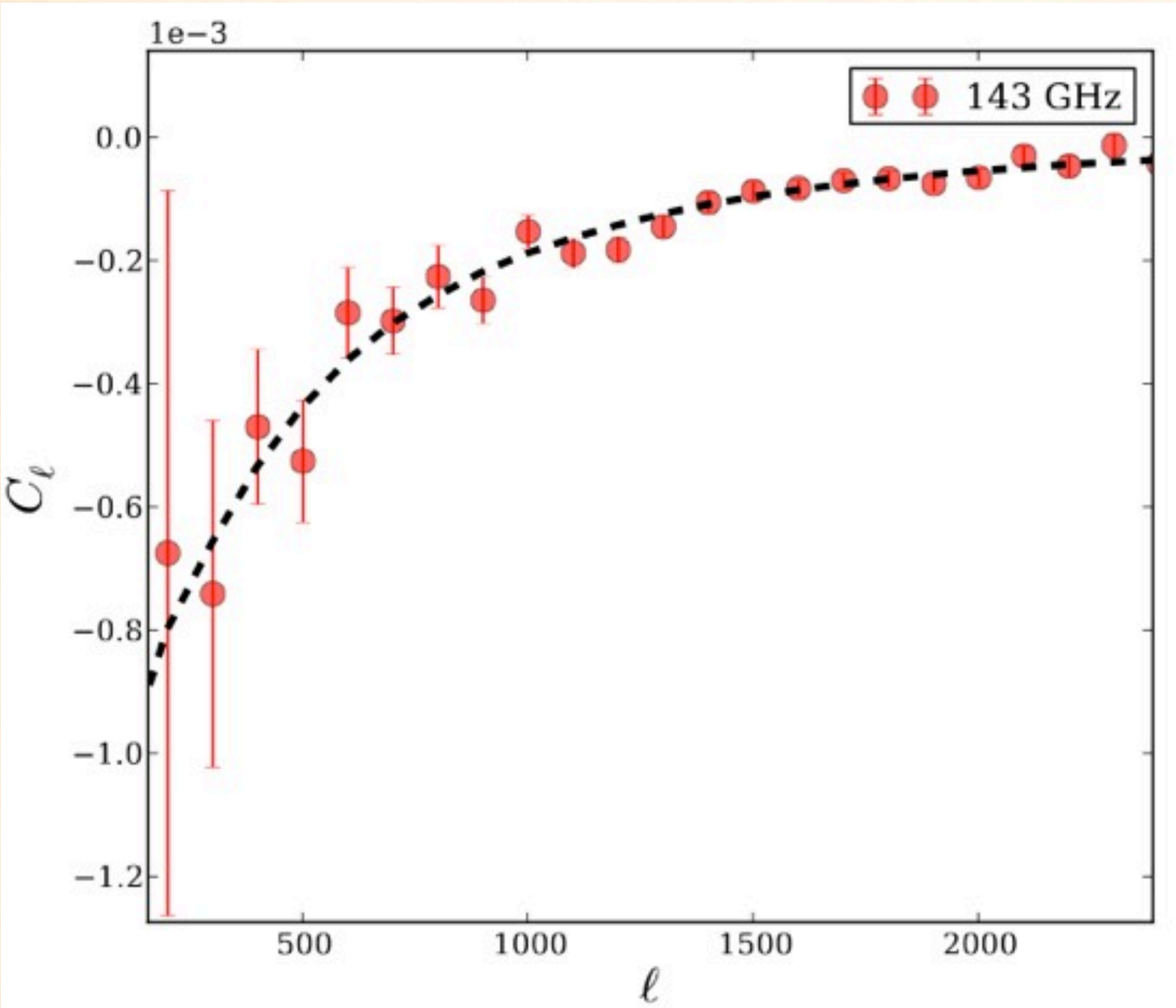
$$\Delta T(\hat{\theta}) = T_{\rm SZ} + T_{\rm CMB} + T_{\rm CIB} + T_{\rm fg} + T_{\rm PS} + N$$

Cluster overdensity map

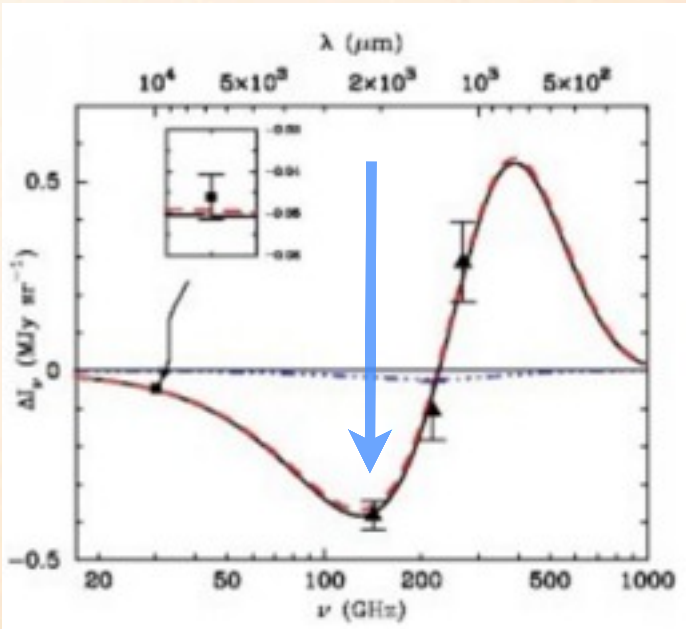
$$\delta_n(\hat{\theta}) = \frac{n(\hat{\theta})}{\bar{n}} - 1$$



R X P143 GHZ

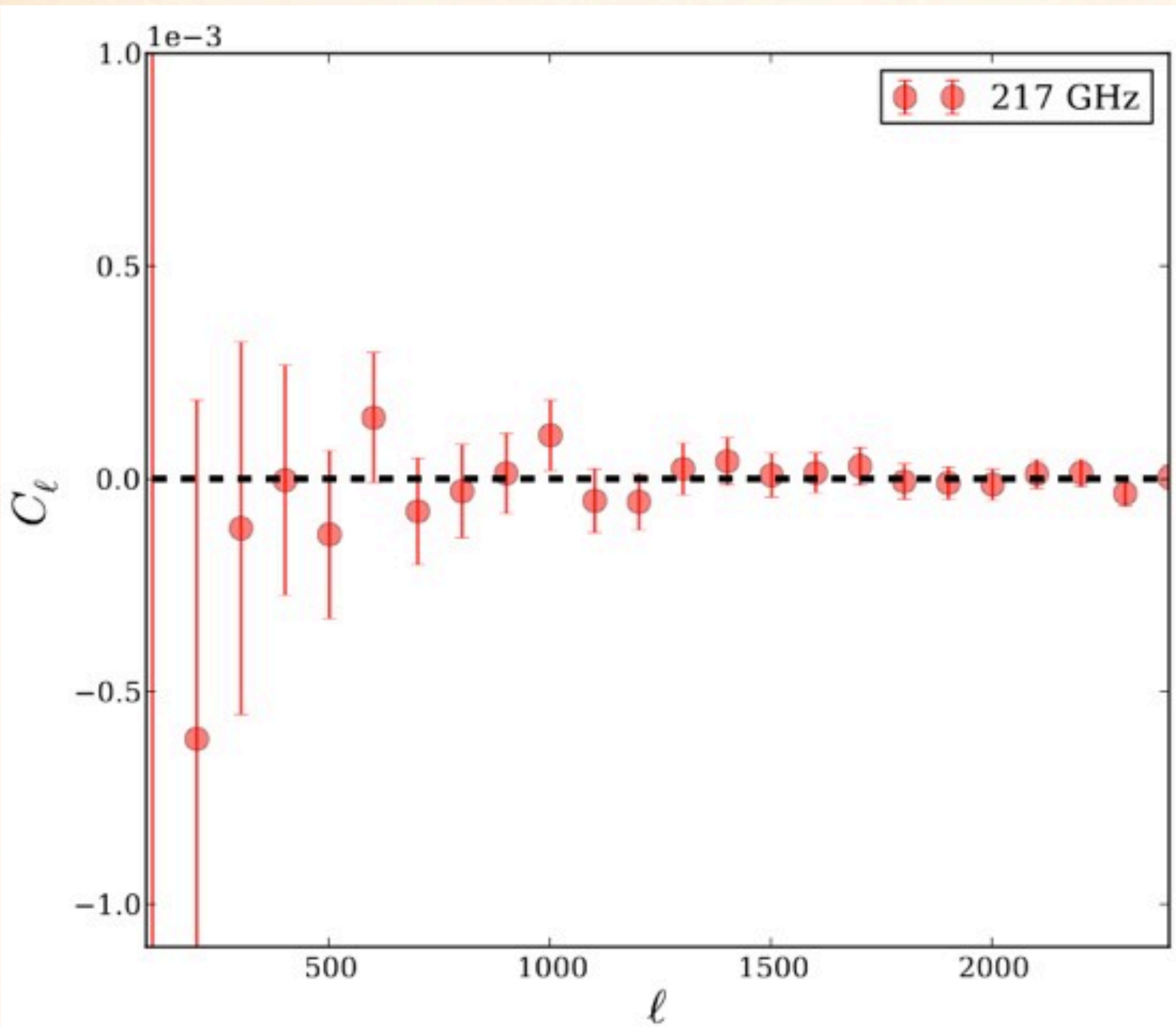


1e−3
143 GHz
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−1.2
C_ℓ
500
1000
1500
2000
ℓ

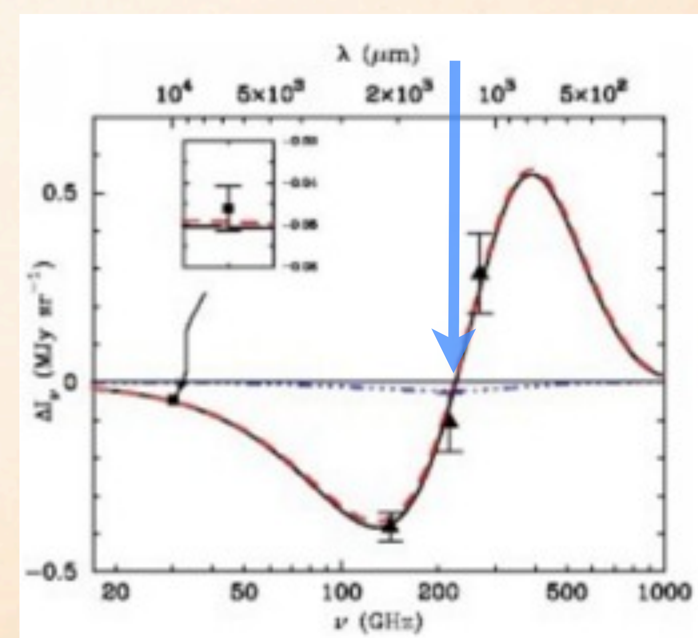


λ (μm)
10⁴
5×10³
2×10³
10³
5×10²
0.5
0
−0.5
ΔI_ν (MJy sr⁻¹)
20
50
100
200
500
1000
ν (GHz)

R X P217 GHZ

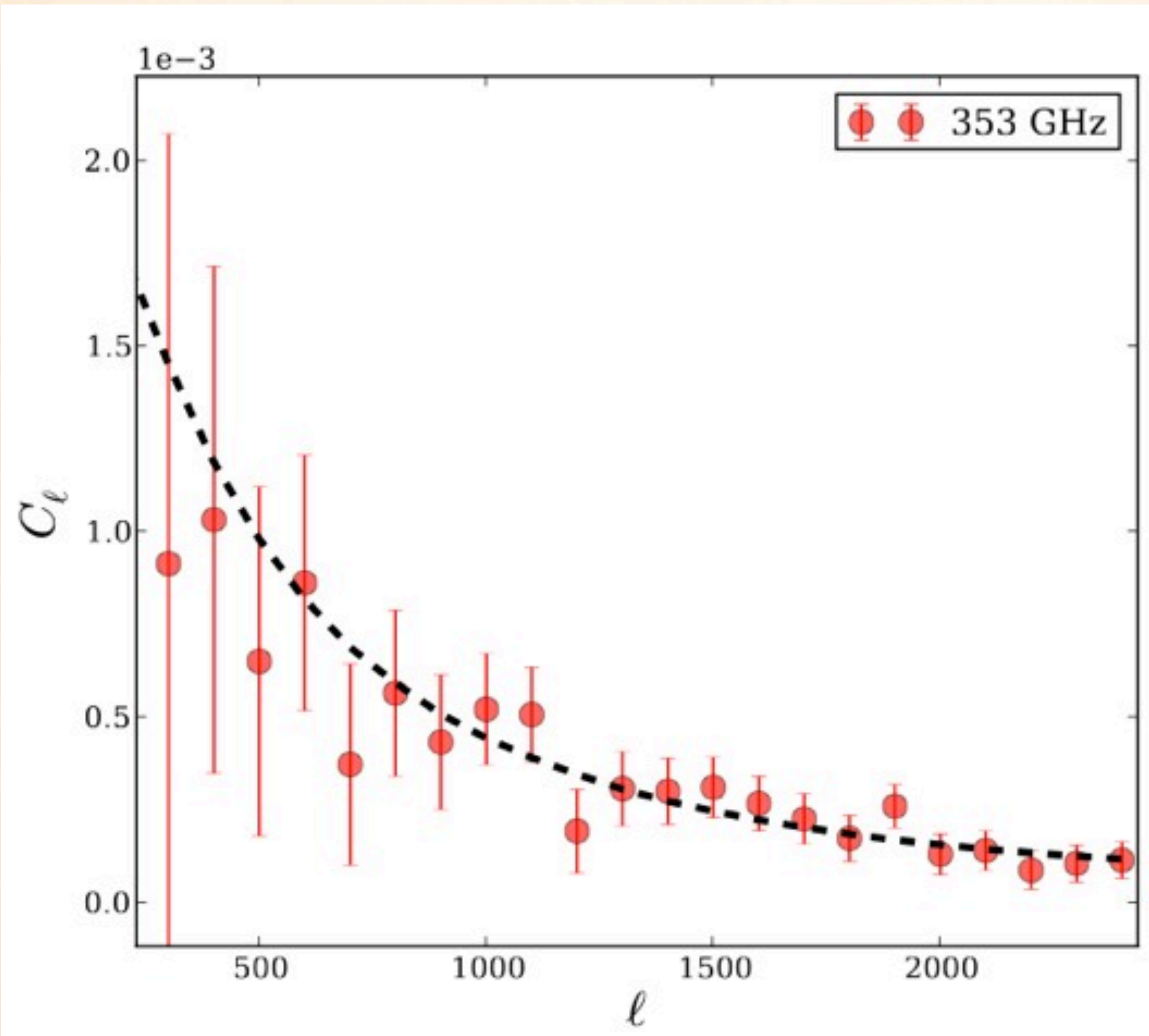


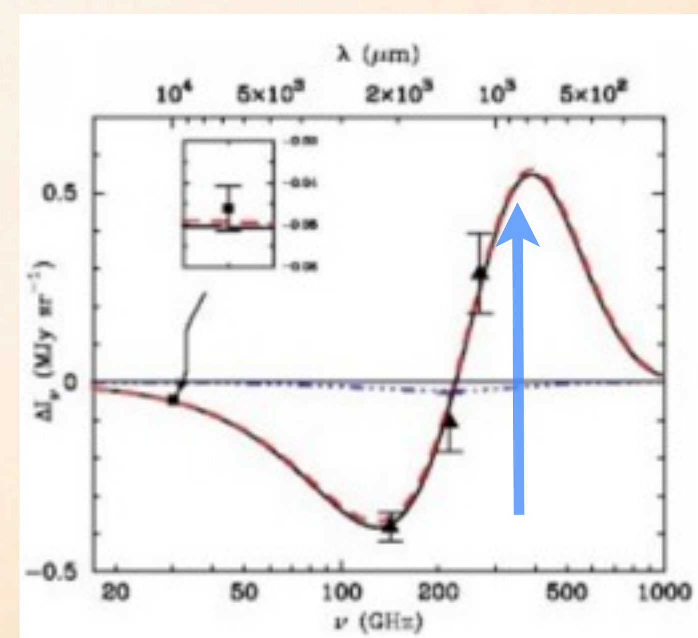
1e−3
1.0
0.5
0.0
−0.5
−1.0
C_ℓ
500
1000
1500
2000
ℓ
217 GHz



λ (μm)
10⁴
5×10³
2×10³
10³
5×10²
0.5
0
−0.5
20
50
100
200
500
1000
ν (GHz)

R X P353 GHZ

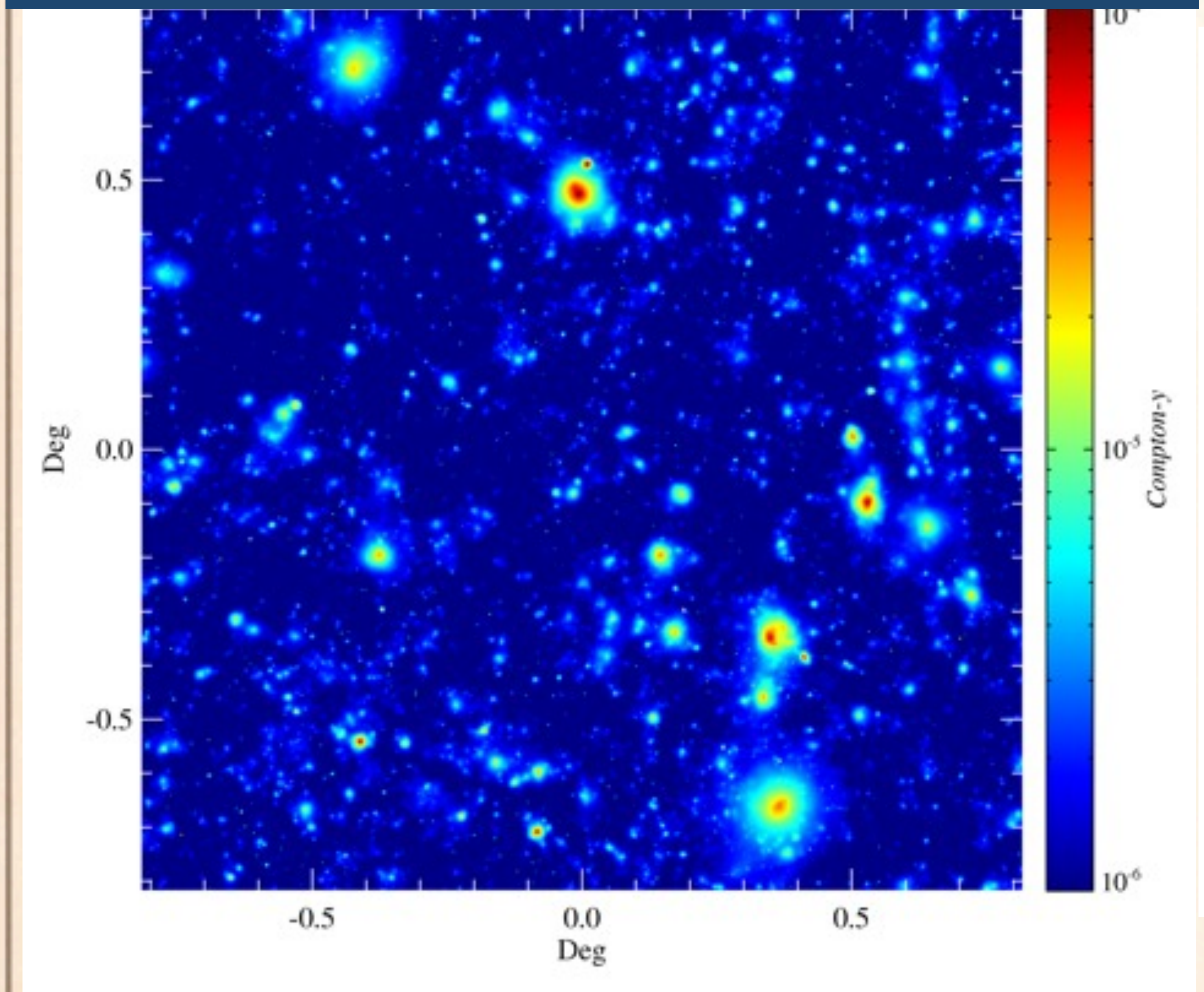

1e−3
353 GHz
2.0
1.5
1.0
0.5
0.0
C_ℓ
500
1000
1500
2000
ℓ

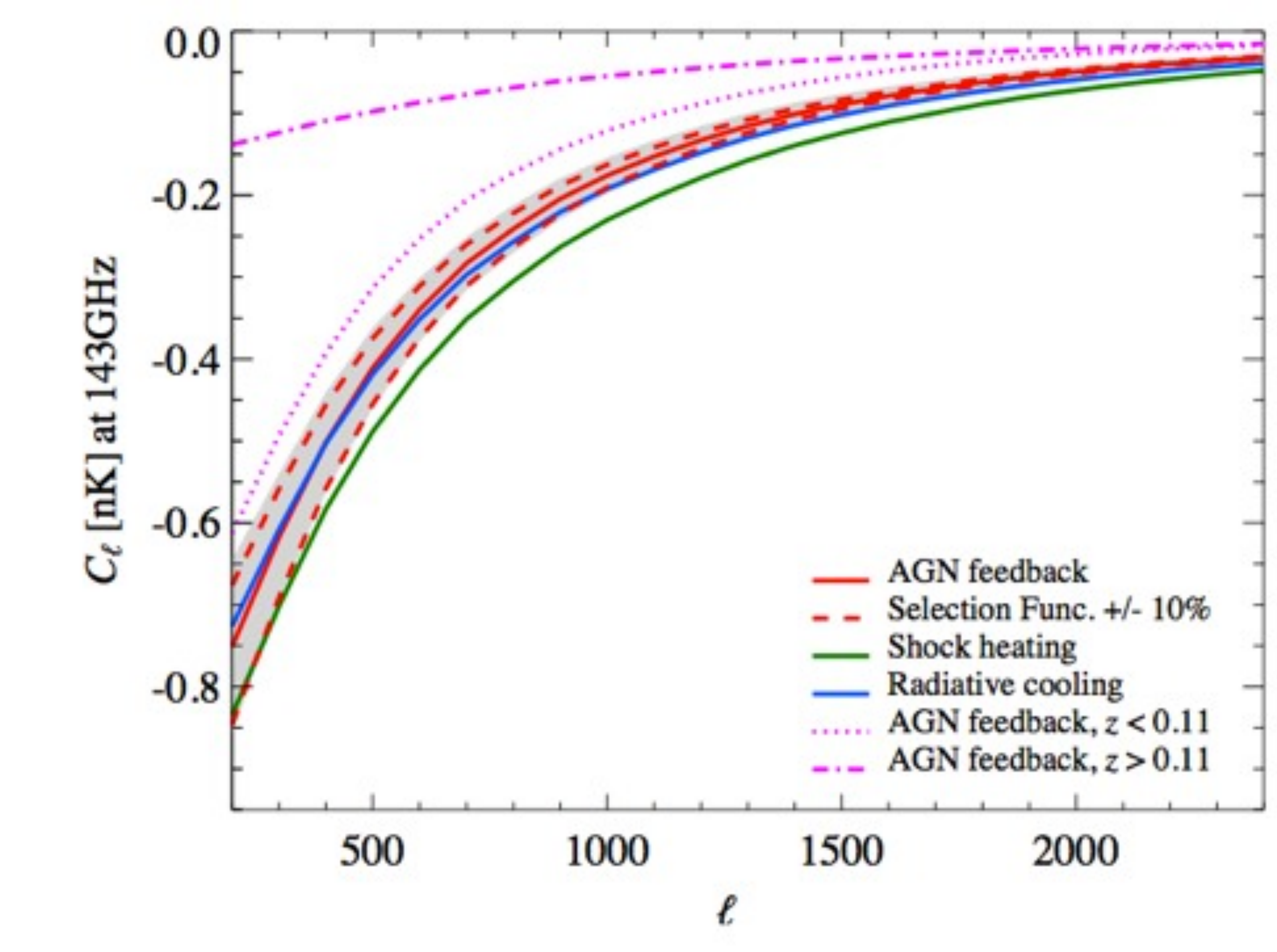

λ (μm)
10⁴
5×10³
2×10³
10³
5×10²
0.5
0
−0.5
20
50
100
200
500
1000
ν (GHz)

MODELLING XSPECTRA

Simulated Compton-y map: Feedback

= AGN or Starburst E-feedback + radiative cool + SN energy + wind

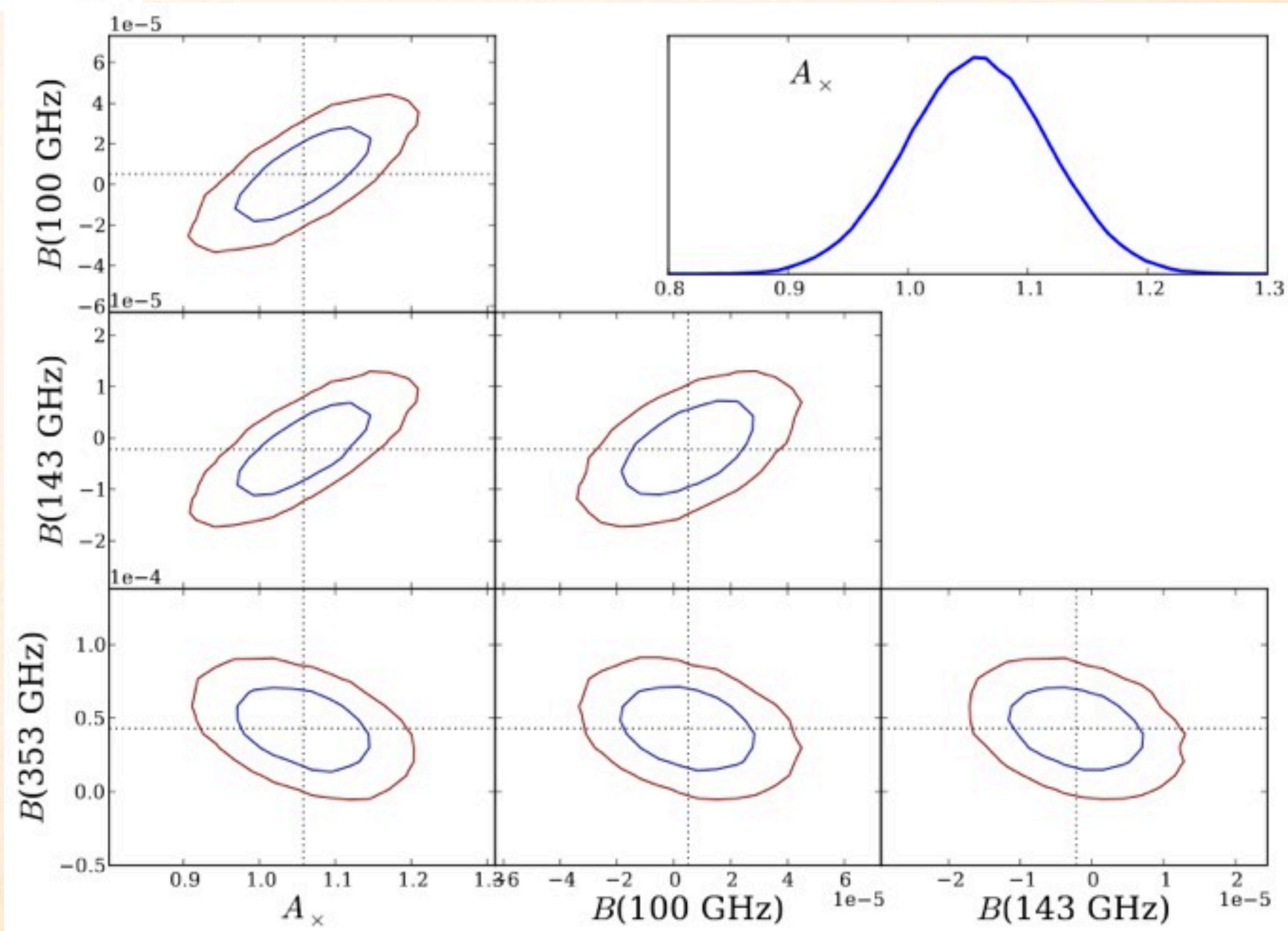


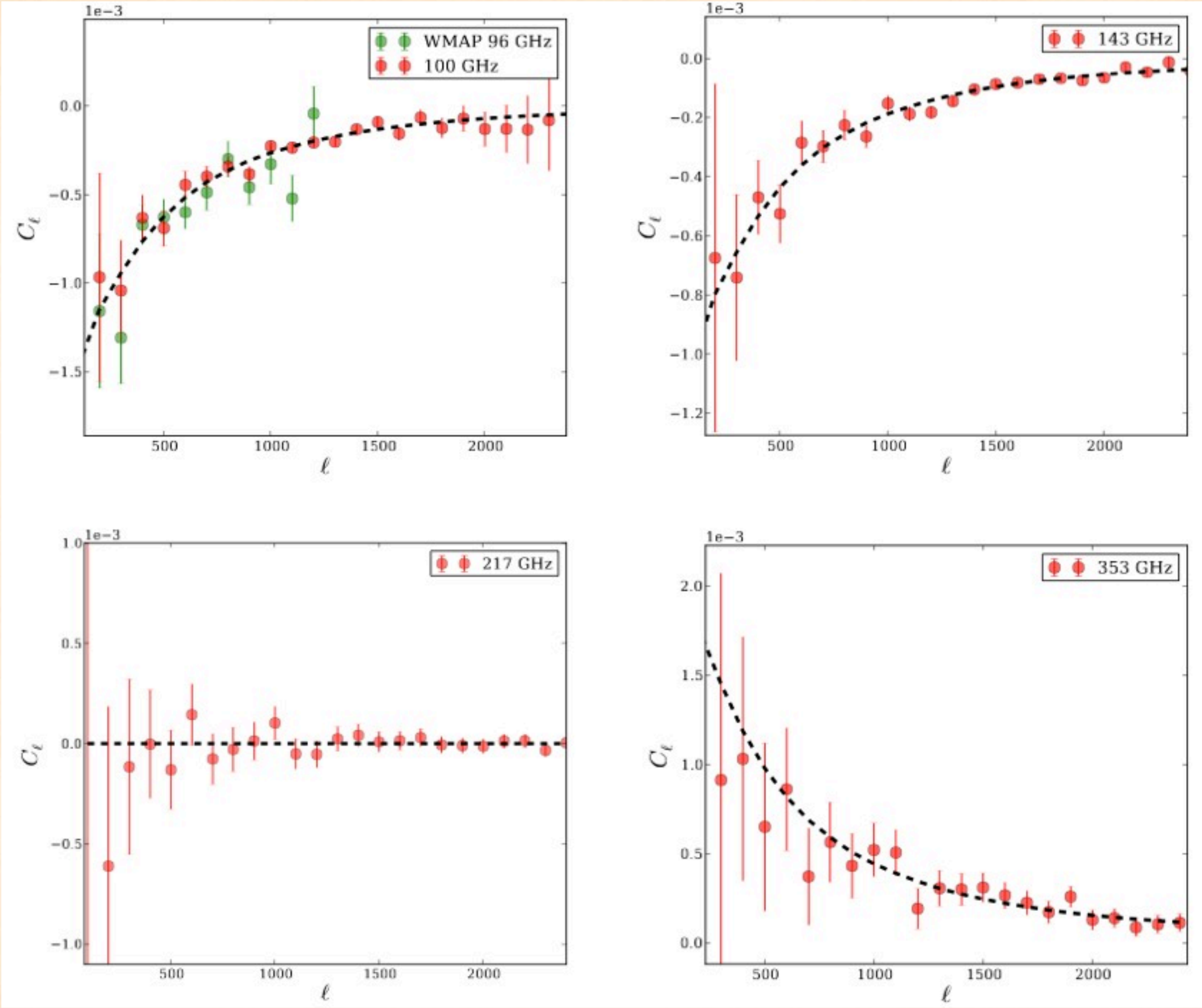


$$C_\ell^{SZ\times n} = f_\nu \int_{0.04}^{\infty} \frac{\mathrm{d}V}{\mathrm{d}z}\mathrm{d}z \int_0^{\infty} \frac{\mathrm{d}n(M,z)}{\mathrm{d}M}\tilde{y}_\ell(M,z)\Theta(M,z)\mathrm{d}M,$$

FITTING XSPECTRA

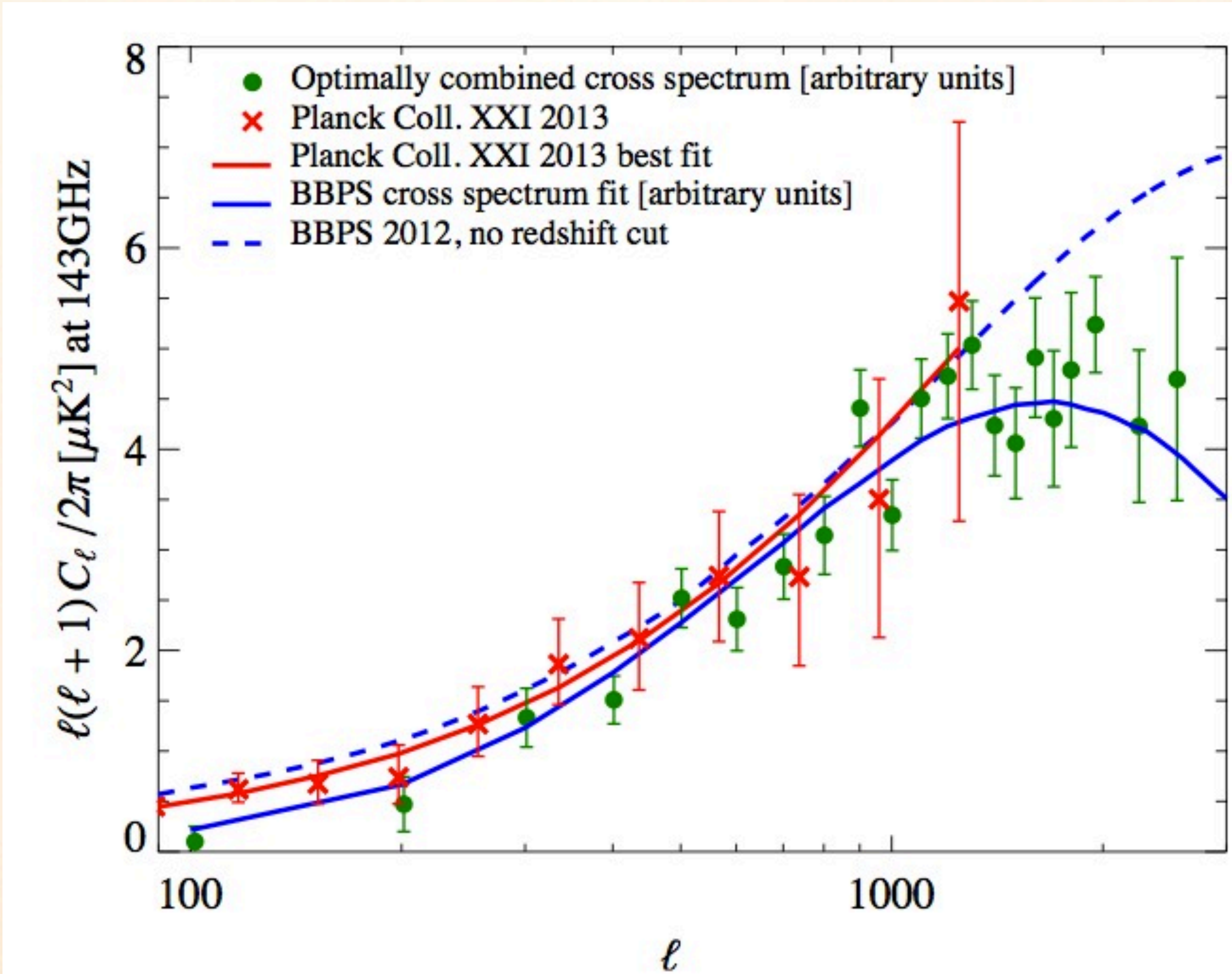
$$C_l^{\mathrm{obs}}(\nu) = A_\times(\nu) C_l(\nu_0) + B(\nu)$$



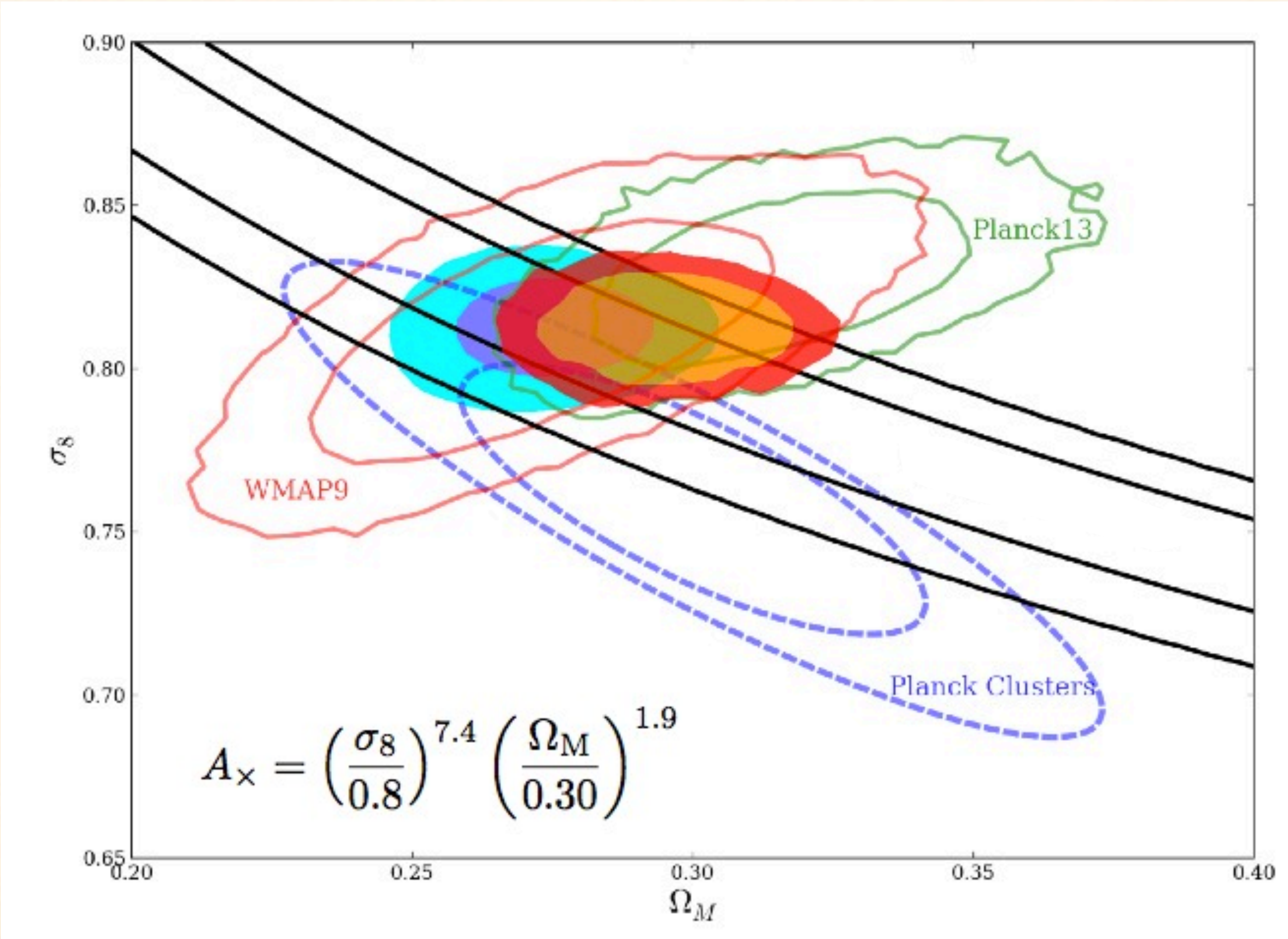


WMAP 96 GHz
100 GHz
143 GHz
217 GHz
353 GHz
1e−3
C_ℓ
ℓ

COMBINED XSPECS



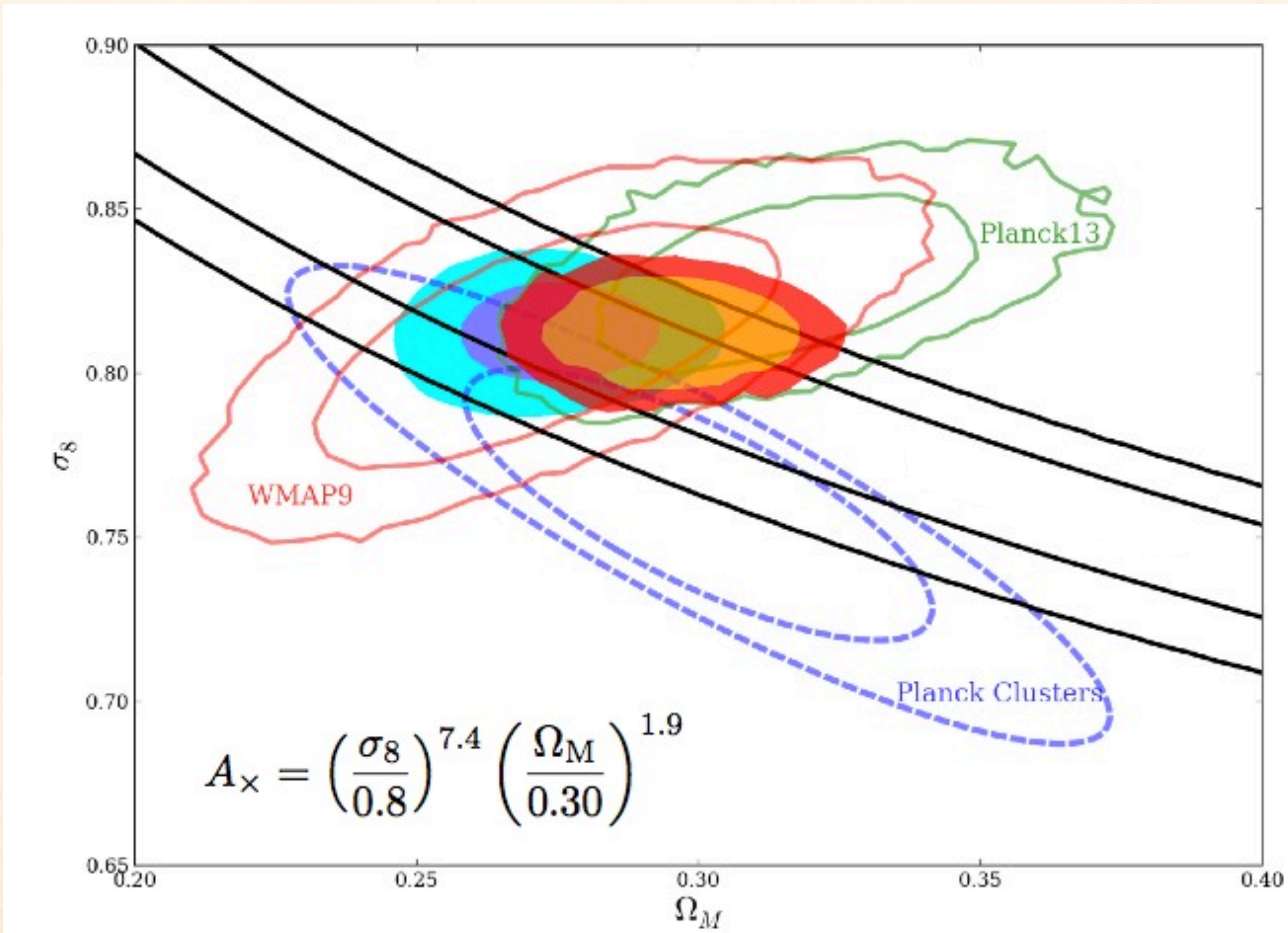
PARAMETERS



Hajian, Battaglia, Spergel, Bond, Pfrommer, Sievers (2013)

PARAMETERS

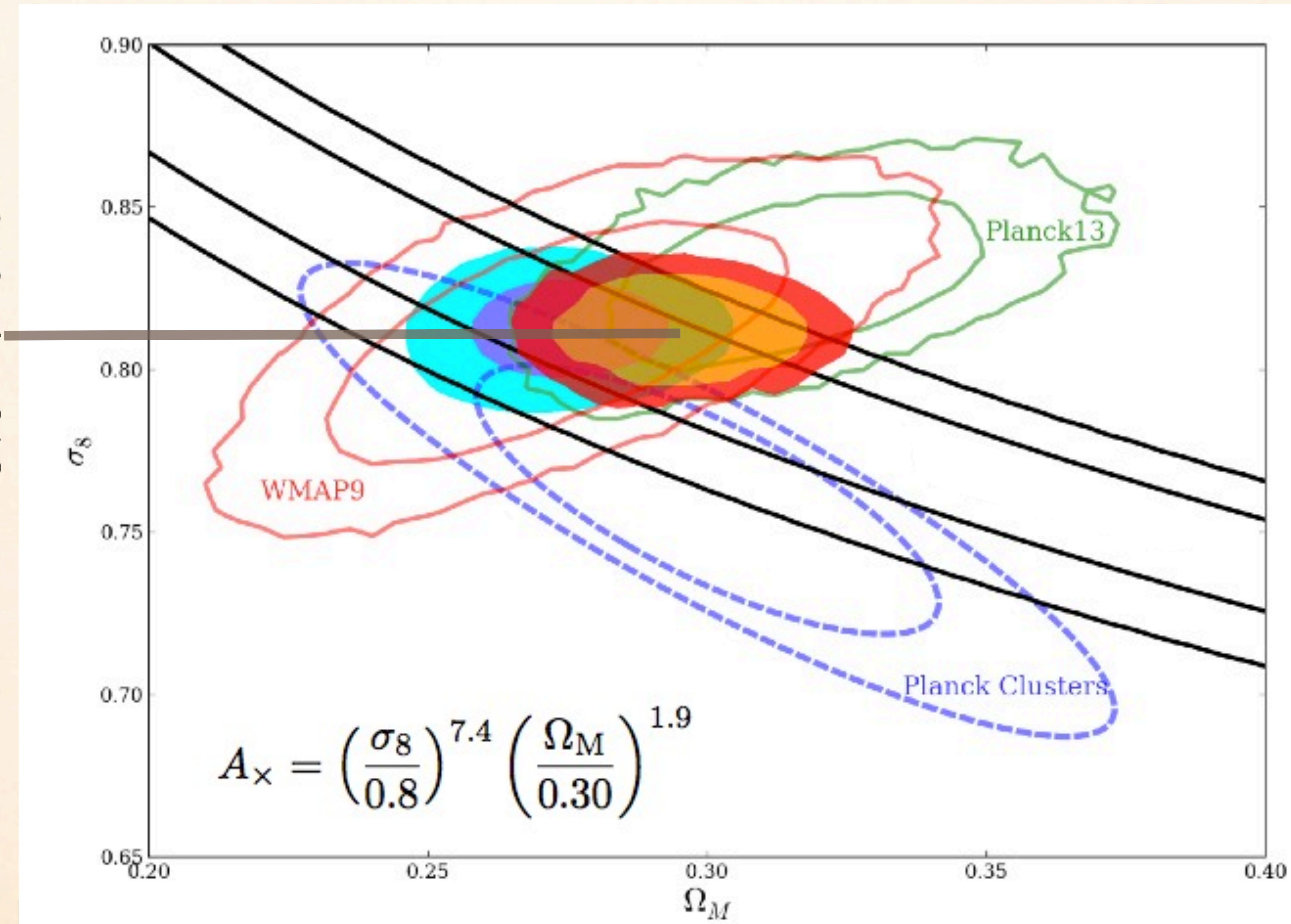
0.81+/-0.01



Hajian, Battaglia, Spergel, Bond, Pfrommer, Sievers (2013)

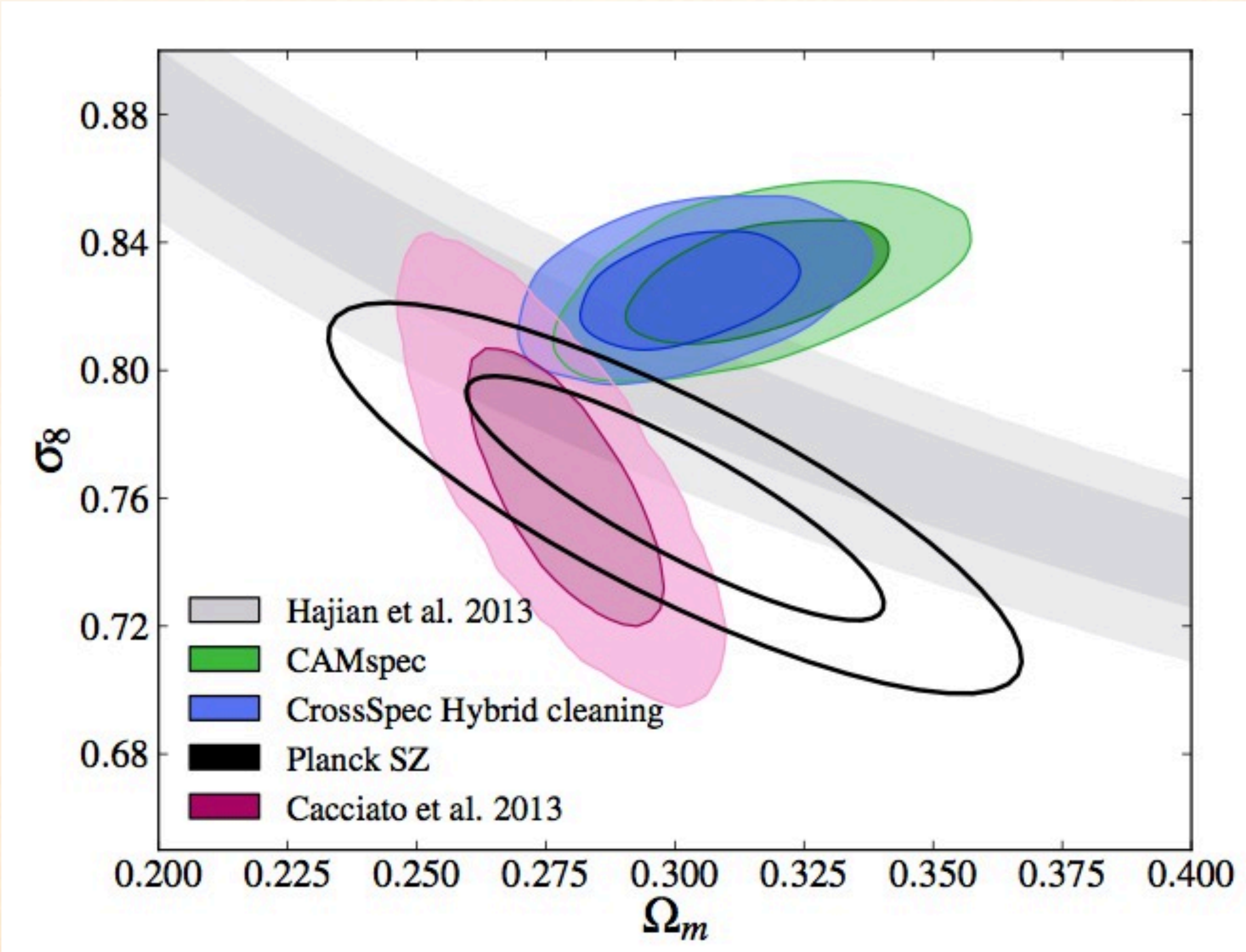
PARAMETERS

0.81+/-0.01



Hajian, Battaglia, Spergel, Bond, Pfrommer, Sievers (2013)

CONSISTENCY



Spergel et al 2013

ASTROPHYSICAL OUTPUTS

	Lensed CMB/ Lensing	CIB	SZ
Lensed CMB/ Lensing	Primordial signals		
CIB			
SZ			

ASTROPHYSICAL OUTPUTS

	Lensed CMB/ Lensing	CIB	SZ
Lensed CMB/ Lensing	Primordial signals		
CIB		Star formation history	
SZ			

ASTROPHYSICAL OUTPUTS

	Lensed CMB/ Lensing	CIB	SZ
Lensed CMB/ Lensing	Primordial signals		
CIB		Star formation history	
SZ			sigma_8

ASTROPHYSICAL OUTPUTS

	Lensed CMB/ Lensing	CIB	SZ
Lensed CMB/ Lensing	Primordial signals	time evolution of potential, measurements of galaxy bias	
CIB		Star formation history	
SZ			sigma_8

ASTROPHYSICAL OUTPUTS

	Lensed CMB/ Lensing	CIB	SZ
Lensed CMB/ Lensing	Primordial signals	time evolution of potential, measurements of galaxy bias	cluster mass measurements
CIB		Star formation history	
SZ			sigma_8

ASTROPHYSICAL OUTPUTS

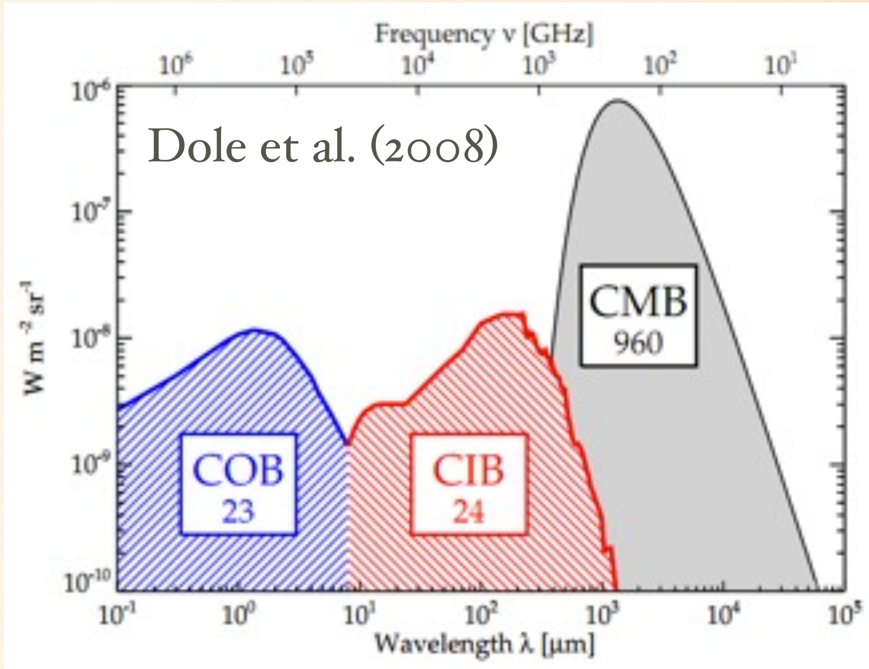
	Lensed CMB/ Lensing	CIB	SZ
Lensed CMB/ Lensing	Primordial signals	time evolution of potential, measurements of galaxy bias	cluster mass measurements
CIB		Star formation history	contamination
SZ			sigma_8

ACT X BLAST

Balloon-borne Large Aperture Submillimeter Telescope

BACKGROUND RADIATION BUDGET OF THE UNIVERSE

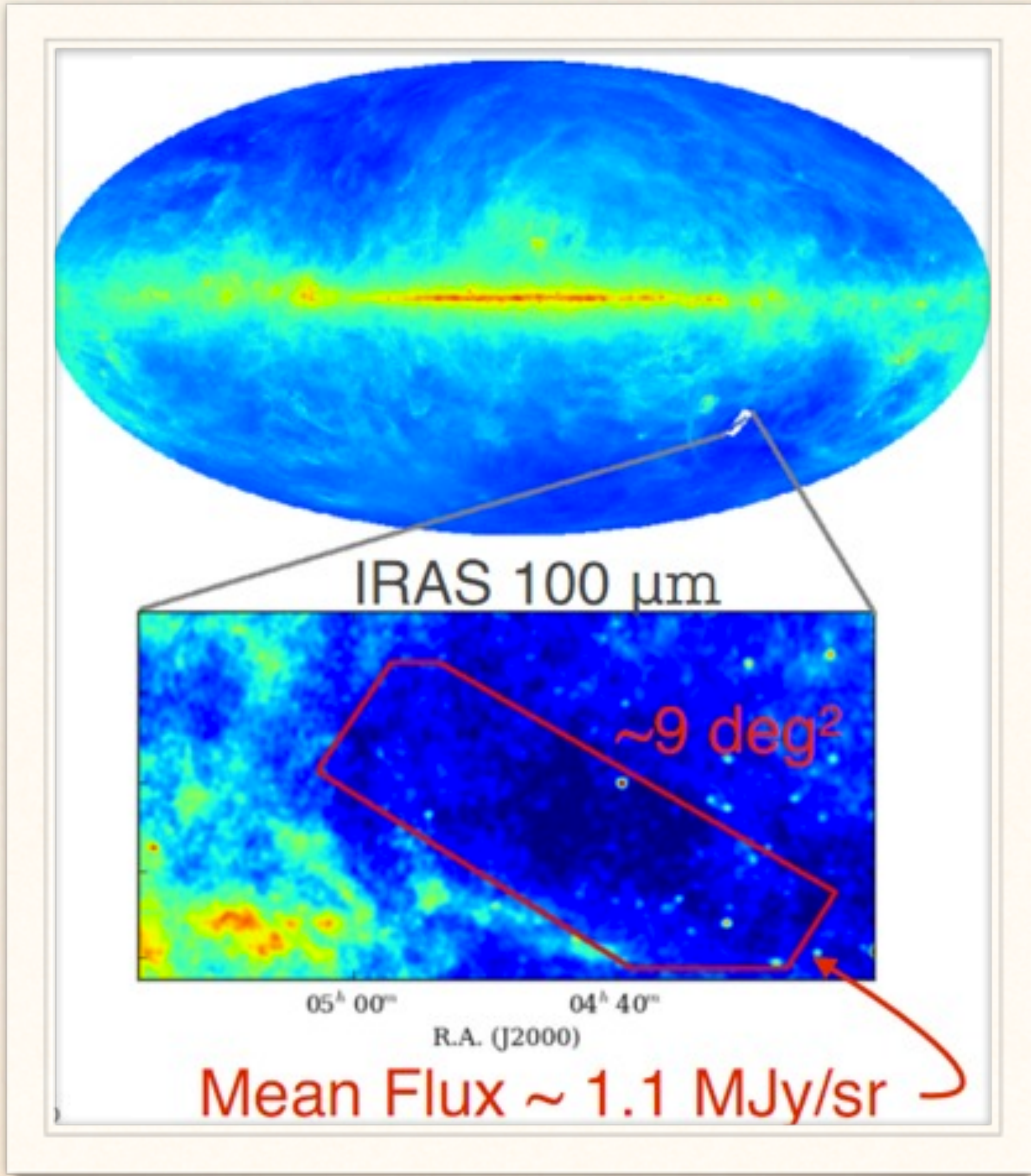
- Star formation takes place in clouds composed of hydrogen and dust.
- Dust absorbs the starlight from young, hot stars, heats to ~30K.
- Light re-emitted at longer (sub)millimeter wavelengths: Cosmic Infrared Background (Bond, Carr, Hogan (1986))



Dust in NGC 1055, a nearby spiral galaxy, seen in emission and absorption.

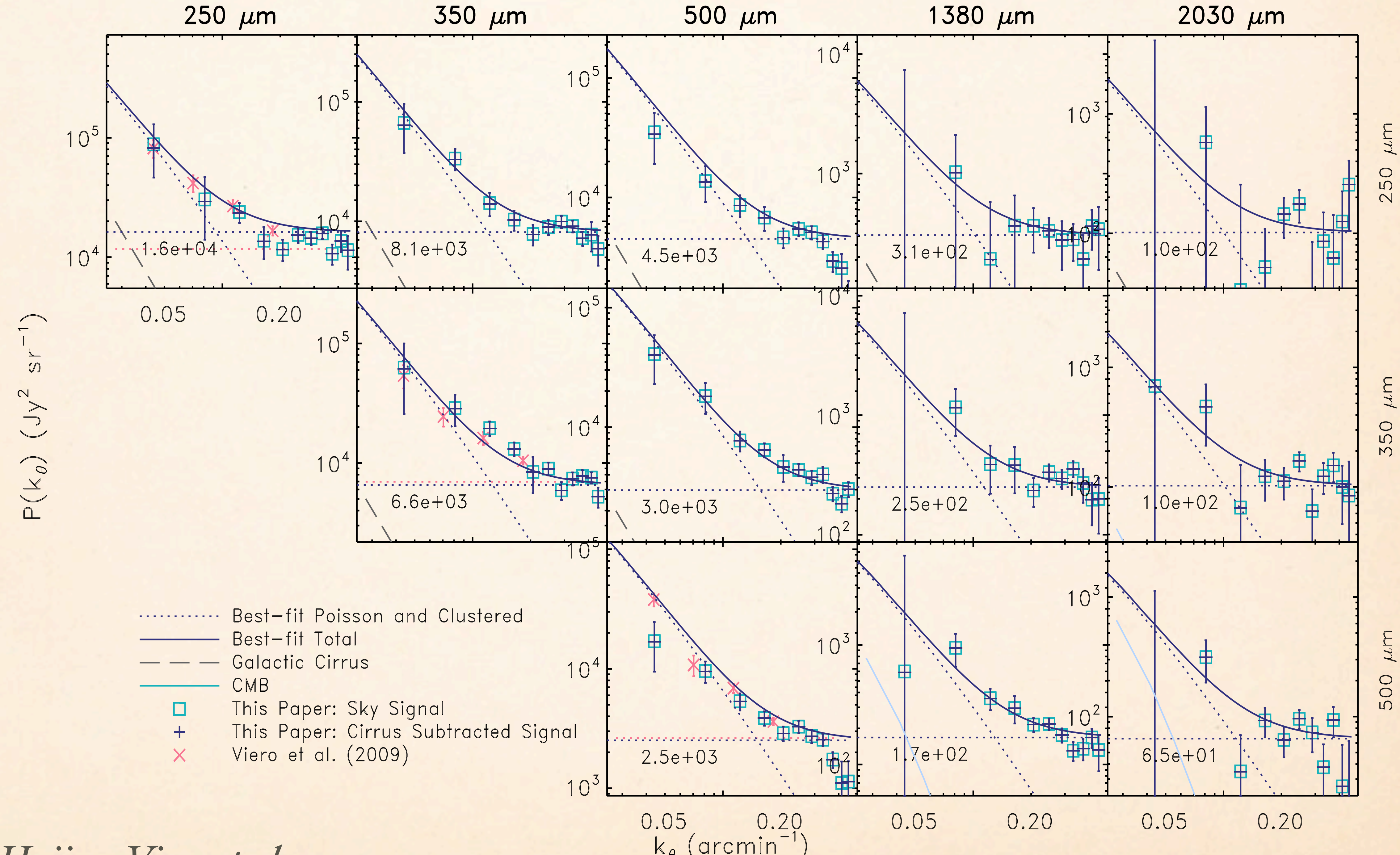
ACT X BLAST

- About 9 sq. deg. overlap with ACT
- Maps in three frequencies: 250 um, 350um and 500um
- Clean from Galactic dust emission



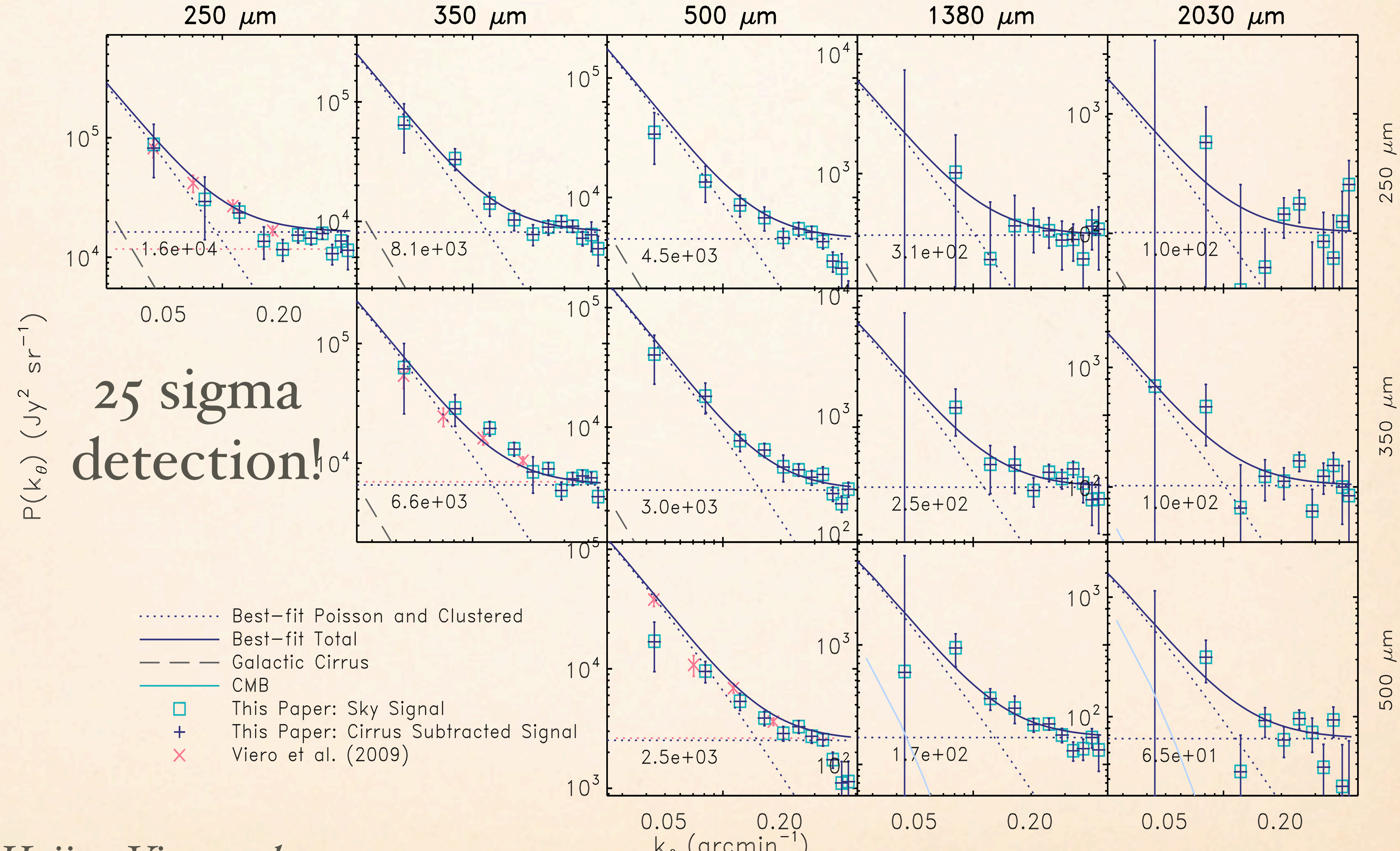
Hajian, Viero et al 2012

ACT X BLAST



Hajian, Viero et al 2012

ACT X BLAST



25 sigma detection!

Hajian, Viero et al 2012

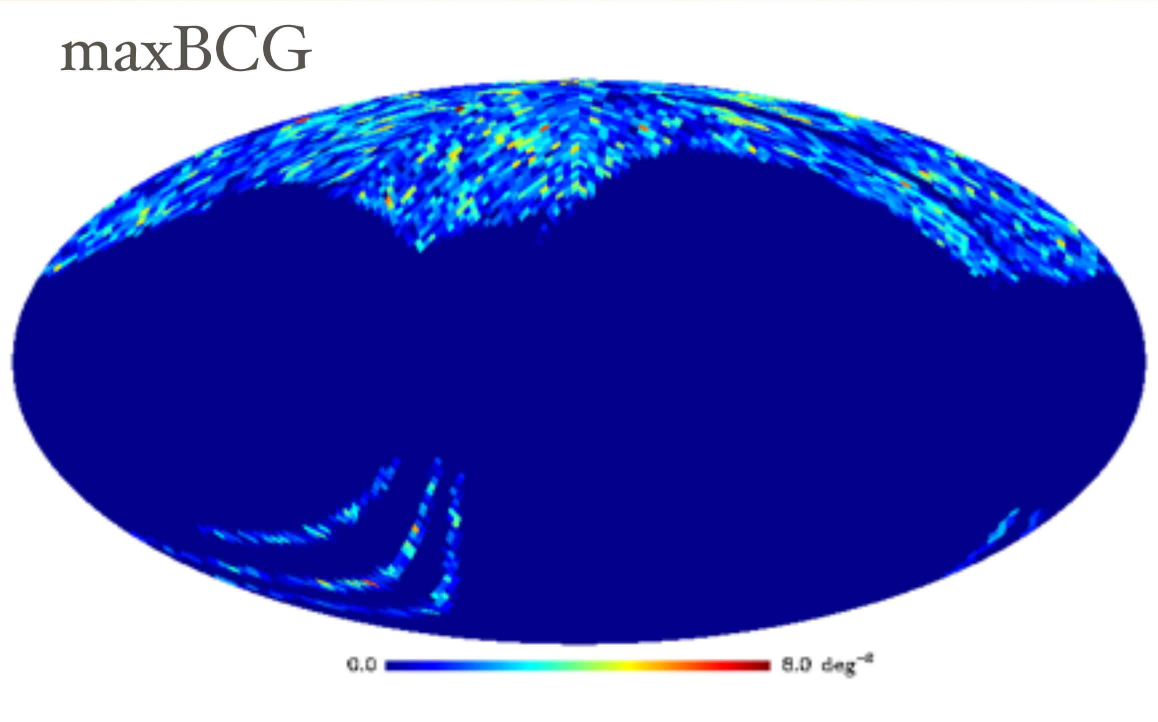
ASTROPHYSICAL OUTPUTS

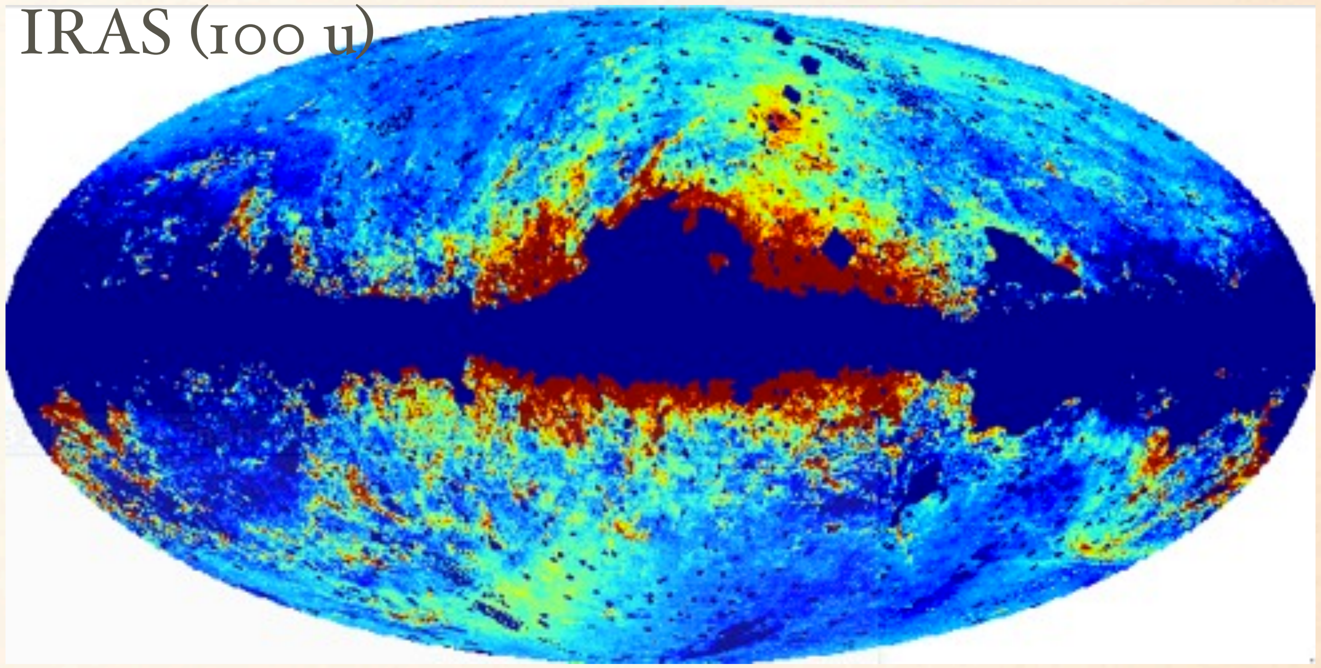
	Lensed CMB/ Lensing	CIB	SZ
Lensed CMB/ Lensing	Primordial signals	time evolution of potential, measurements of galaxy bias	cluster mass measurements
CIB		Star formation history	contamination
SZ			sigma_8

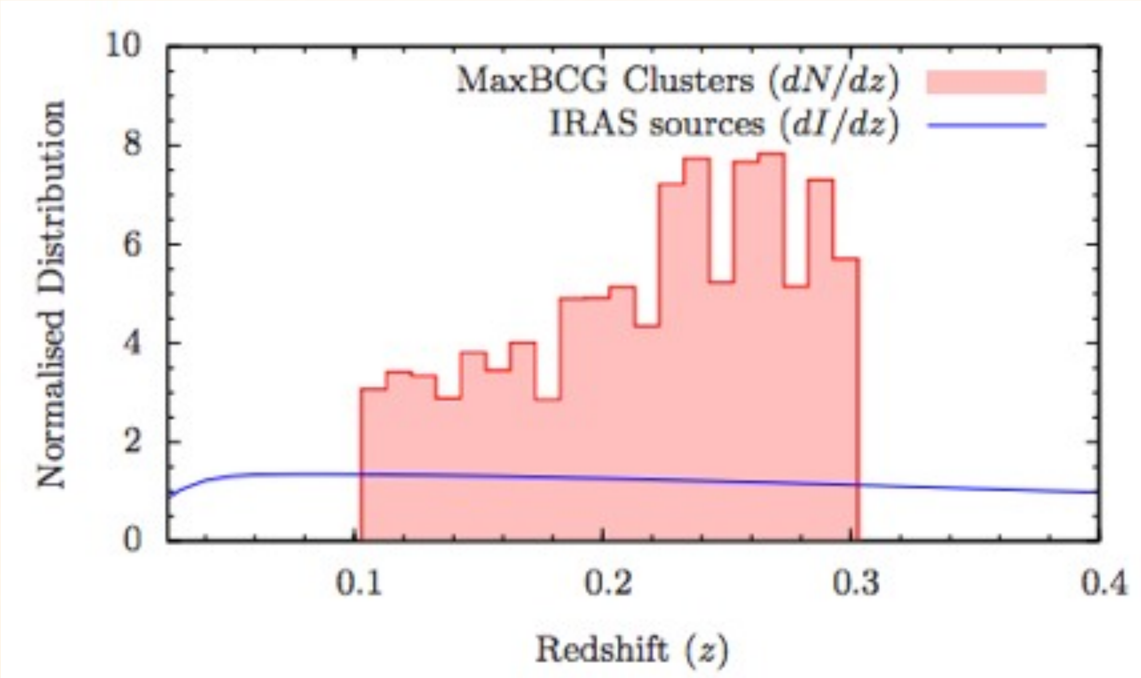
CLUSTERS AND CIB

Both are correlated with the underlying dark matter density like a landscape covered by snow

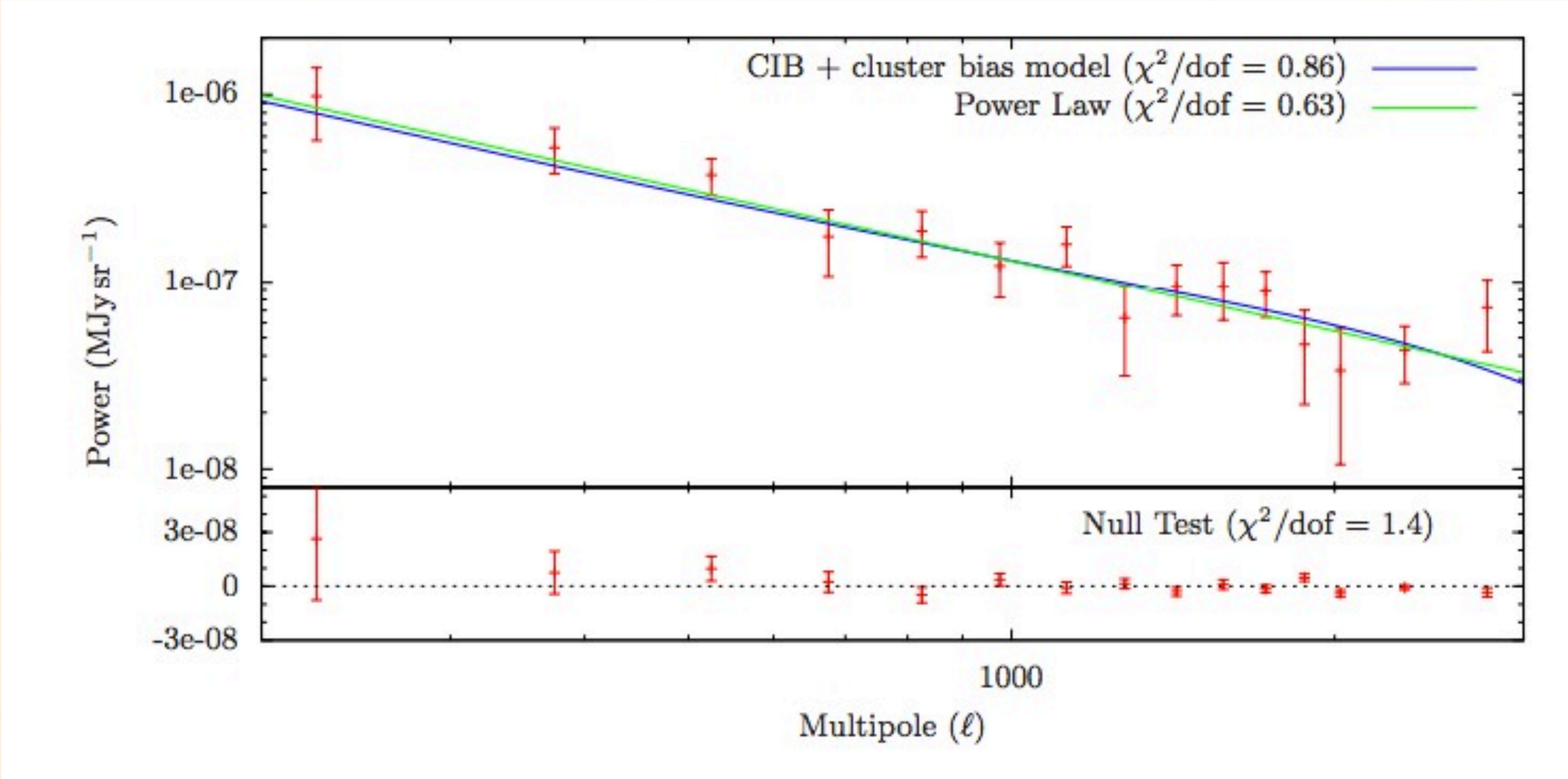
CLUSTERS AND CIB





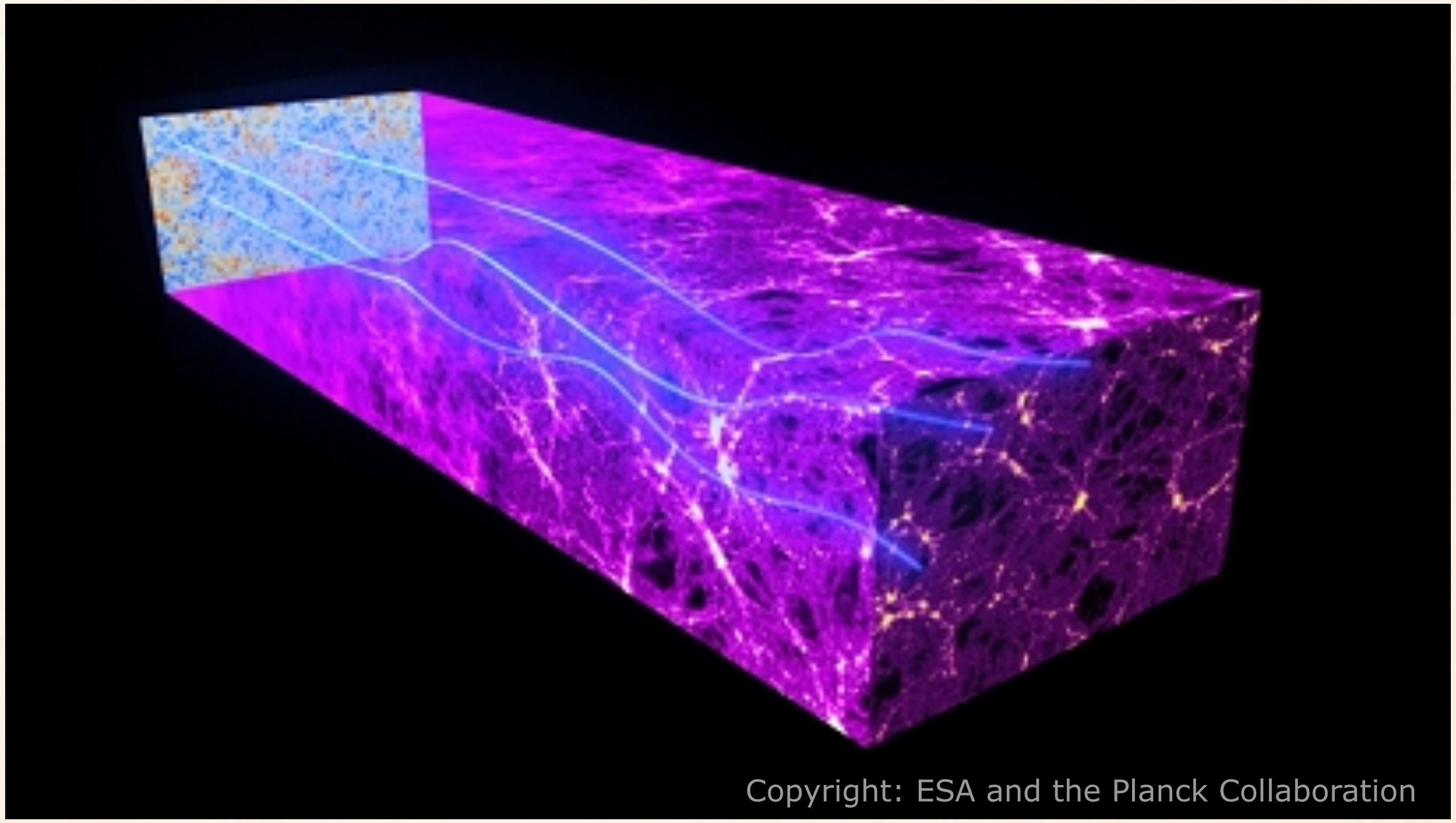


40 SIGMA DETECTION!

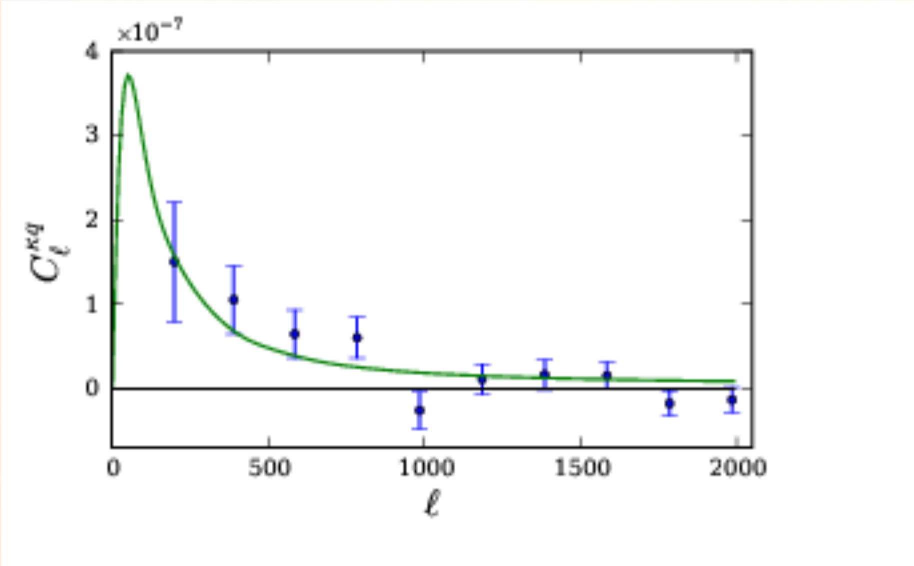


Hincks, Hajian, Addison (2013)

CMB LENSING

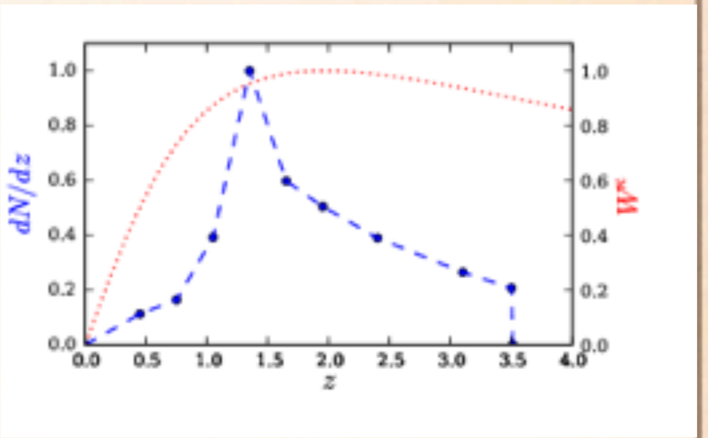


QUASAR BIAS MEASUREMENTS



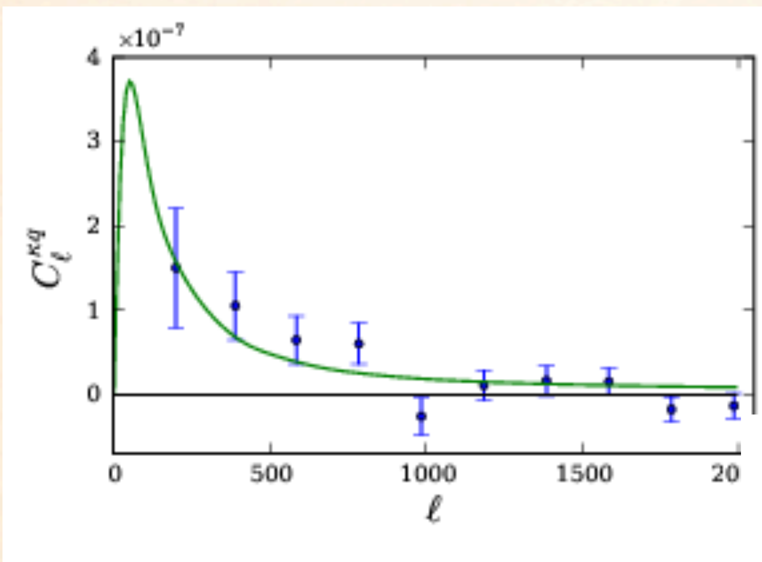
$$C_\ell^{\kappa q} = \int \frac{dz H(z)}{\eta^2(z)} W^\kappa(z) W^q(z) P(k = \ell/\eta(z), z)$$

$b(z)\frac{dN}{dz}$



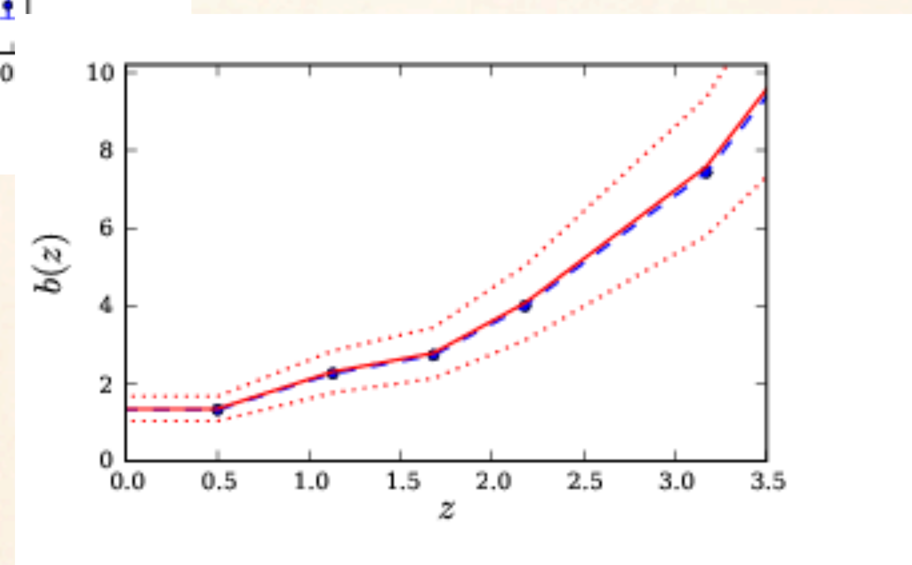
Sherwin, Das, Hajian + (2012)

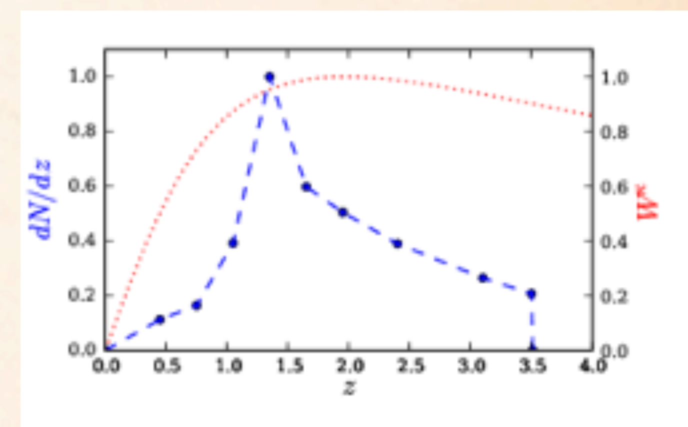
QUASAR BIAS MEASUREMENTS



$$C_\ell^{\kappa q} = \int \frac{dz H(z)}{\eta^2(z)} W^\kappa(z) W^q(z) P(k = \ell/\eta(z), z)$$

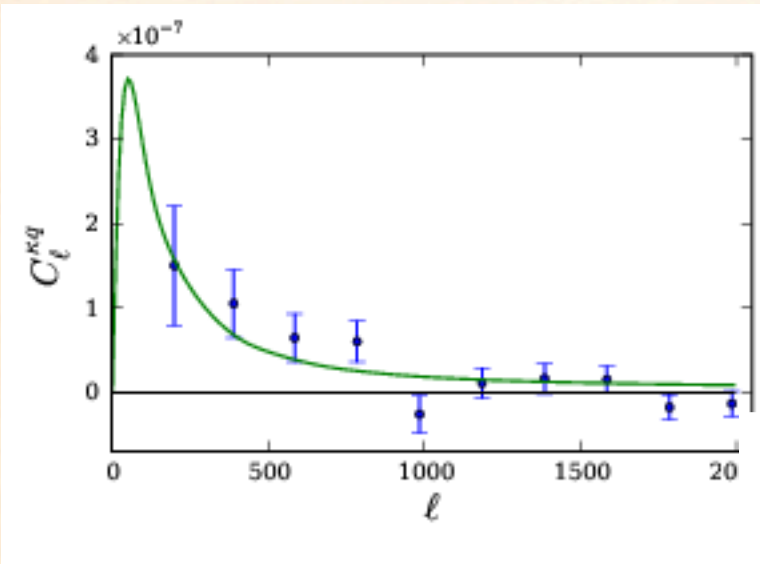
$$b(z)\frac{dN}{dz}$$





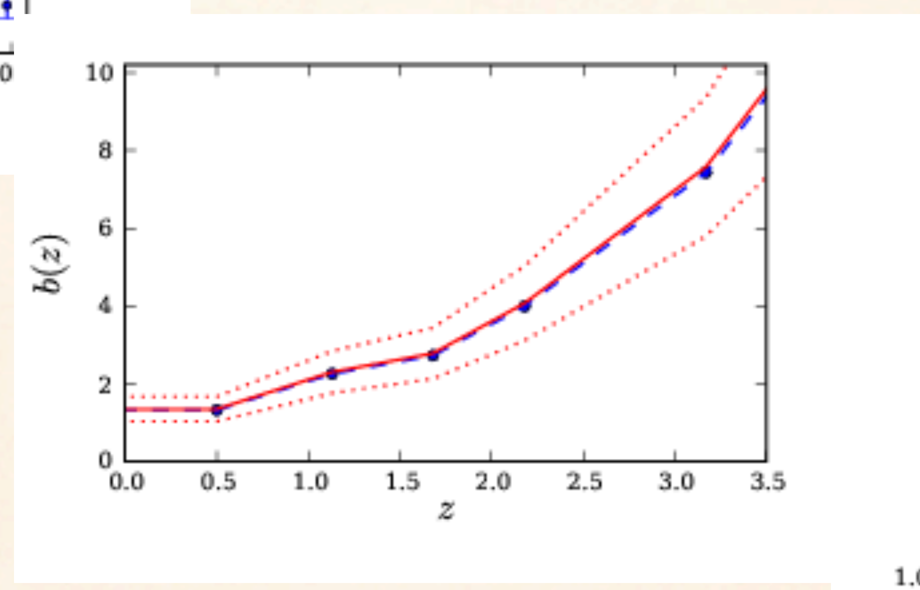
Sherwin, Das, Hajian + (2012)

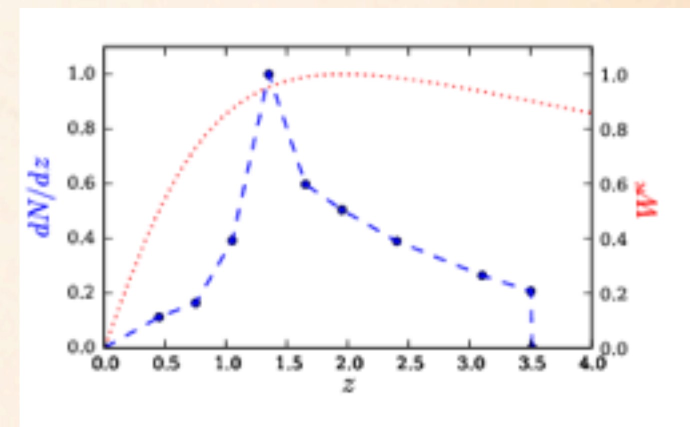
QUASAR BIAS MEASUREMENTS

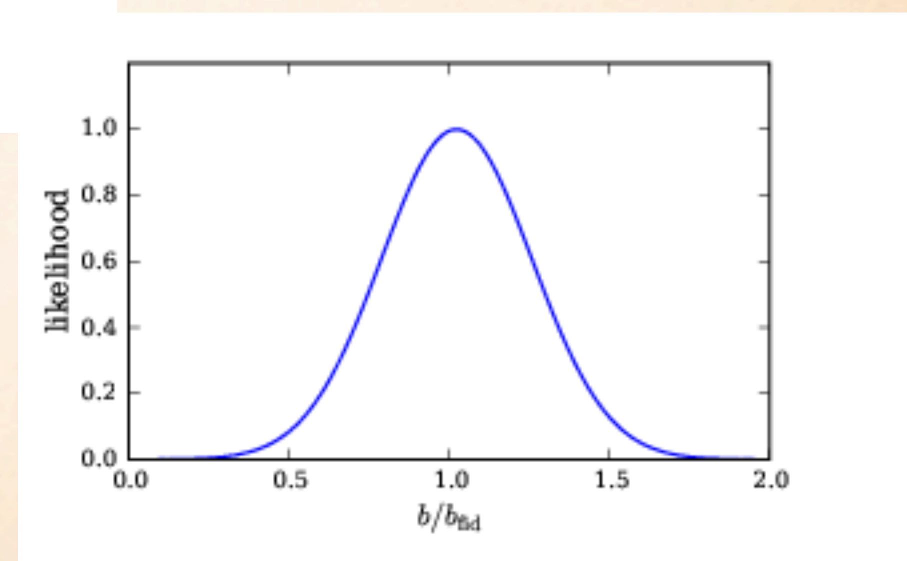


$$C_\ell^{\kappa q} = \int \frac{dz H(z)}{\eta^2(z)} W^\kappa(z) W^q(z) P(k = \ell/\eta(z), z)$$

$W^q(z) \rightarrow b(z)\frac{dN}{dz}$







Sherwin, Das, Hajian + (2012)

WHAT'S NEXT

	Lensed CMB/ Lensing	CIB	SZ
Lensed CMB/ Lensing	Primordial signals	time evolution of potential, measurements of galaxy bias	cluster mass measurements
CIB		Star formation history	contamination
SZ			sigma_8


1
no, its a throne!
its a hose!
its a trunk, dudes!
nah, mate its a fan!
2
wackywisdom.com