BRUCE AND ASTRID MCWILLIAMS
Center for Cosmology

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Cosmology with CMB Secondary Anisotropies

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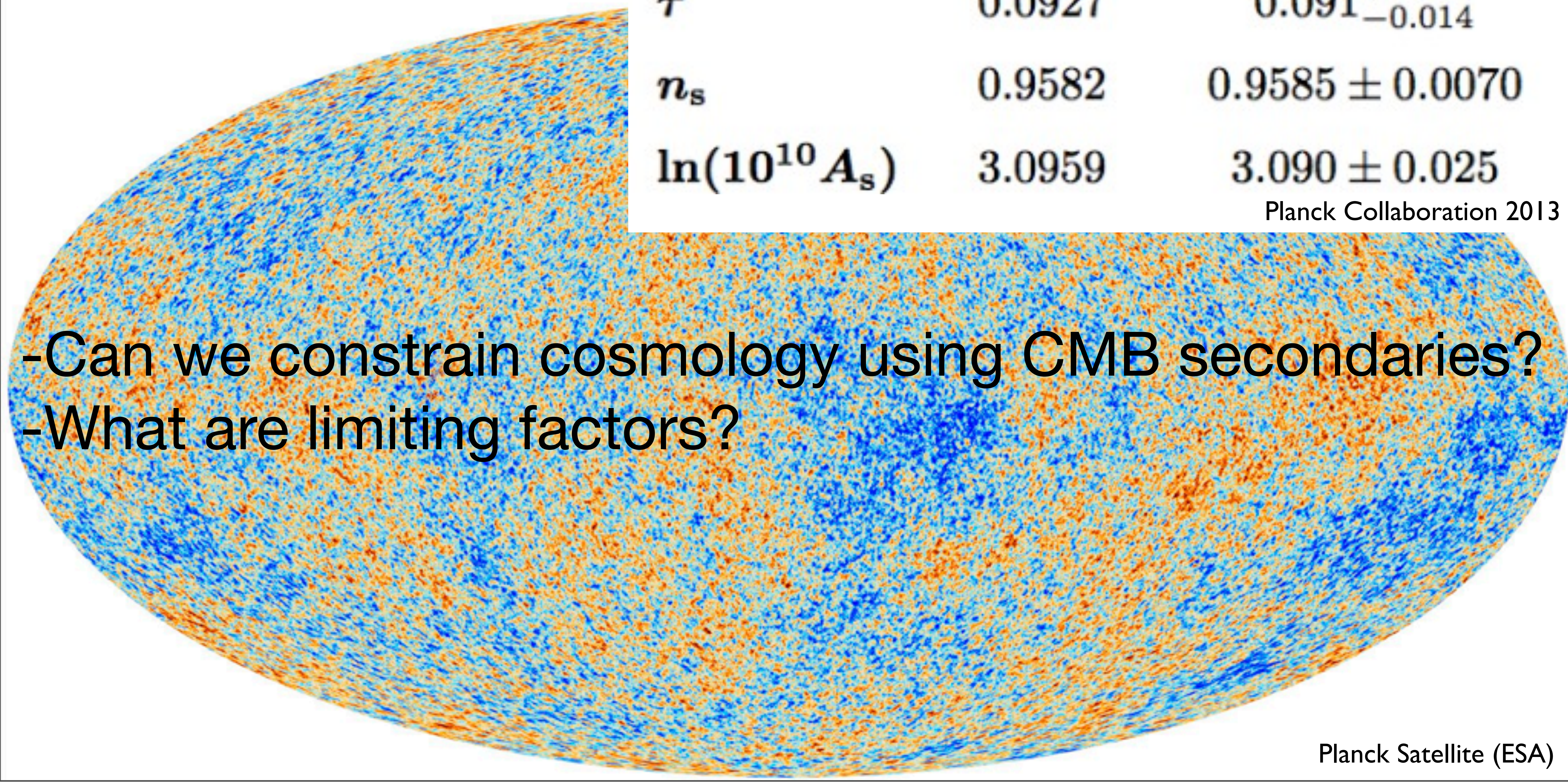
Berkeley
Oct. 22 2013

Primary CMB
The foundation of
modern cosmology

Parameter	Best fit	68% limits
$\Omega_b h^2$	0.022069	0.02207 ± 0.00027
$\Omega_c h^2$	0.12025	0.1198 ± 0.0026
$100\theta_{MC}$	1.04130	1.04132 ± 0.00063
τ	0.0927	$0.091^{+0.013}_{-0.014}$
n_s	0.9582	0.9585 ± 0.0070
$\ln(10^{10} A_s)$	3.0959	3.090 ± 0.025

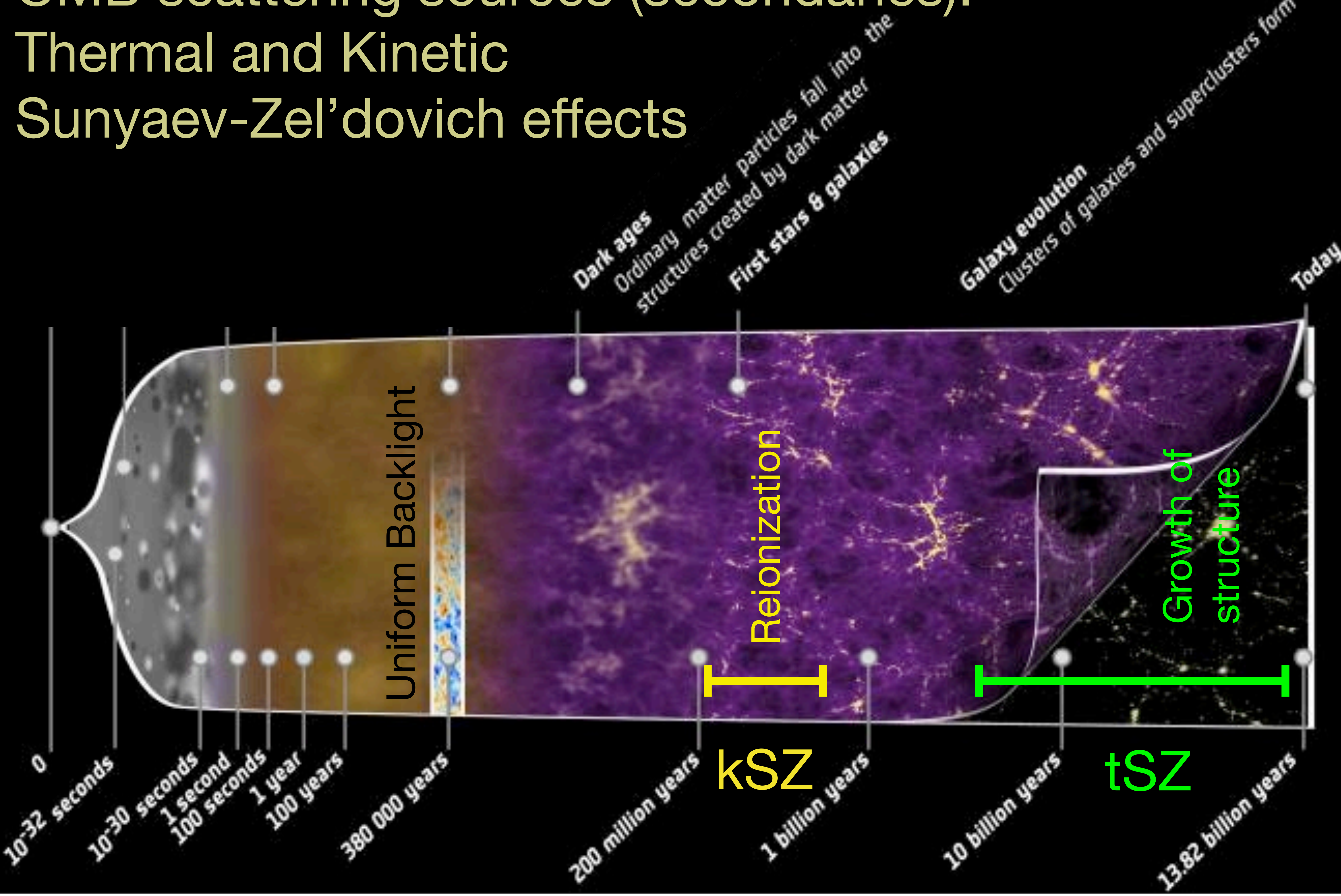
Planck Collaboration 2013

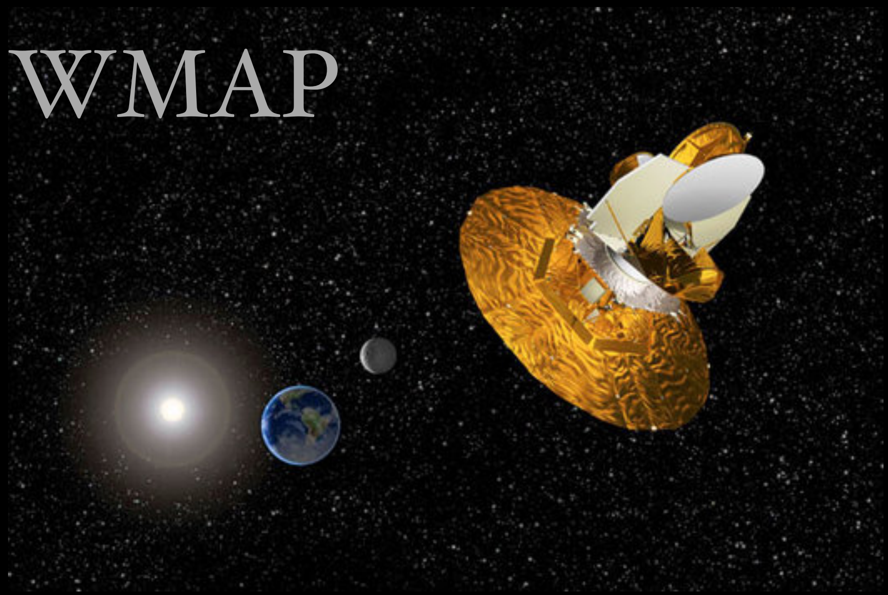


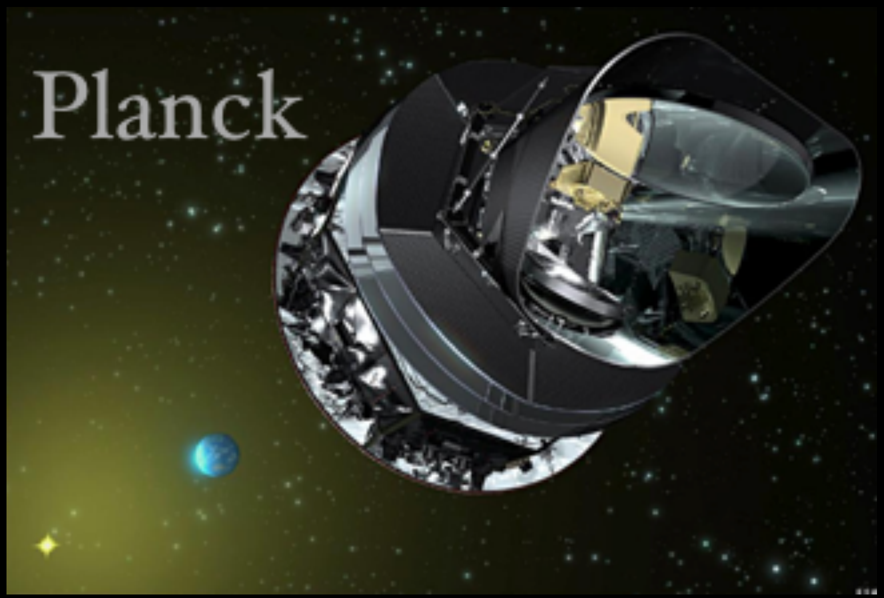
-Can we constrain cosmology using CMB secondaries?
-What are limiting factors?

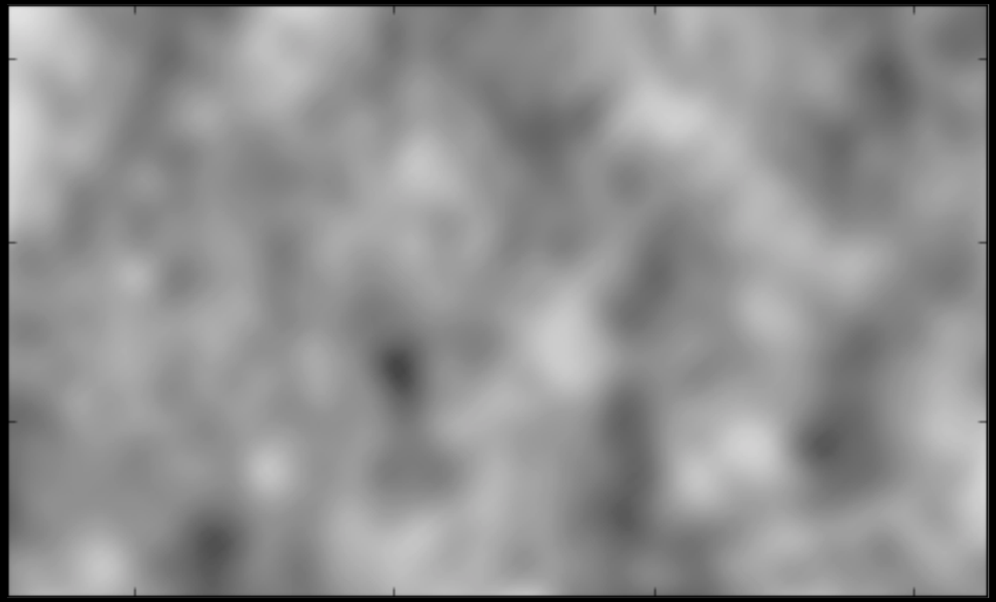
Planck Satellite (ESA)

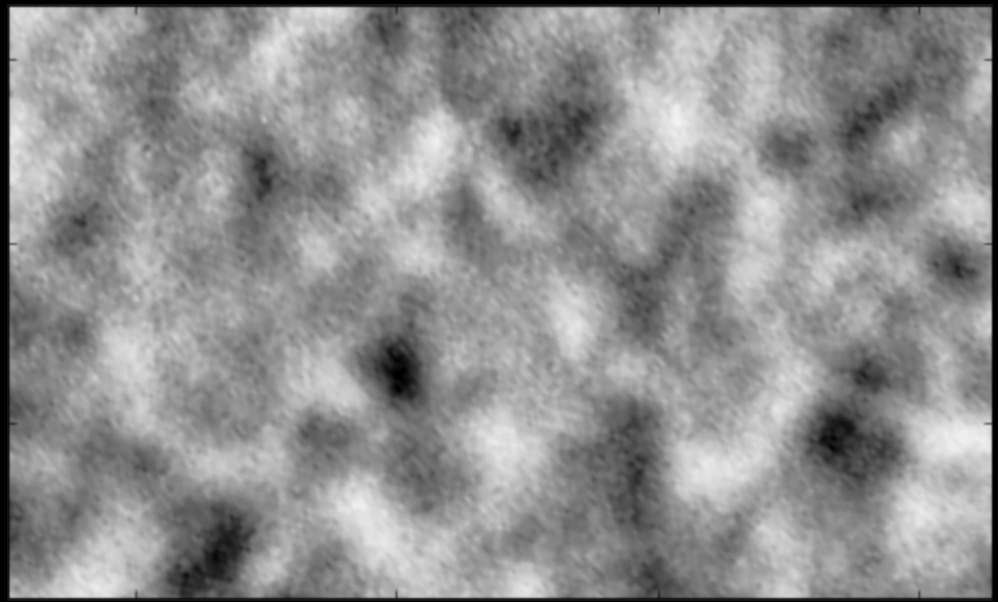
CMB scattering sources (secondaries): Thermal and Kinetic Sunyaev-Zel'dovich effects

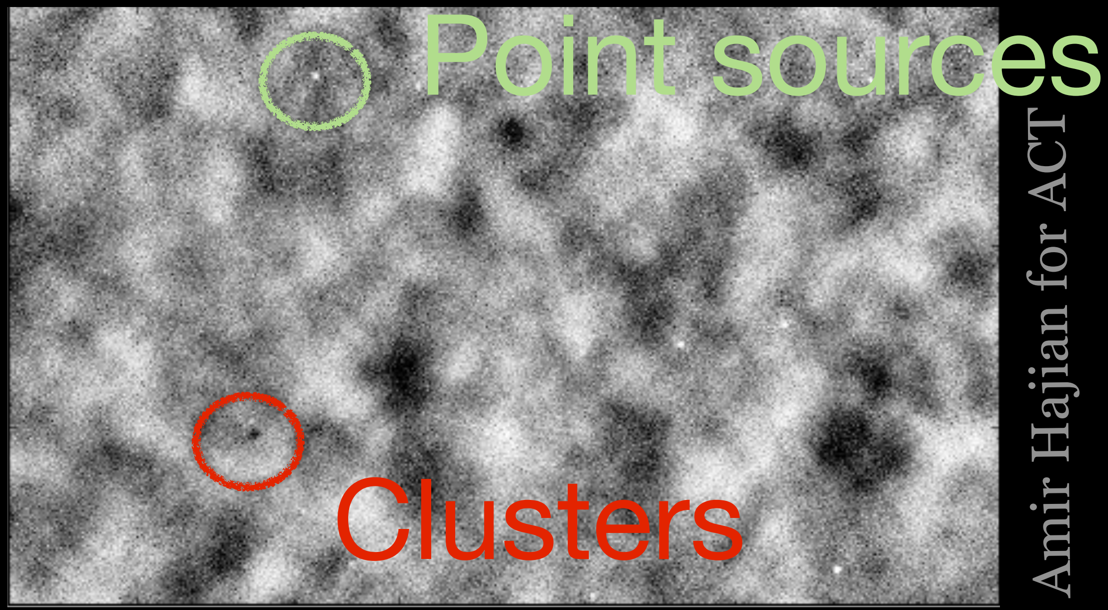






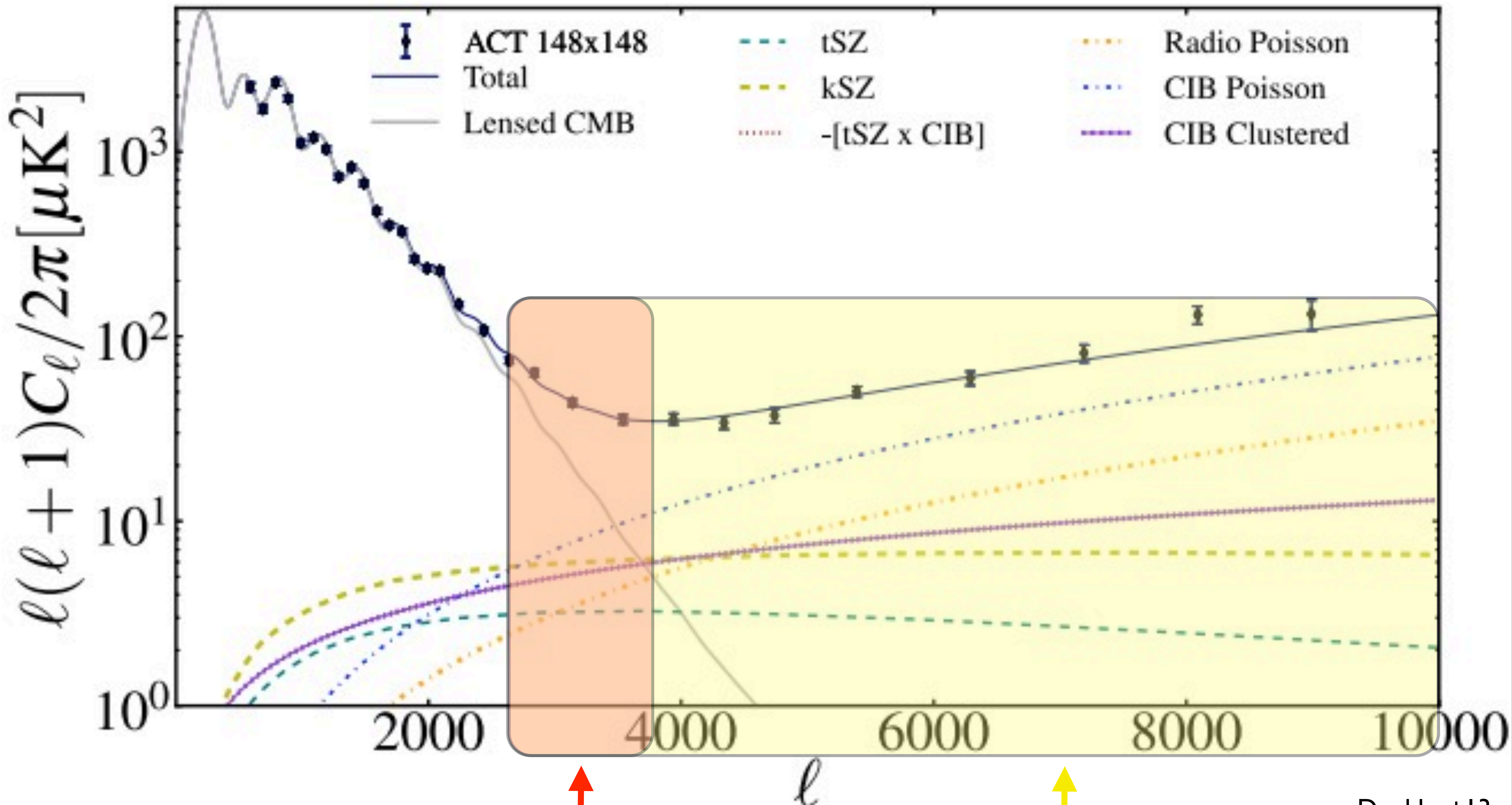






Amir Hajian for ACT

Statistically speaking



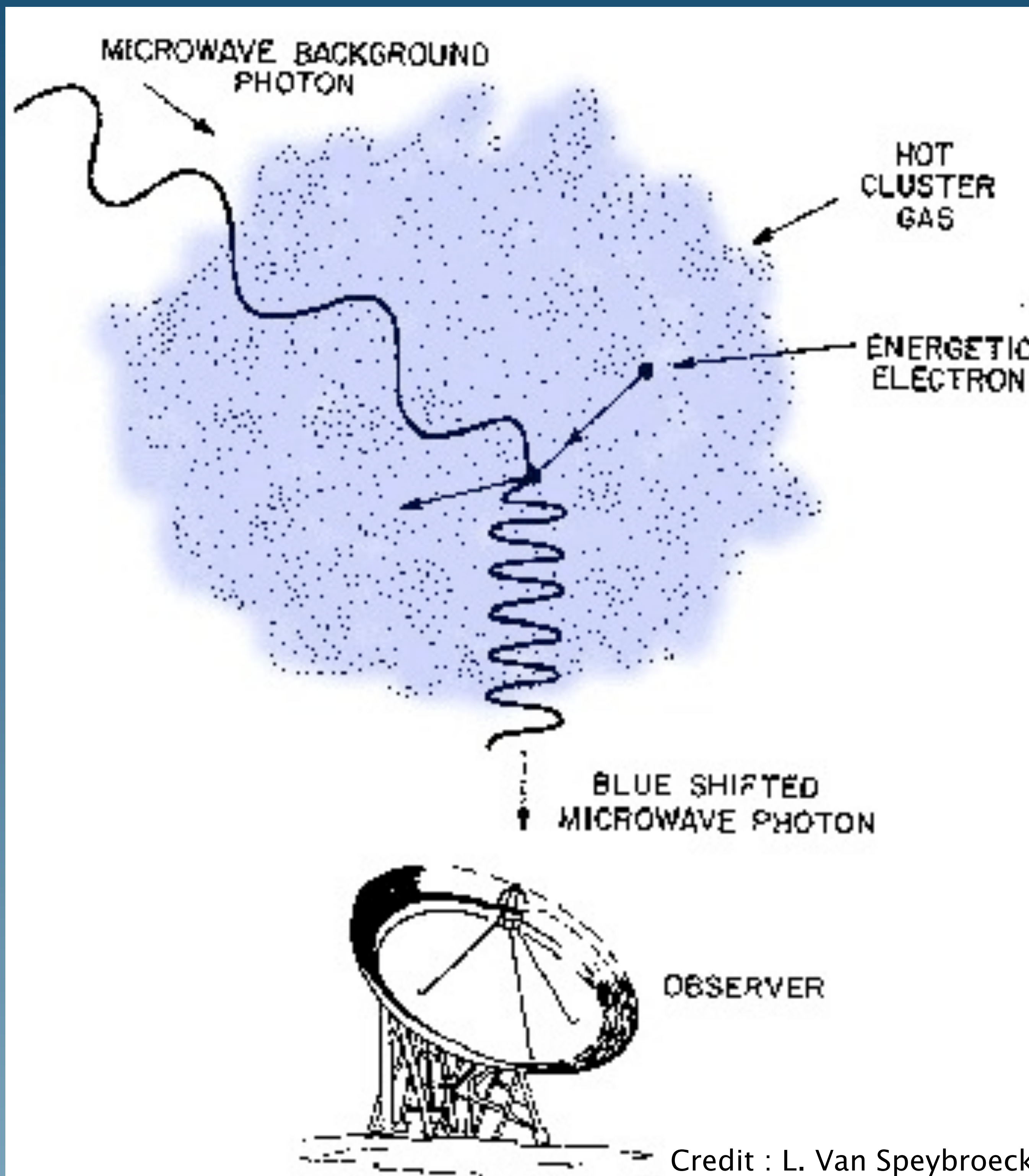
Dunkley+13

tSZ & kSZ

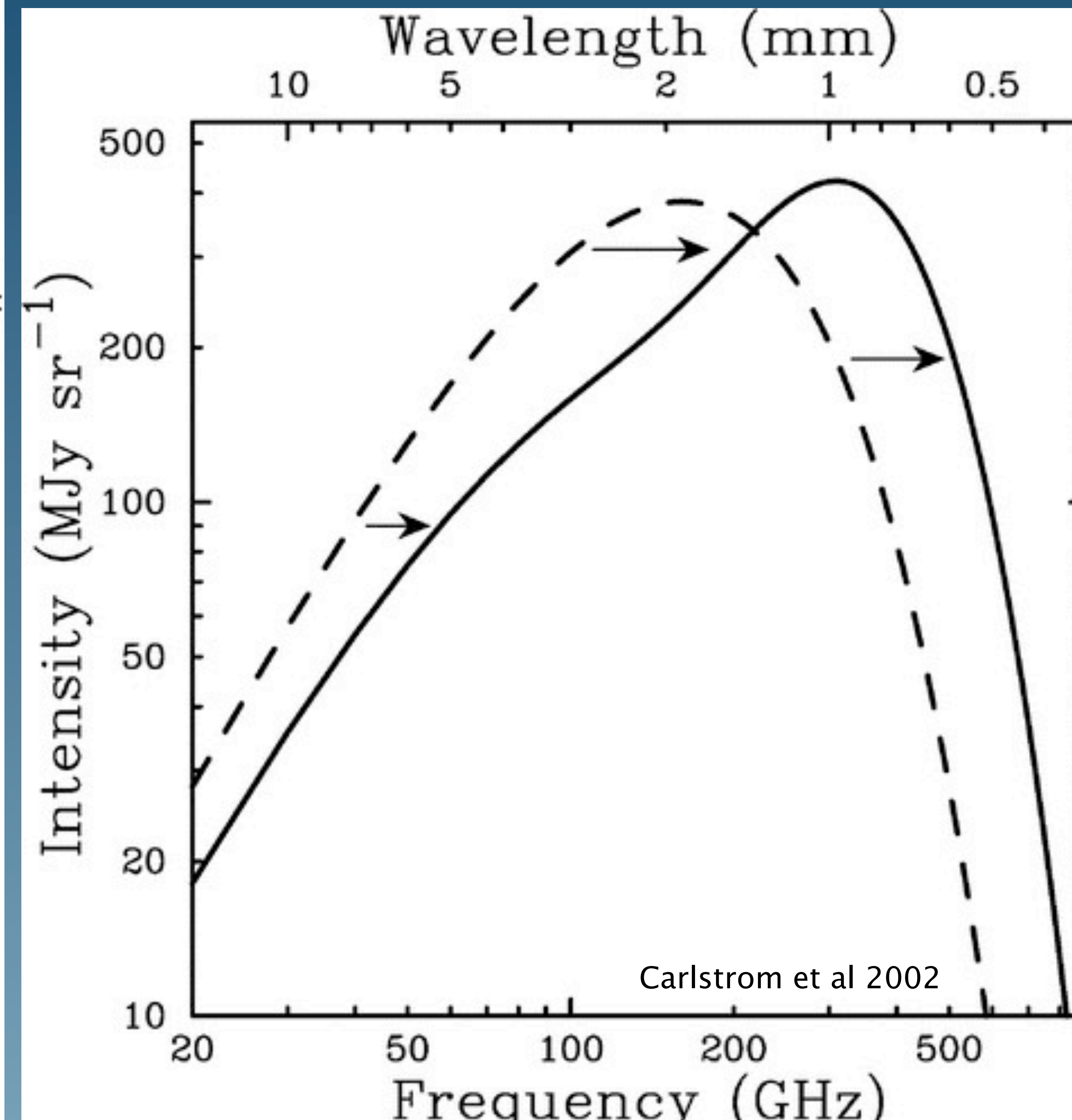
Other secondaries

Thermal Sunyaev-Zel'dovich Effect

- Inverse Compton scattering of CMB photons



Credit : L. Van Speybroeck



Carlstrom et al 2002

Thermal Sunyaev-Zel'dovich Effect

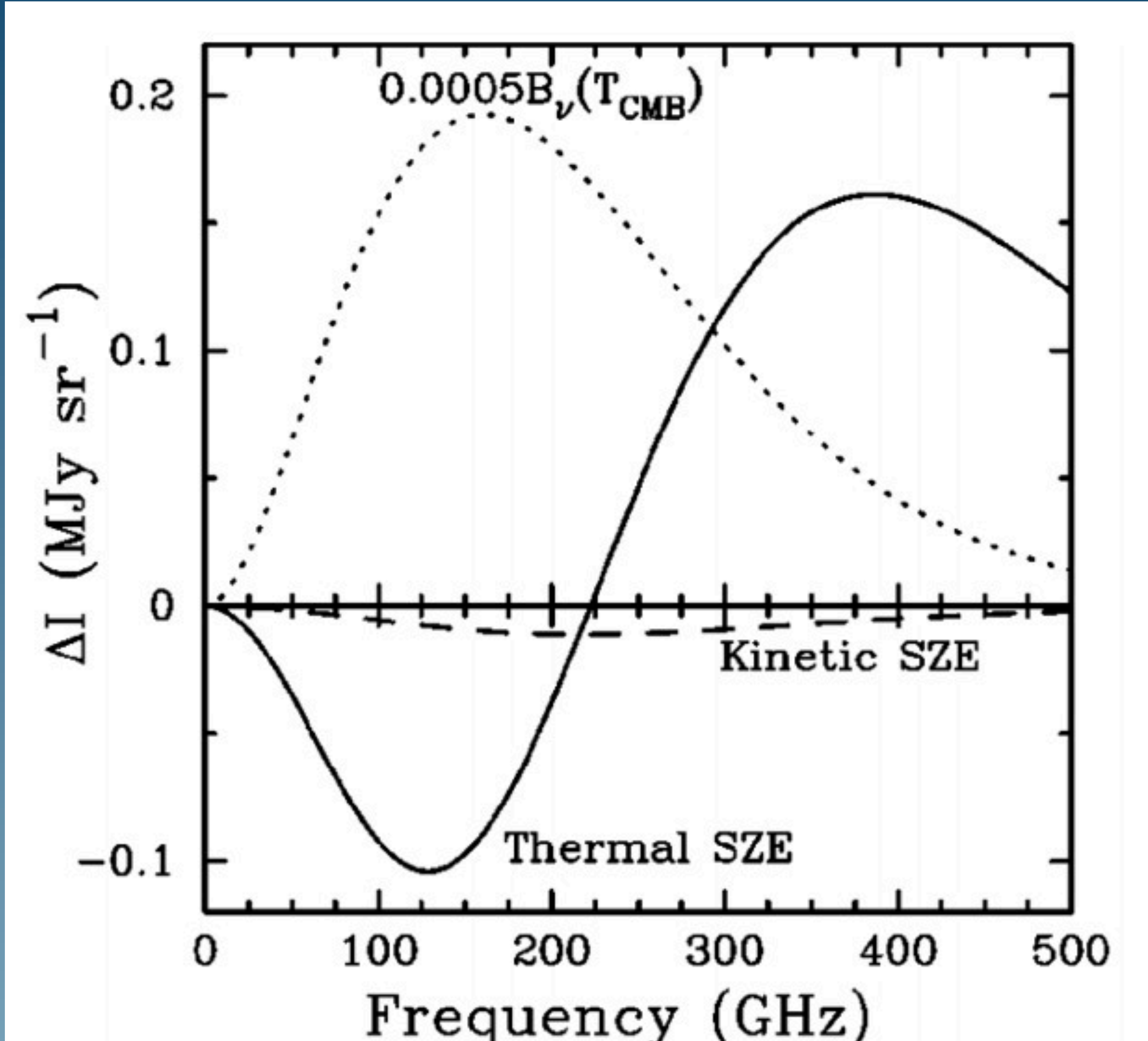
- Secondary anisotropies in the CMB

$$\frac{\Delta T}{T_{CMB}} = g_\nu y$$

$$y = \frac{k_b \sigma_T}{m_e c^2} \int n_e T_e dl$$

- Integrated pressure

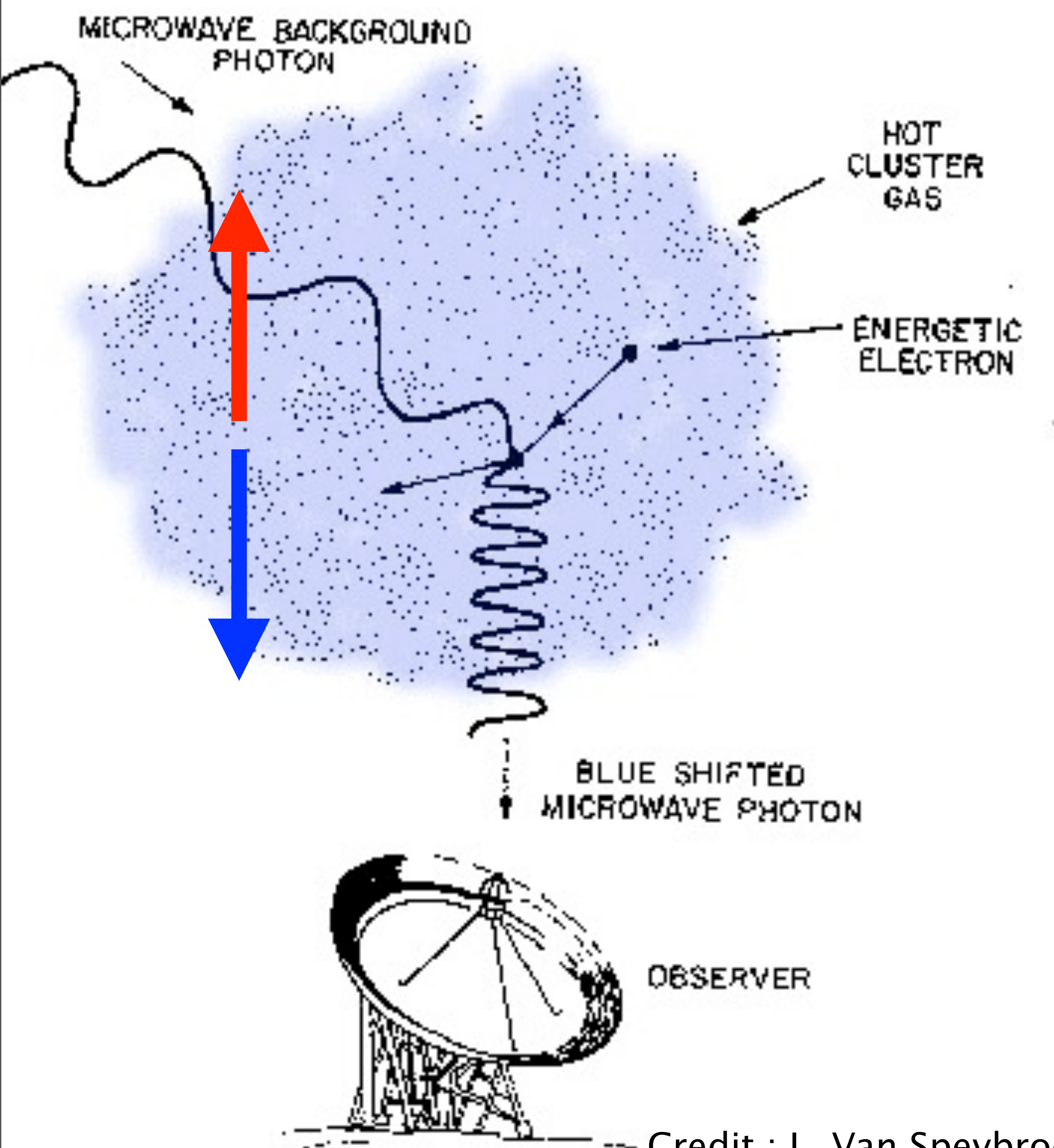
relativistic terms are small and not included



Carlstrom et al 2002

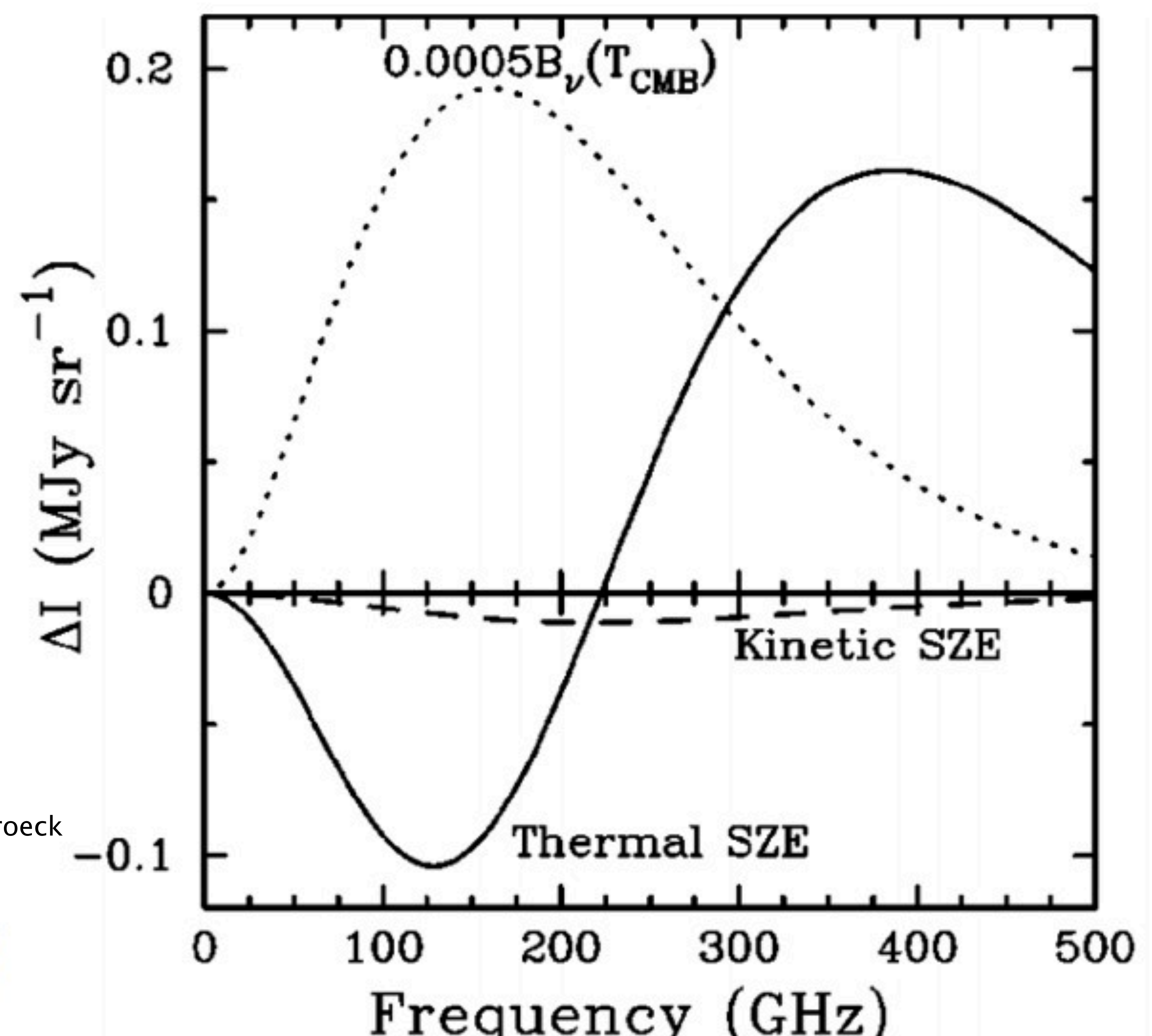
Kinetic Sunyaev-Zel'dovich Effect

- Doppler boosting of CMB photons



Credit : L. Van Speybroeck

$$b \equiv \frac{\sigma_T}{c} \int n_e v_{\rm los} dl$$



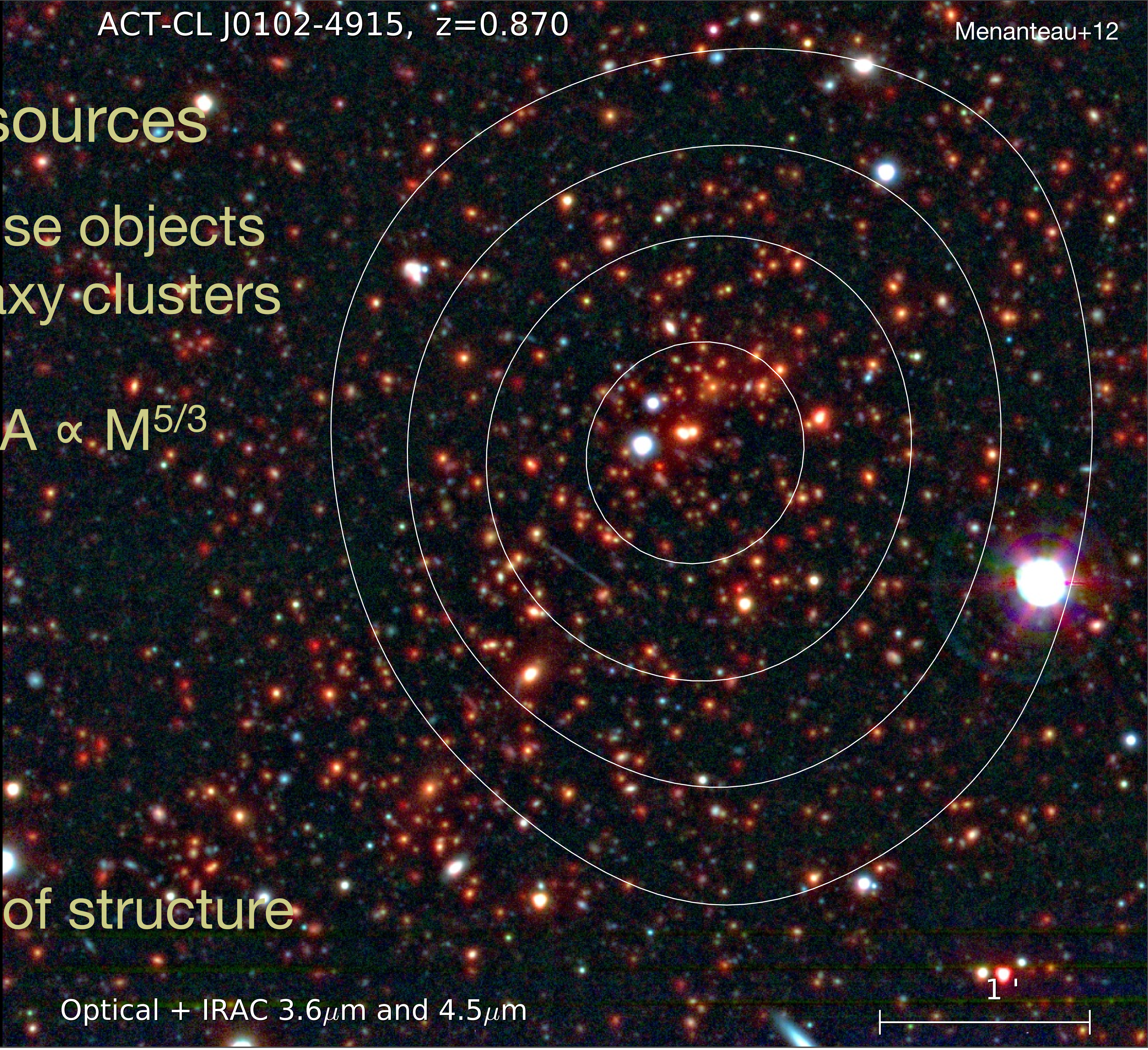
Carlstrom et al 2002

tSZ sources

Hot dense objects like galaxy clusters

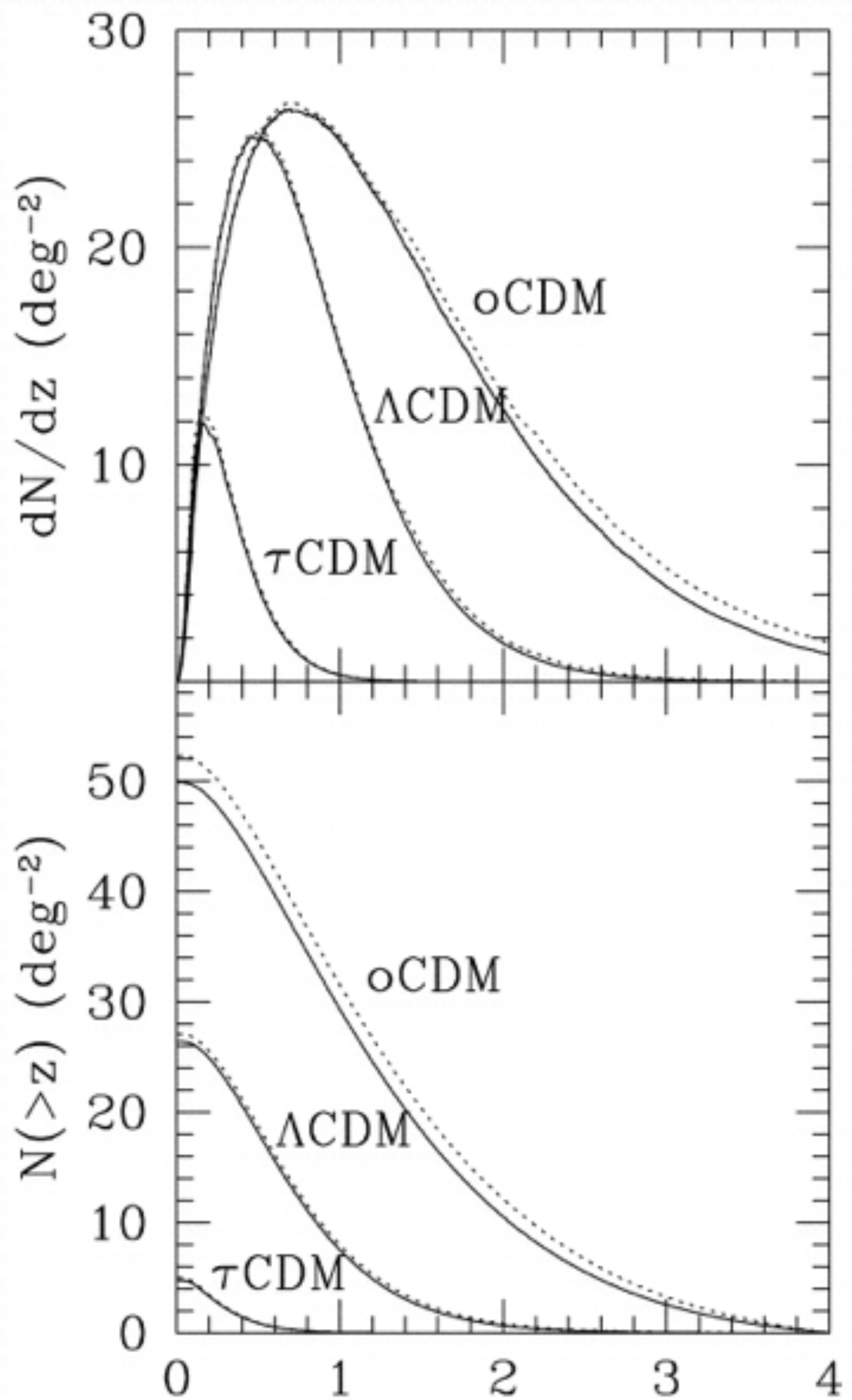
$Y \sim \int y \, dA \propto M^{5/3}$

Growth of structure

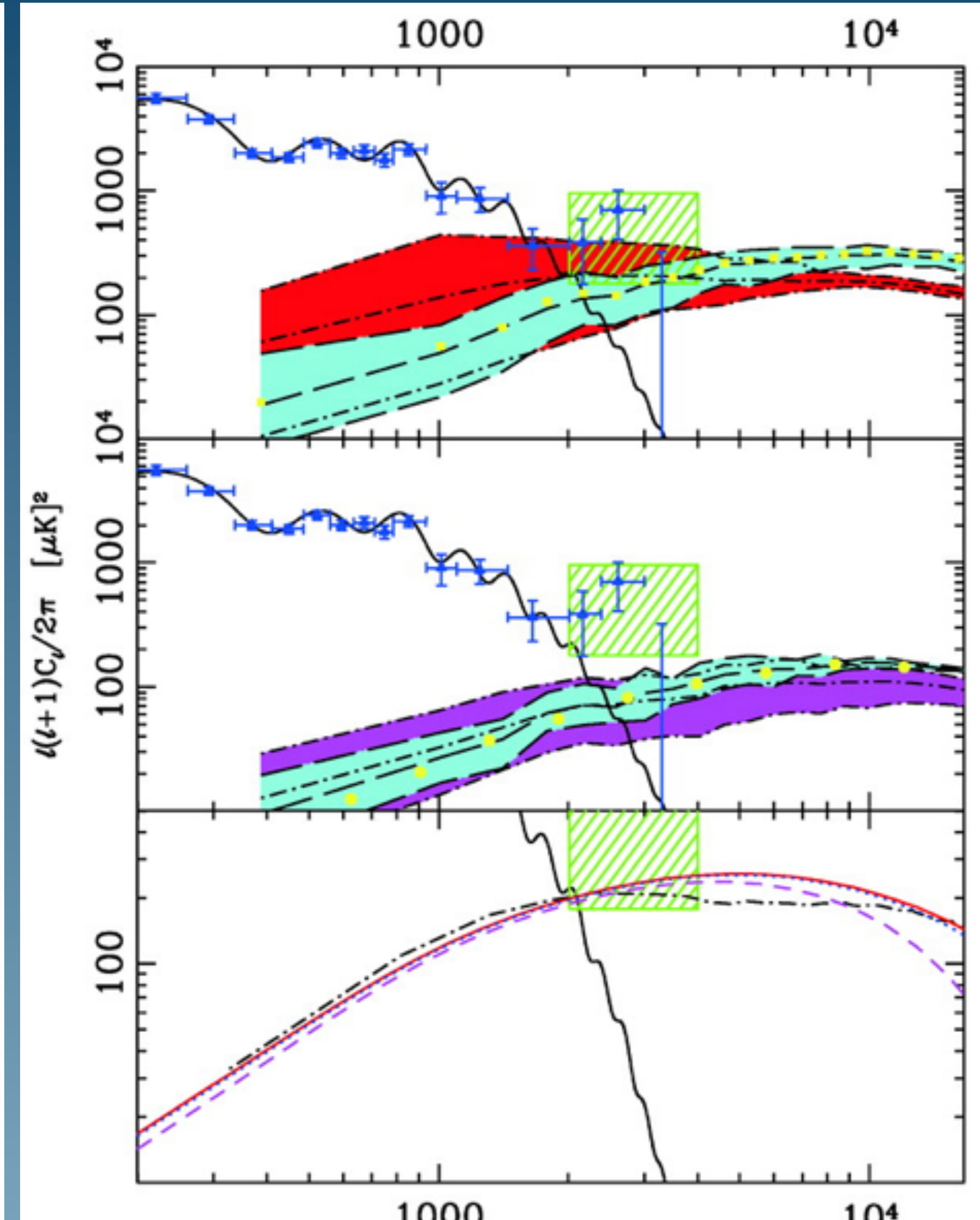


“Standard” Measurements

Number counts or power spectrum



Holder et al 2000



Bond et al 2004

Also: higher order meas.

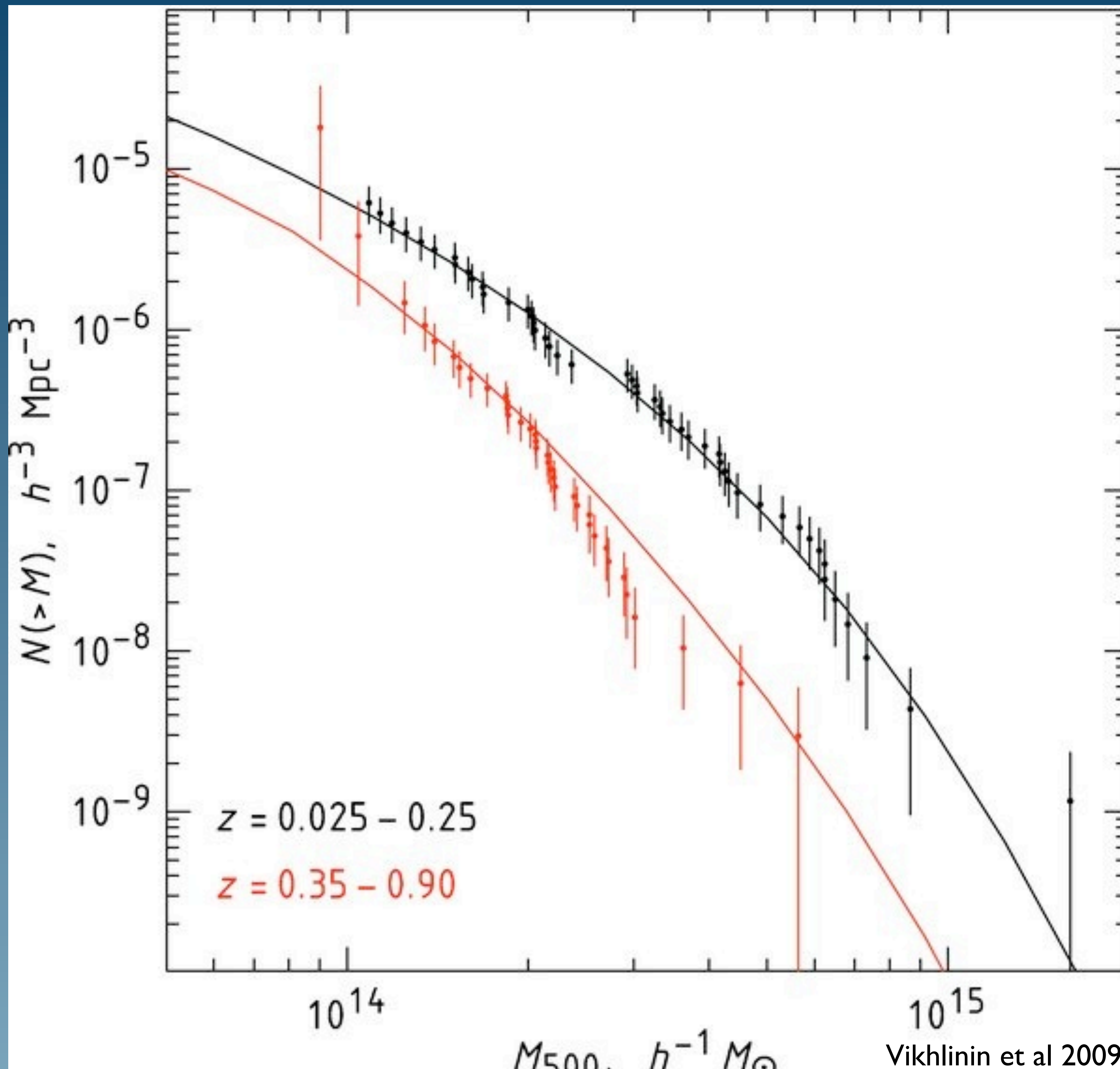
e.g. Wilson+13, Hill+13, Bhattacharya+13 Crawford+13

f_{gas}

e.g. Mantz+10

Mass Function Ex.

- X-ray (Chandra) measurements using the Y_x - M relation
- Use N-body simulations to determine N(>M)
- ~50 Clusters



Vikhlinin et al 2009

Mass proxies & form-factors

Selection function & Mass proxy

Cluster counts

$$N = \int_0^{z_{\max}} dz \frac{dV}{dz} \int dM \frac{dn(M,z)}{dM}$$

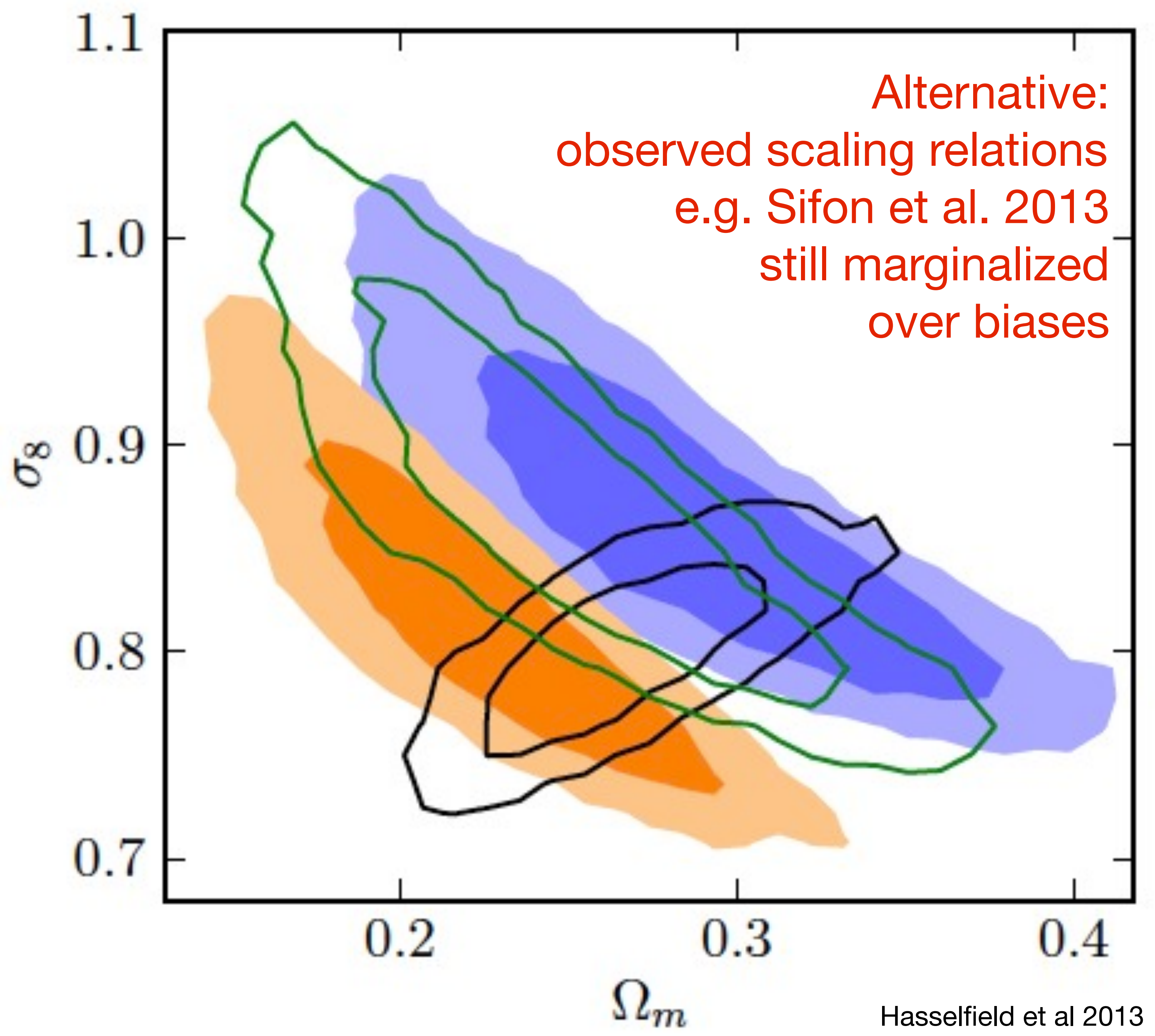
Gastrophysics

tSZ power spectrum $\quad A_{tSZ} \propto \sigma_8^{8}$

$$C_l = g_\nu^2 \int_0^{z_{\max}} dz \frac{dV}{dz} \int dM \frac{dn(M,z)}{dM} \left|\tilde{y}_l(M,z)\right|^2$$

+ Clustering of clusters (Sub-dominant)

X-roads Cosmology & Astrophysics



Hasselfield et al 2013

Latest cluster cosmology

Limited by uncertainty in the Y-M relation & Pressure profile

e.g. Benson et al 2013, Hasselfield et al 2013, Rozo et al 2013, & Planck Coll. XX 2013

Simulations are a tool for understanding and quantifying the important gastrophysics, biases, and scatter in surveys

Modeling the ICM

Simulations or (Semi)Analytical

e.g. Da Silva et al 2000, Springel 2001, Bond et al 2002, BBPSS 2010

e. g. Komatsu & Seljak 2001, Ostriker et al. 2005, Bode et al 2009(12), Sehgal et al 2010, Shaw et al 2010, Trac et al 2011

Processes that need to be included (Sub-grid)

- Radiative cooling
- Star formation
- Feedback (AGN, stellar)
- Non-thermal pressure support

  P_{KIN}, CR, P_B …
- Asphericity and sub-structure
- Plasma processes
- etc...

The ICM is complex!

Our Simulations

Box lengths 200-400 Mpc h^{-1}(256^3, 512^3)
Halo Mass resolution 10^{13} $M_\odot$ h^{-1}
Gadget2+ (SPH) with 3 "physics" models

- Non-radiative (Adiabatic)

- Radiative cooling + SF + SNe + CR

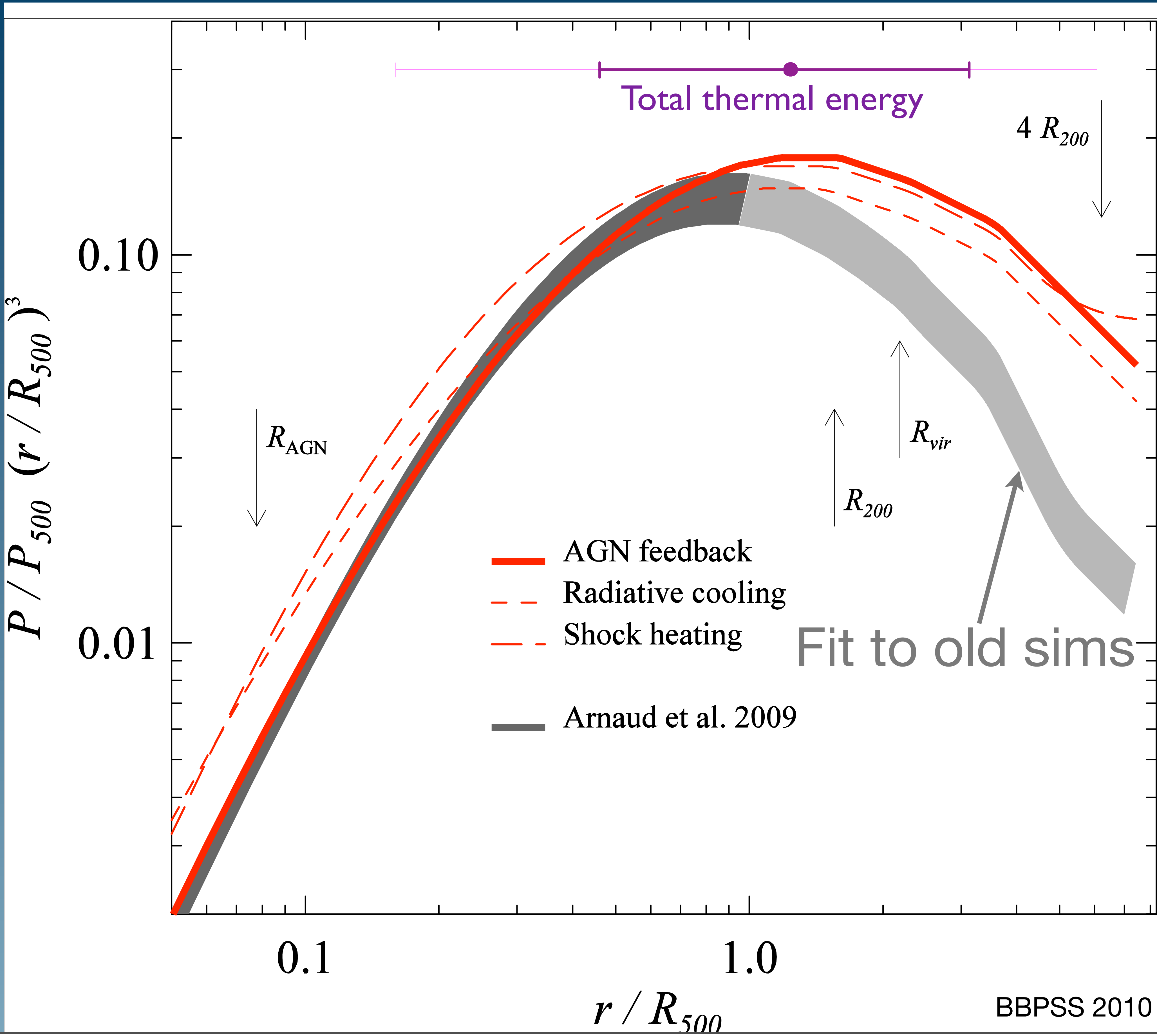
- "AGN" feedback (NEW!)

~ 800 clusters with $M_{200} > 10^{14}$ $M_\odot$ h^{-1}

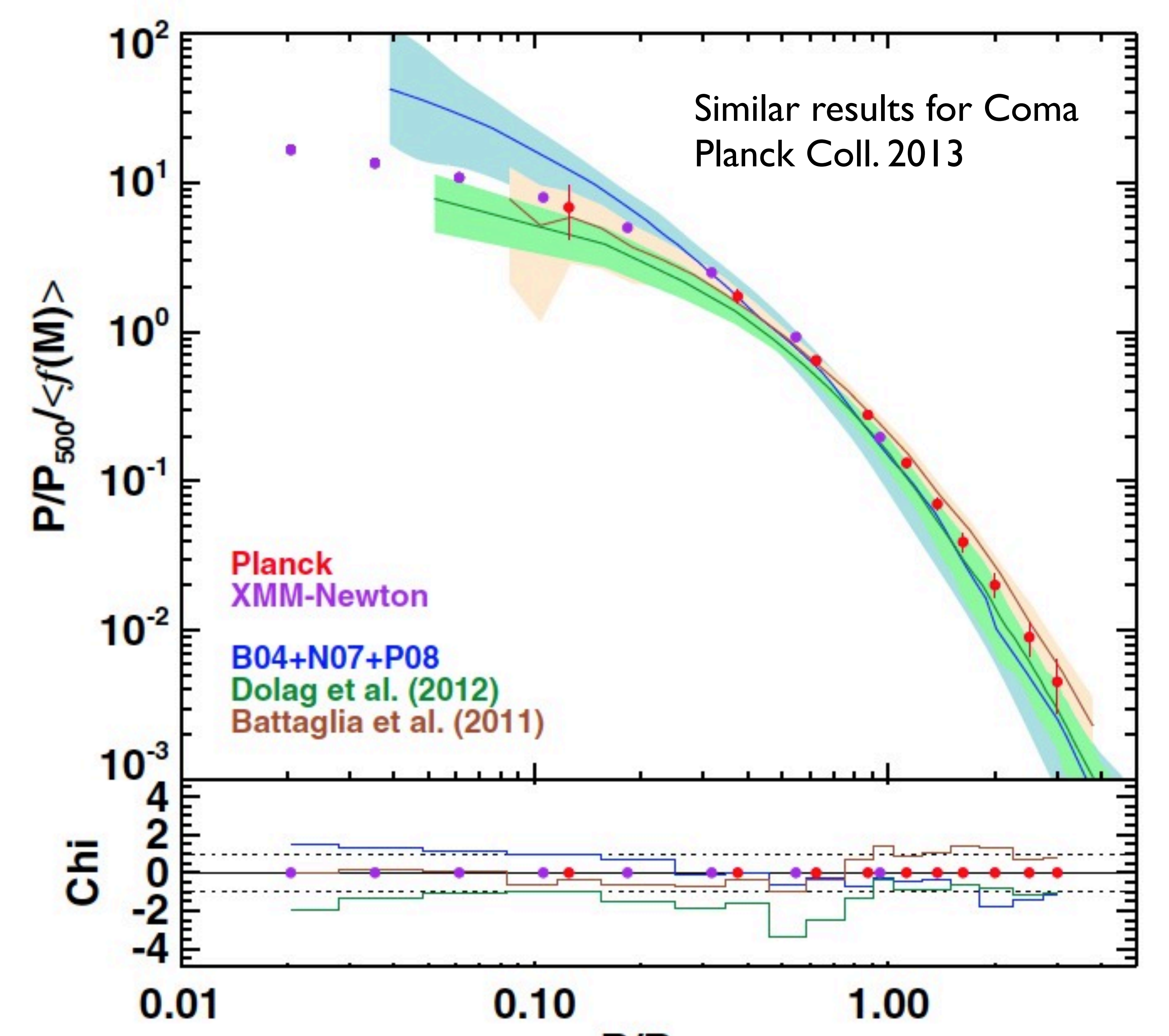
Lots of data to still be mined

A new set of simulations is coming soon

Simulation P_{th} Profile

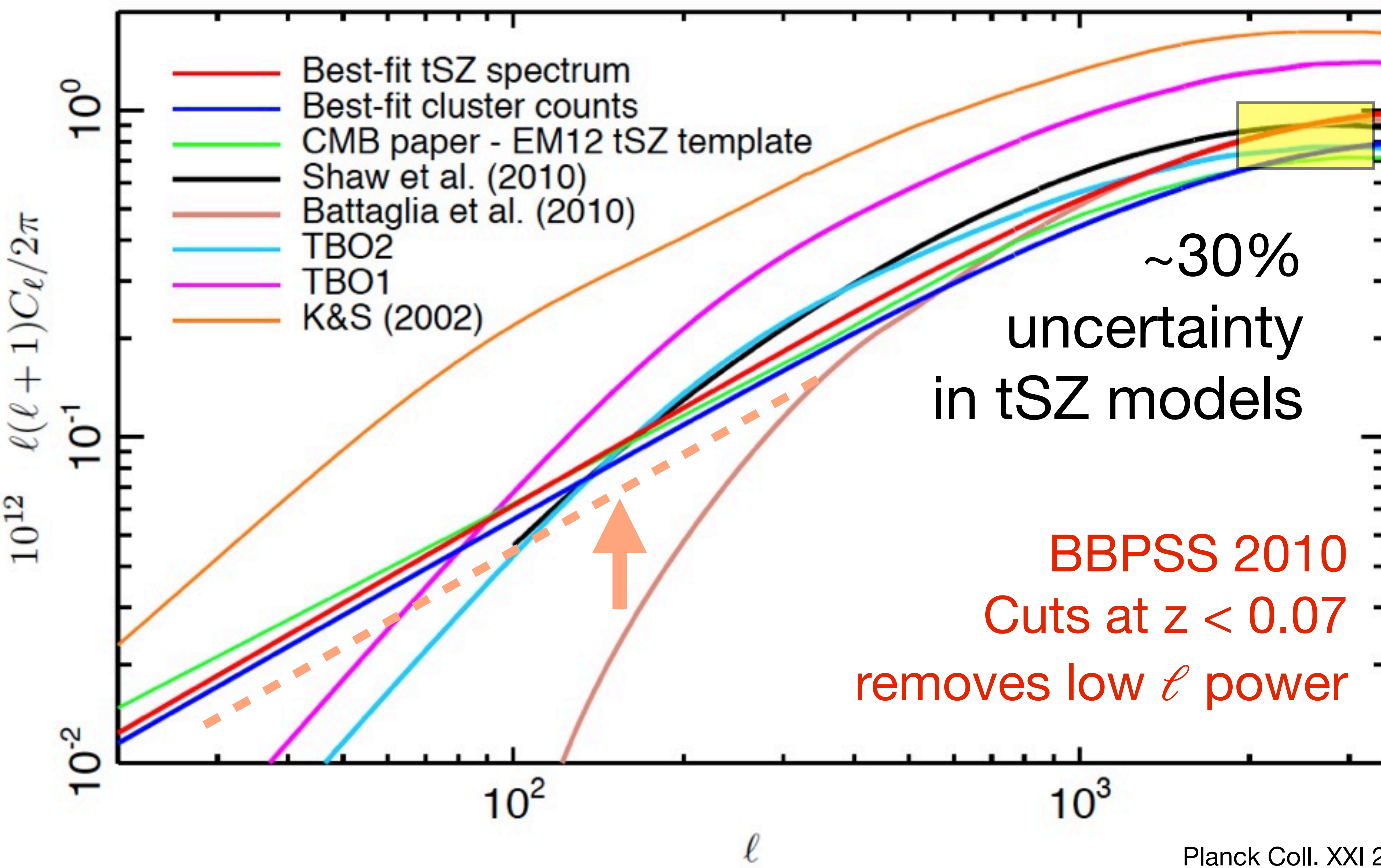


Planck P_{th} Profile



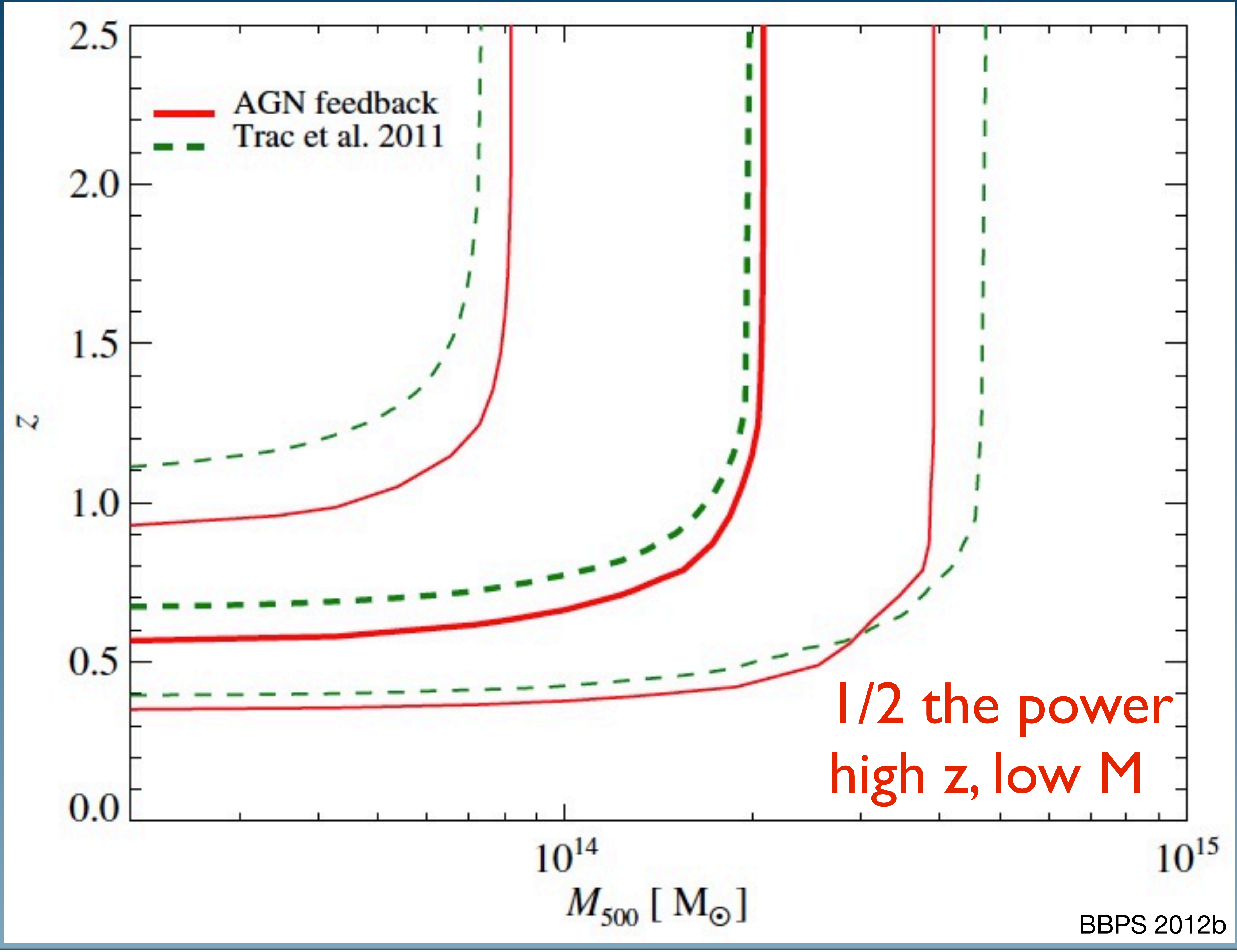
Planck Coll. 2013

tSZ theory PS



Planck Coll. XXI 2013

C_ℓ(M,z)

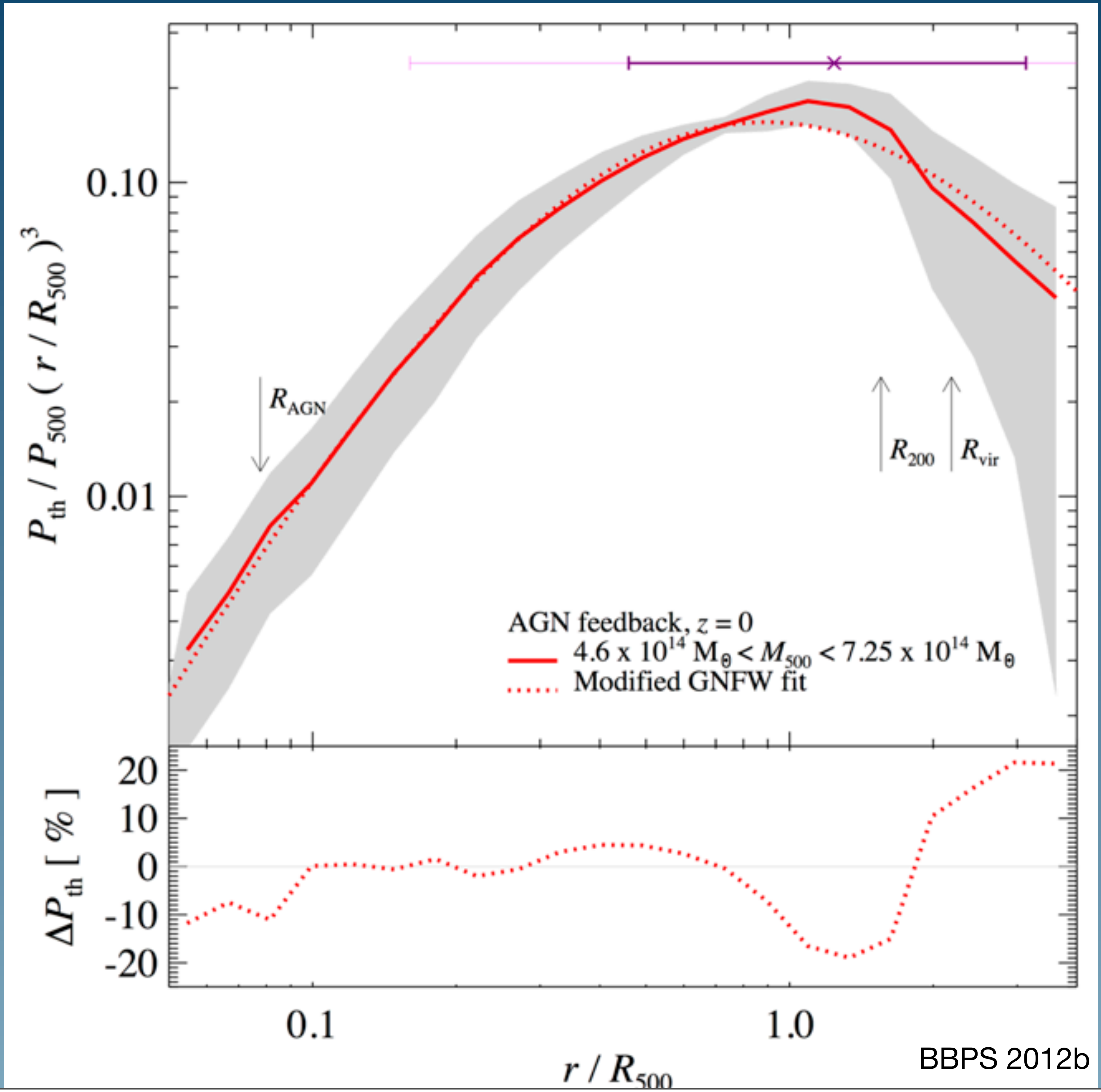


BBPS 2012b

Variance in P_{th} Profiles

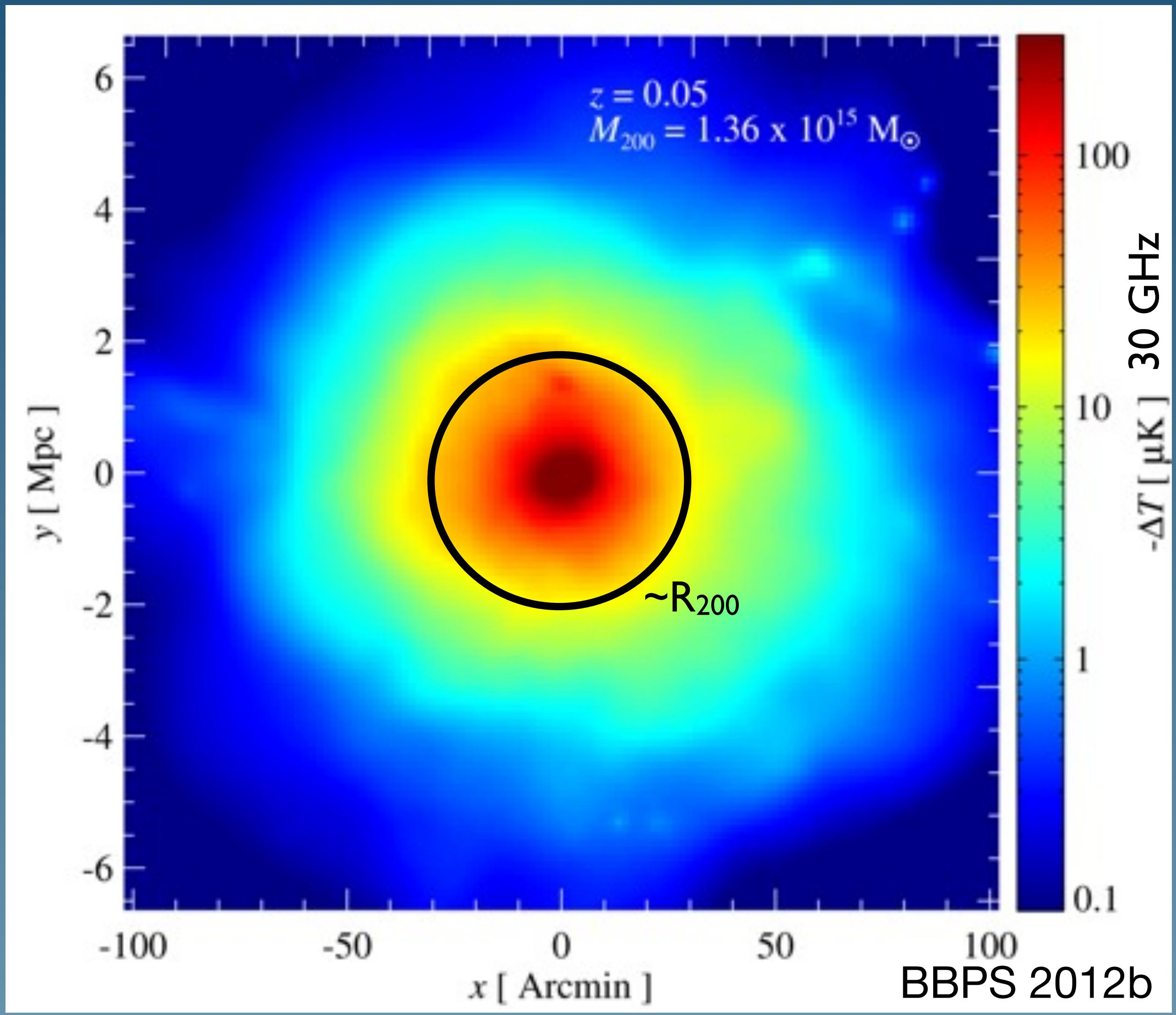
Impact:

- tSZ power spectrum halo calculations
- Y-M relation (scatter)

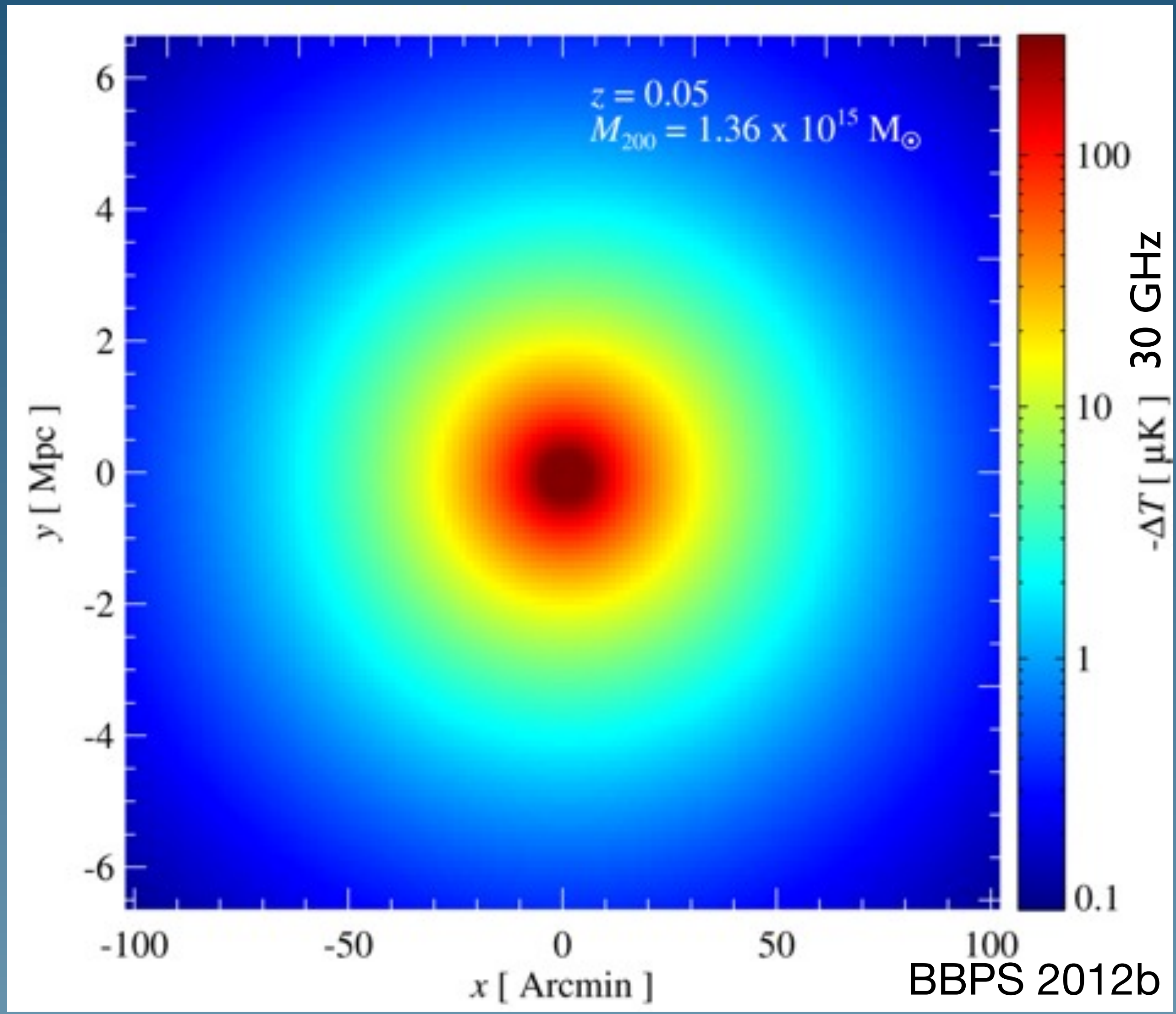


BBPS 2012b

ICM inhomogeneities

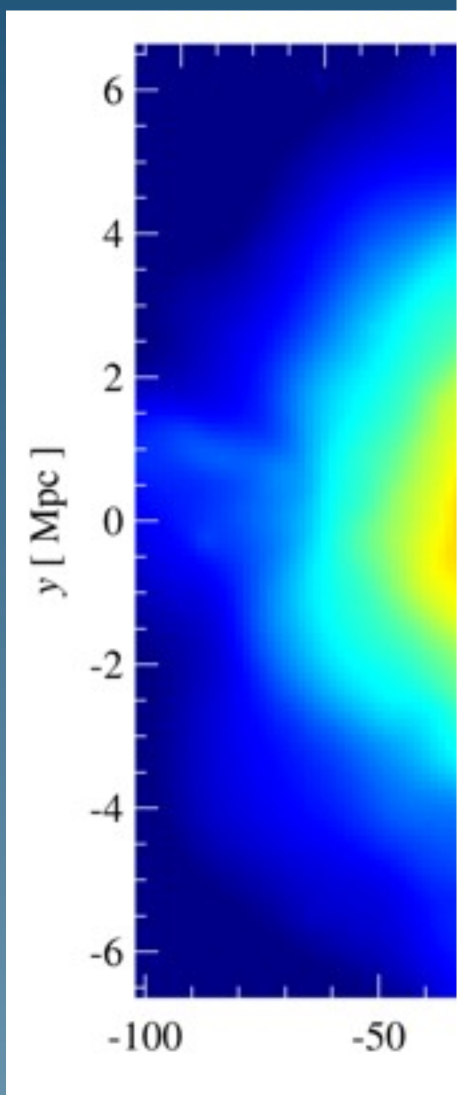


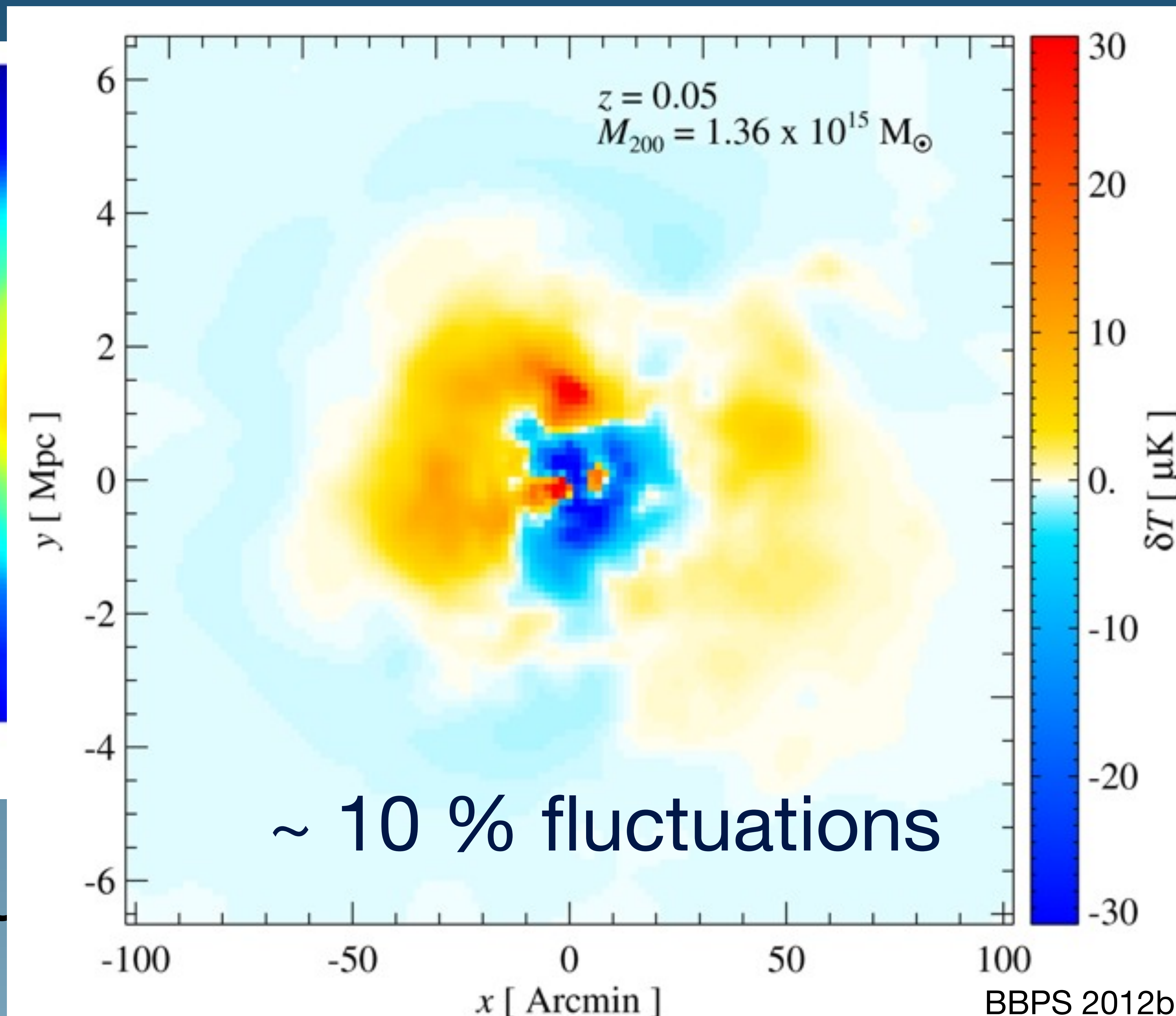
Simulated cluster



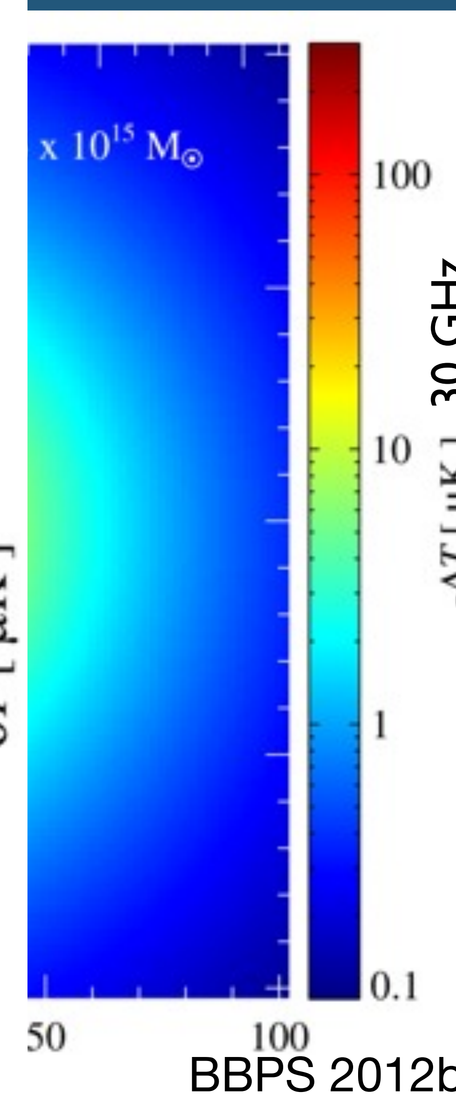
Spherical fit
from simulations

ICM inhomogeneities





~ 10 % fluctuations



Simu

fit

tions

ICM inhomogeneities & tSZ PS

$$C_l = g_\nu^2 \int_0^{z_{\max}} dz \frac{dV}{dz} \int dM \frac{dn(M,z)}{dM} \left| \tilde{y}_l(M,z) \right|^2$$

Gastrophysics

+ Clustering of clusters (Sub-dominant)

Self consistently compared tSZ power spectrum methods

- Use the global pressure profile from the simulations:

1) Given a Mass Function: calculate the analytical spectrum

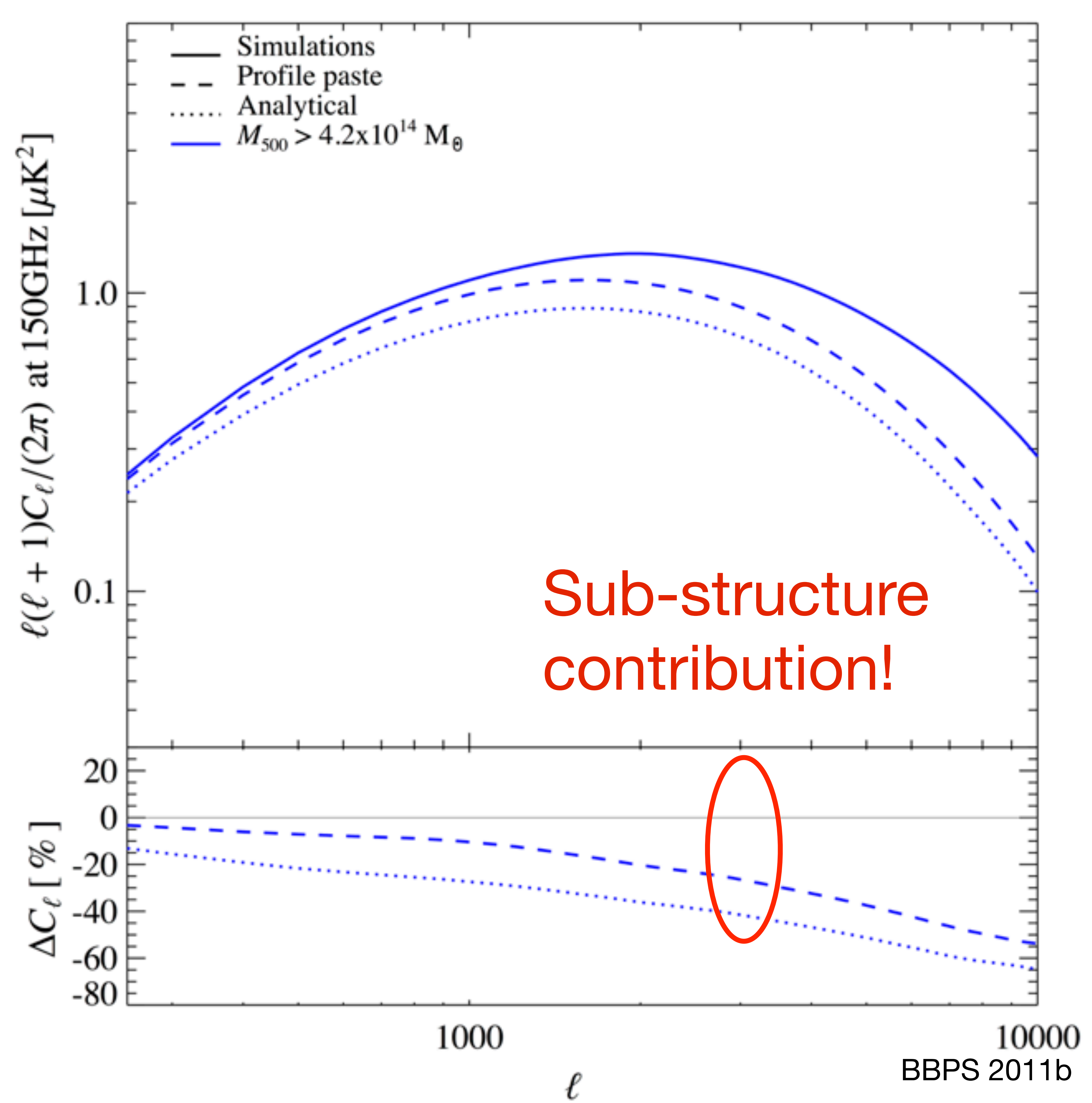
2) Paste the global pressure profile at cluster locations in the simulations

3) FFT the full simulation maps

Determine systematic differences between methods

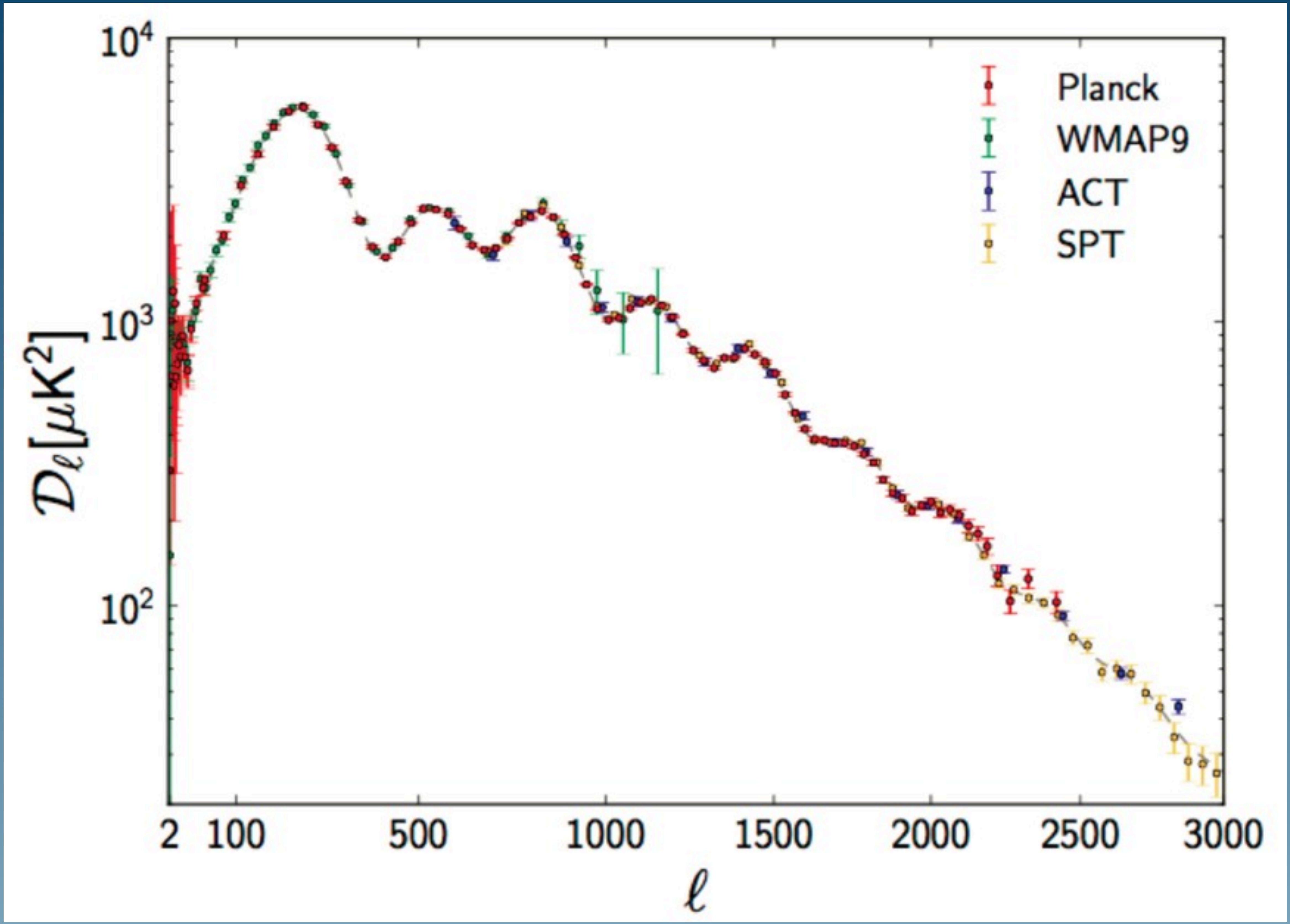
ICM inhomogeneities & tSZ PS

- High mass halos
  25% at ℓ ~3000
- All masses
  15% at ℓ ~3000
- Additional power from Non-uniformity must be included in Analytic calculations

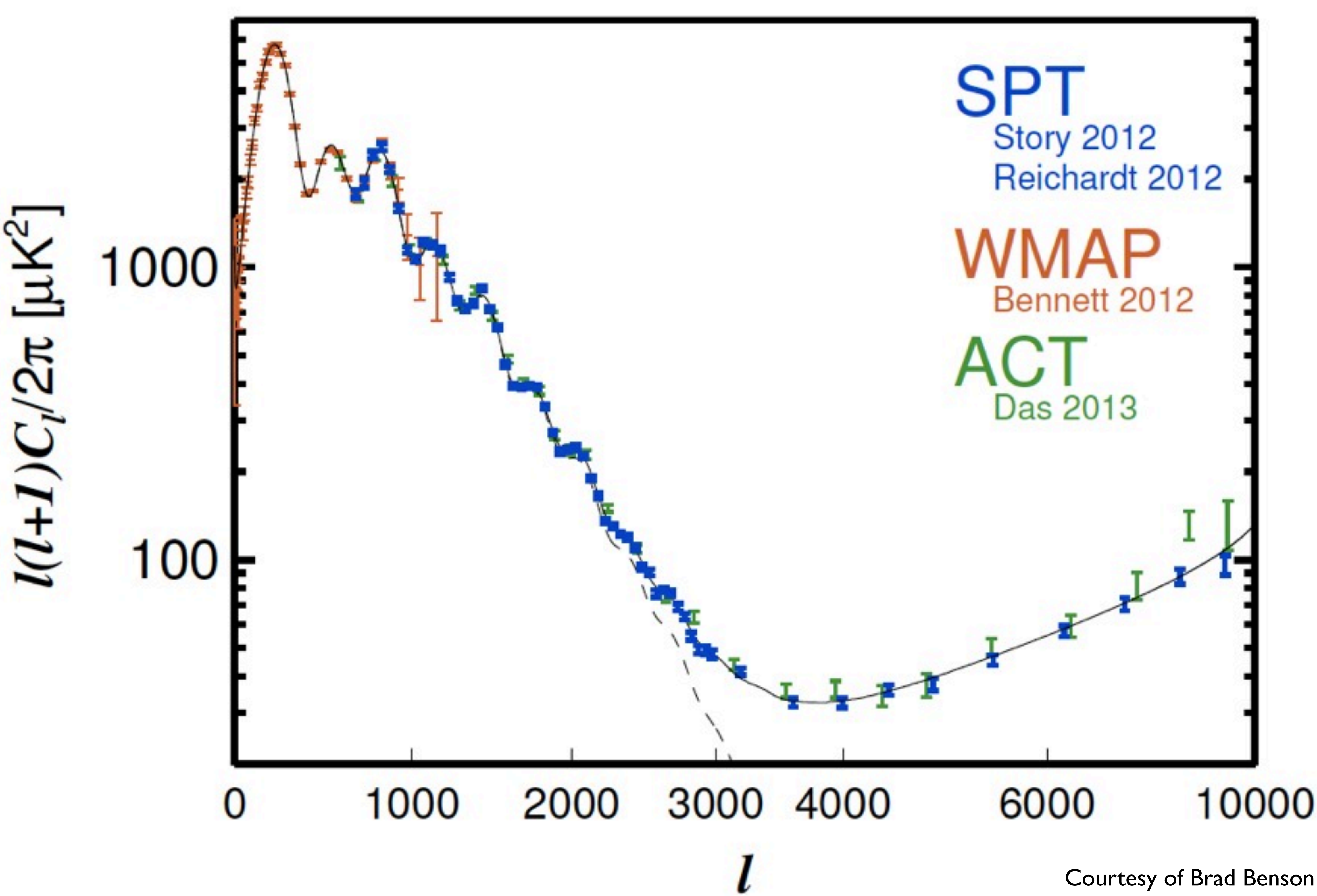


BBPS 2011b

State of tSZ PS

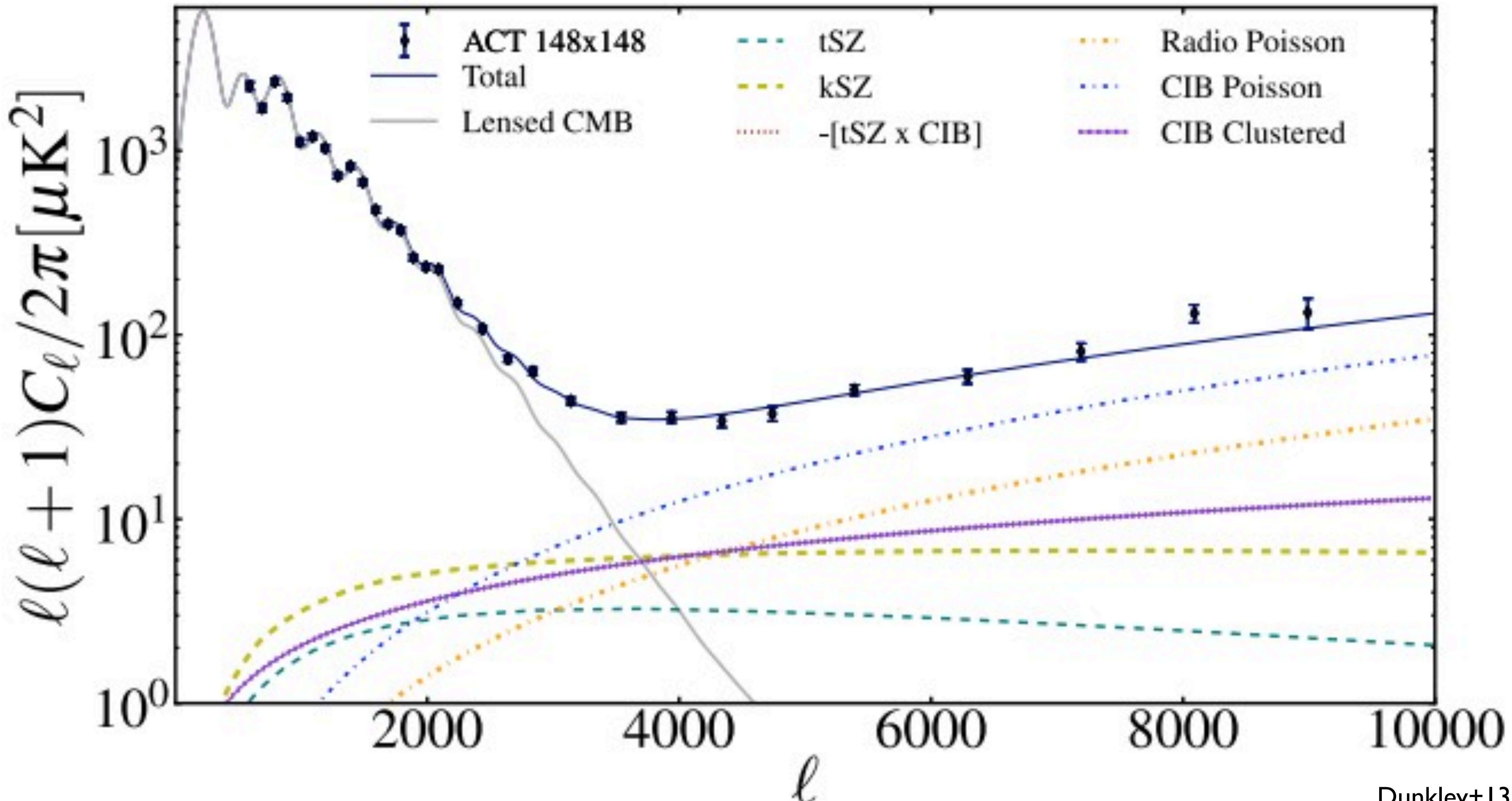


State of tSZ PS



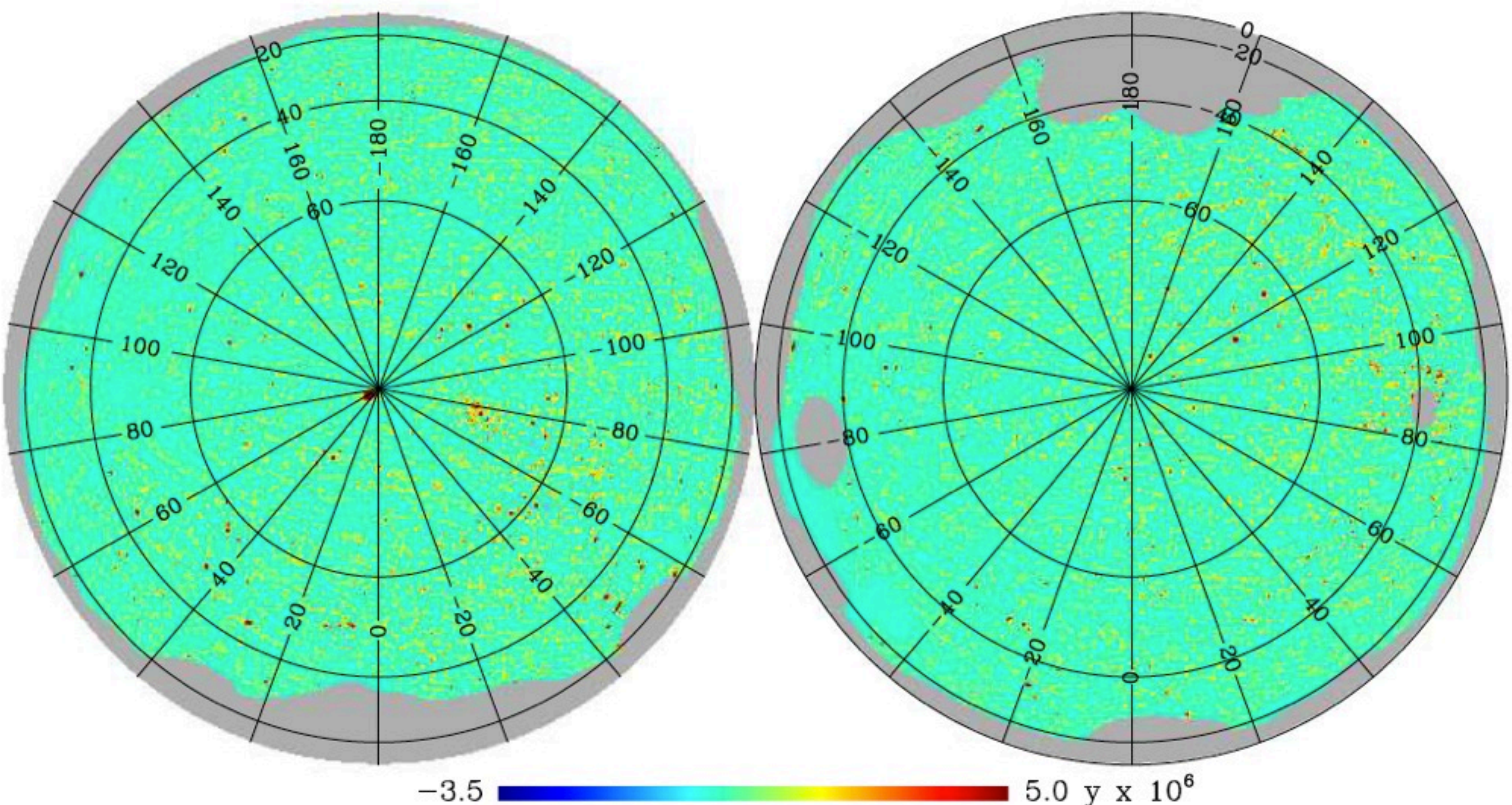
Courtesy of Brad Benson

State of tSZ PS



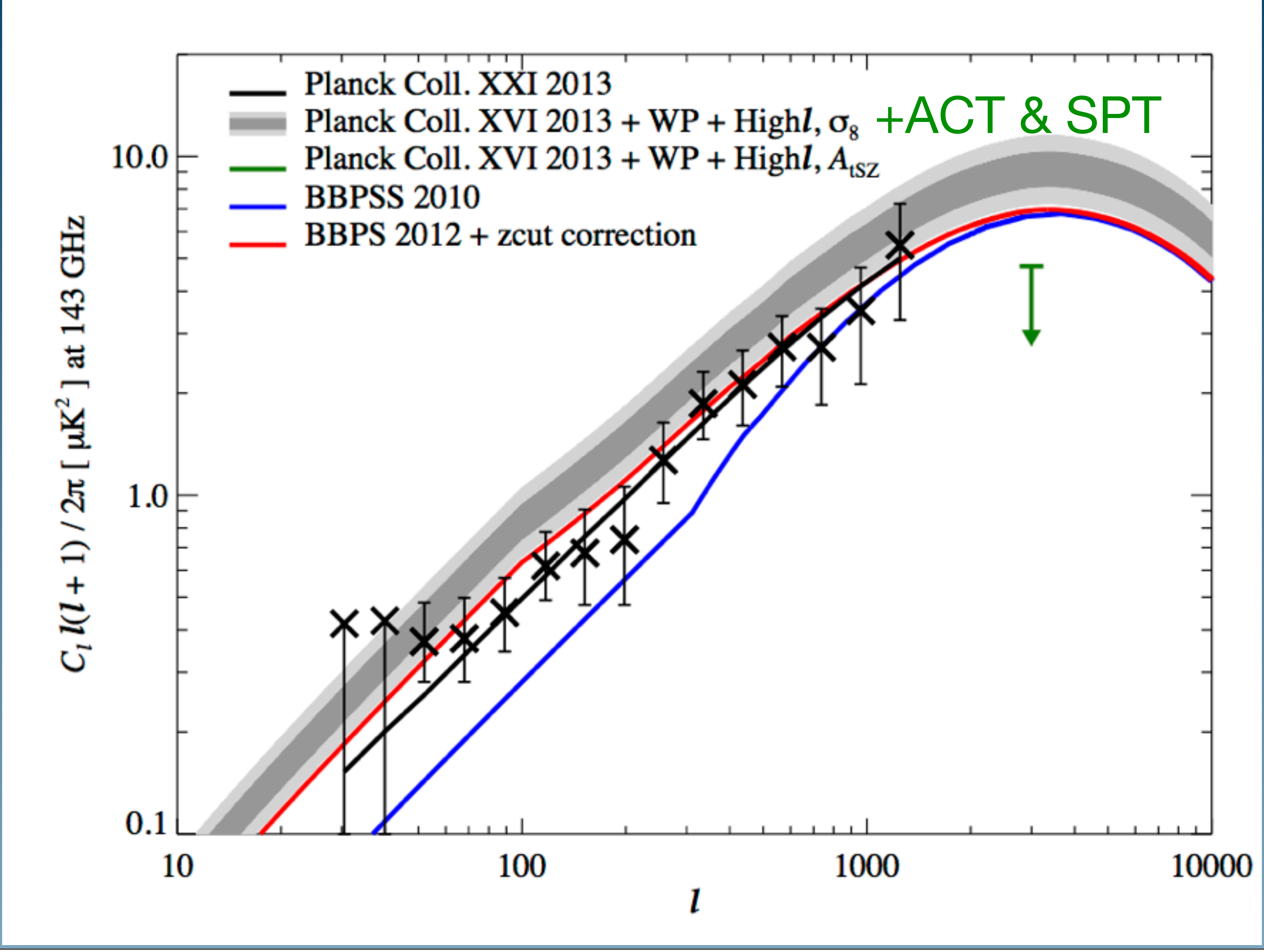
Dunkley+13

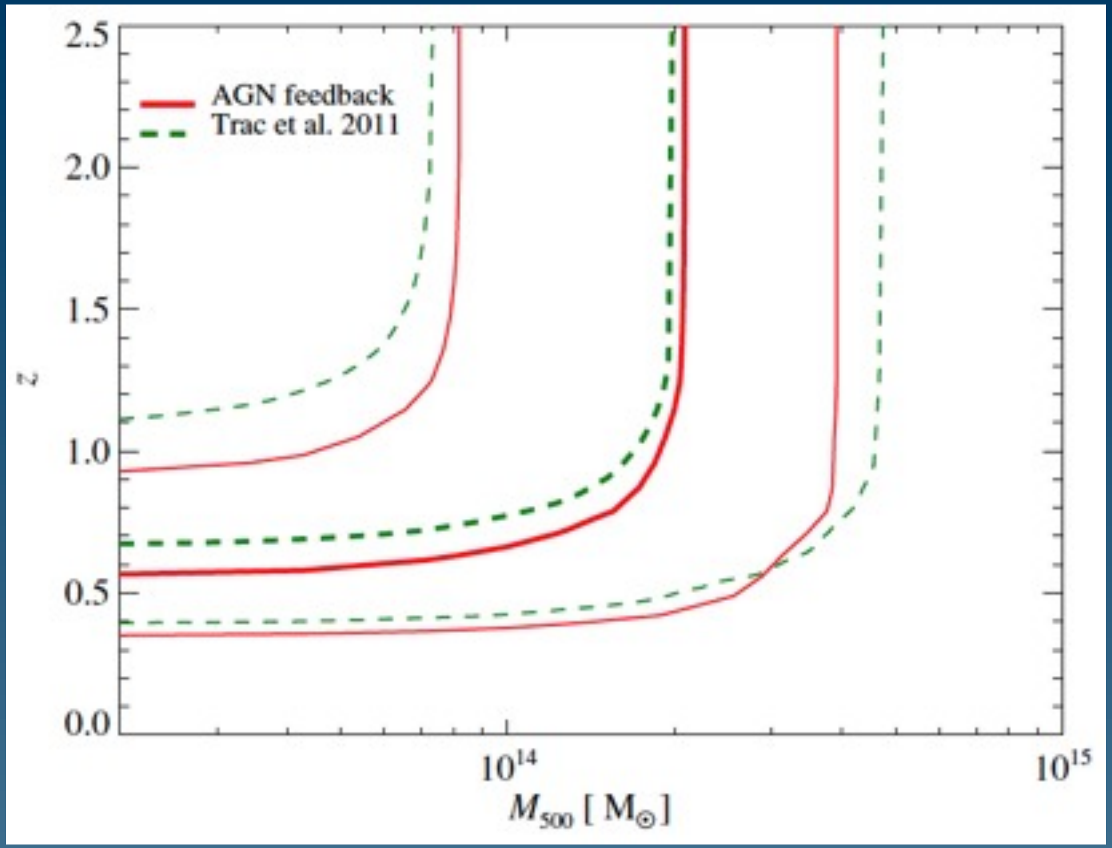
Planck y-map

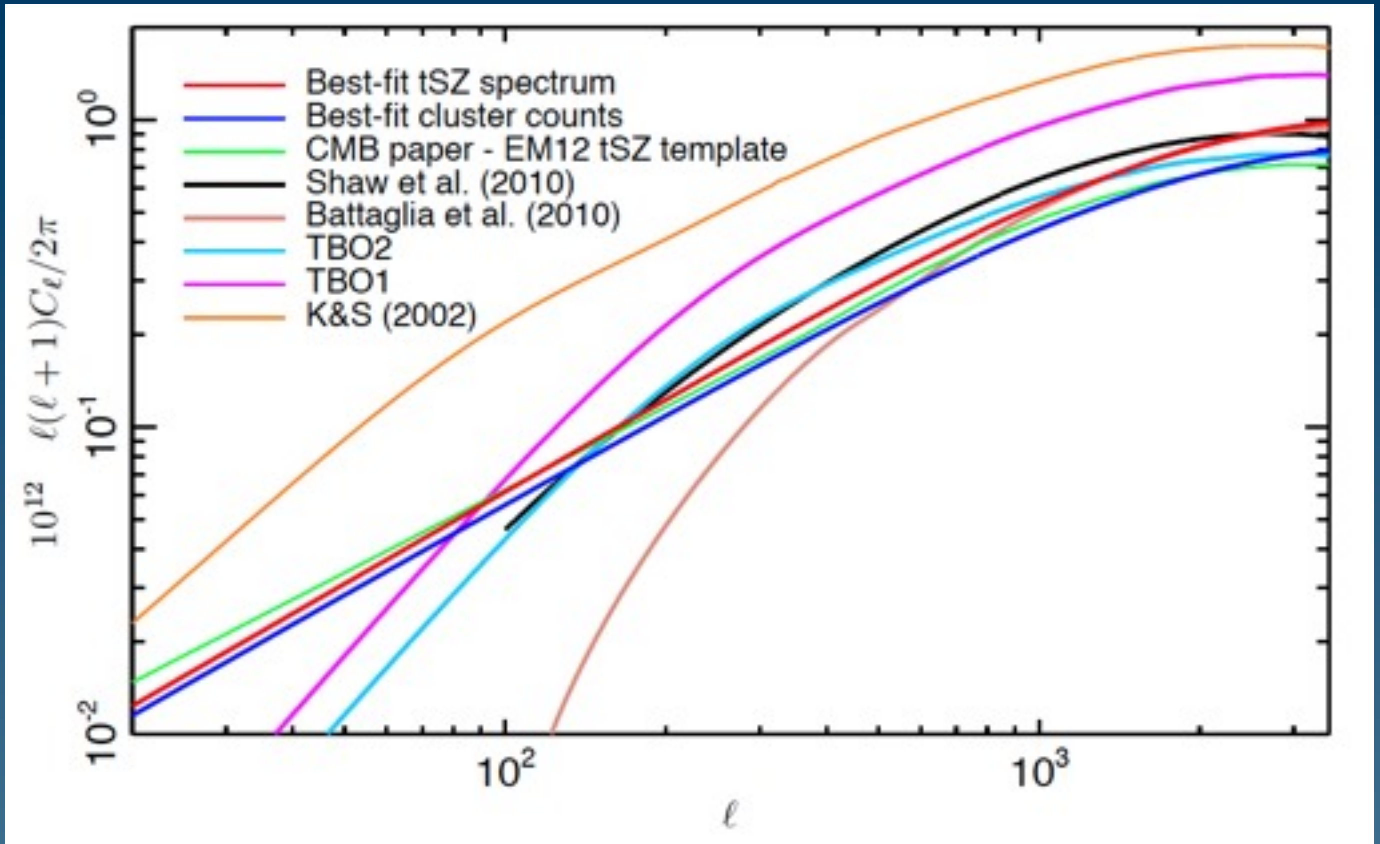


Planck Coll. XXI 2013

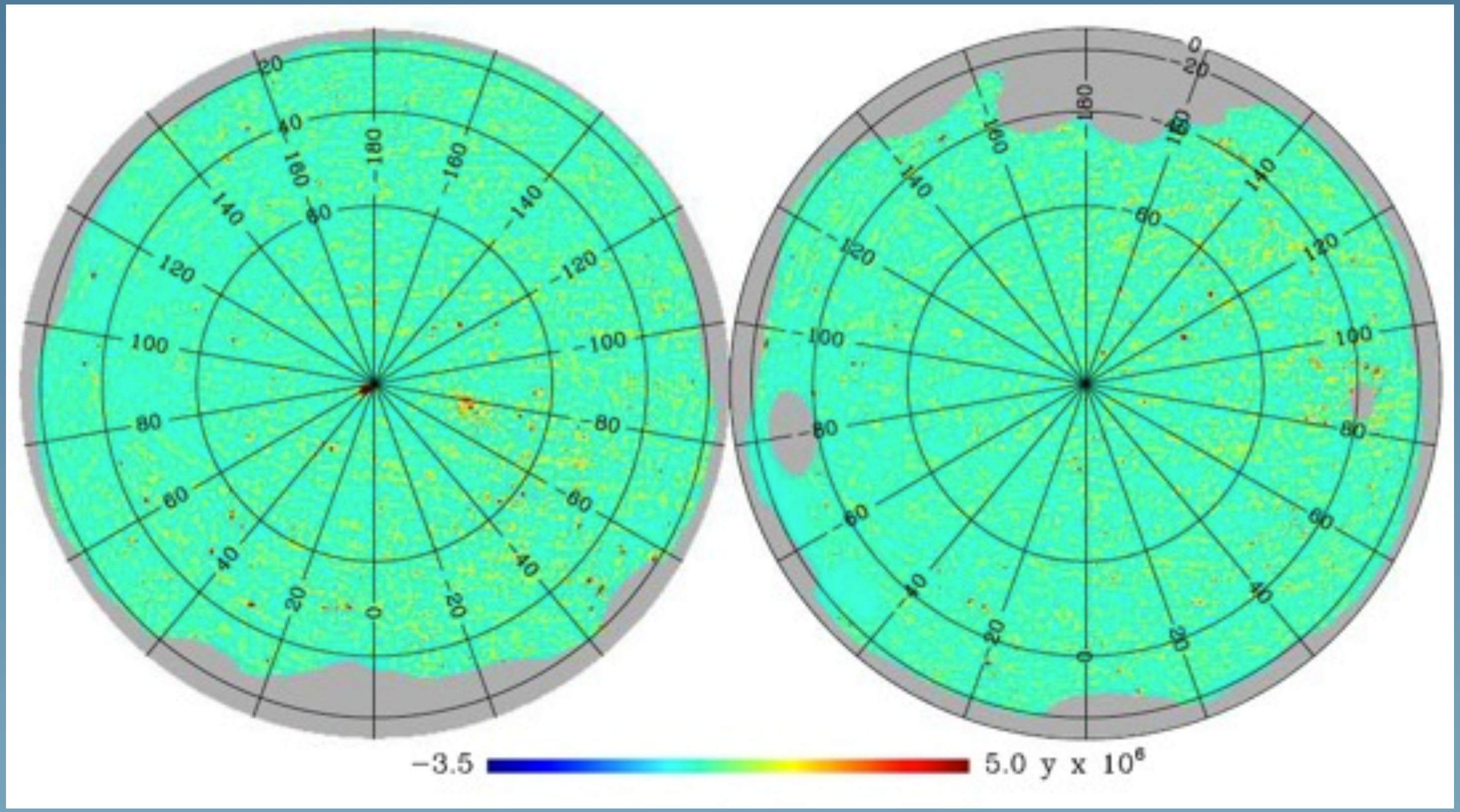
tSZ PS from y-map

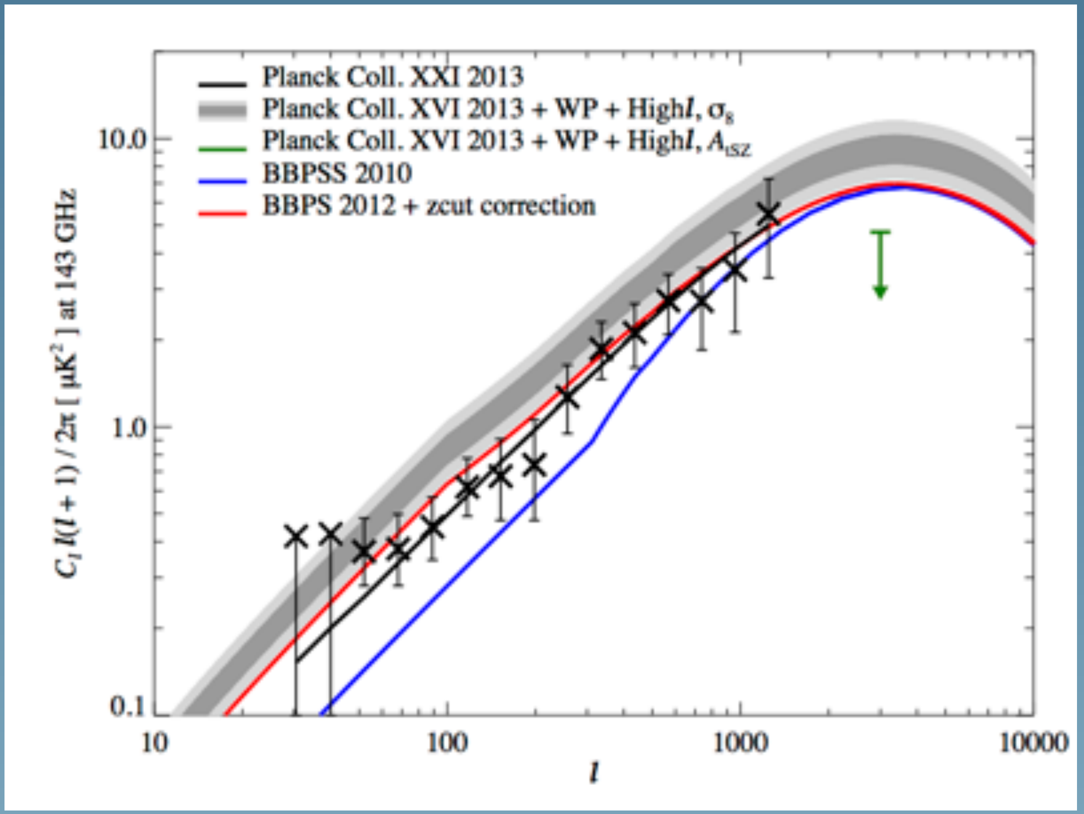




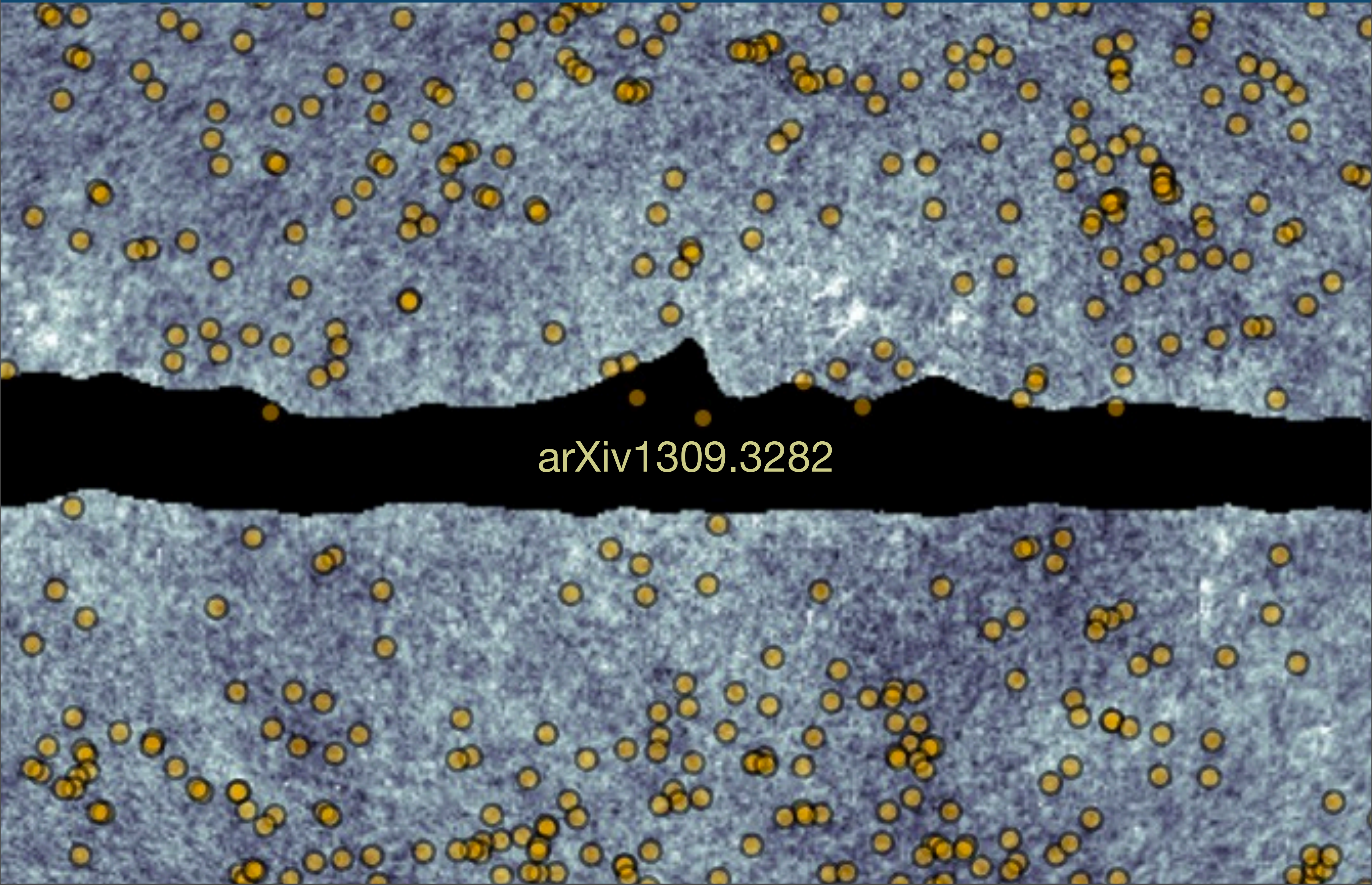


Can we do better?

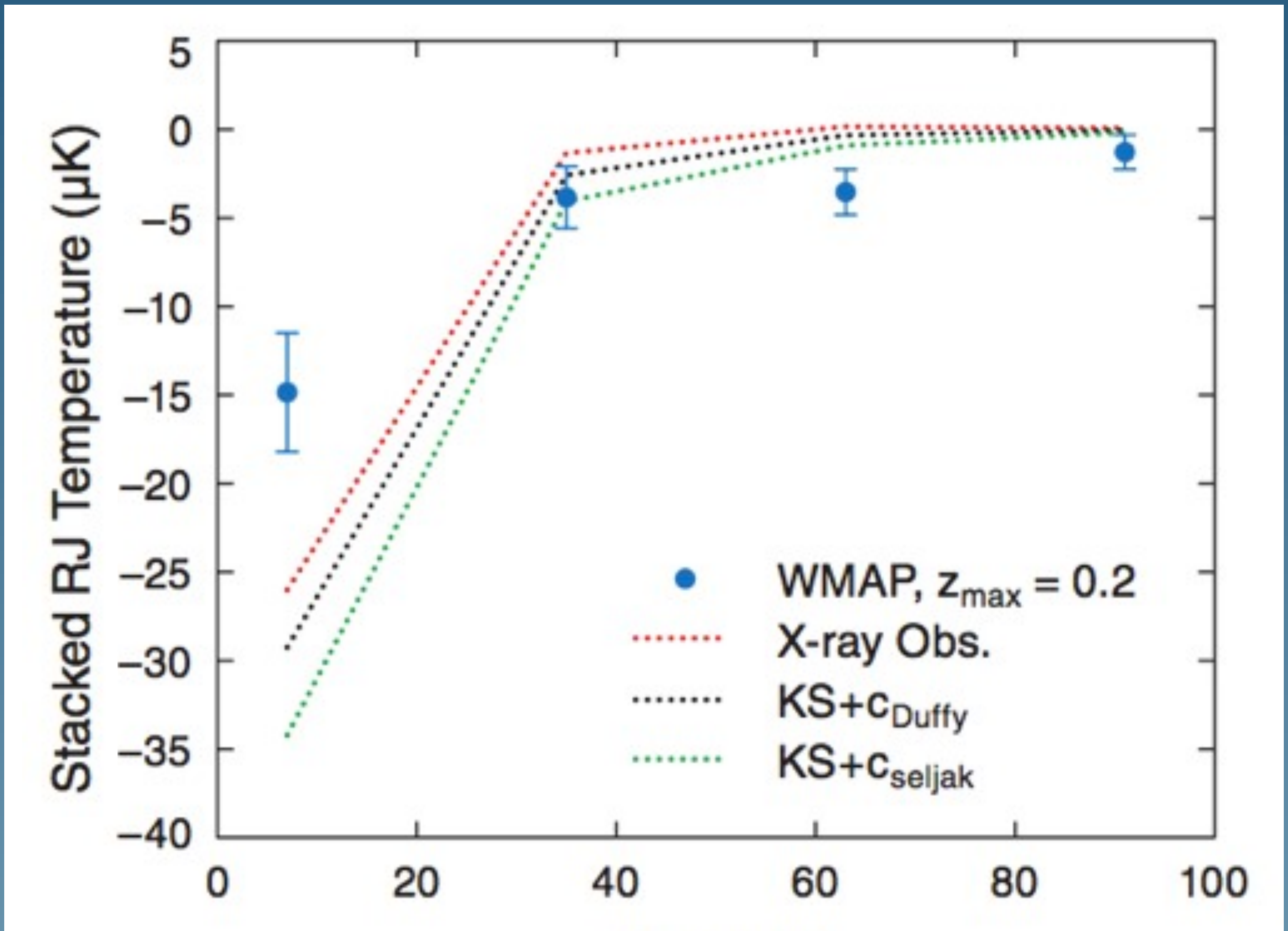




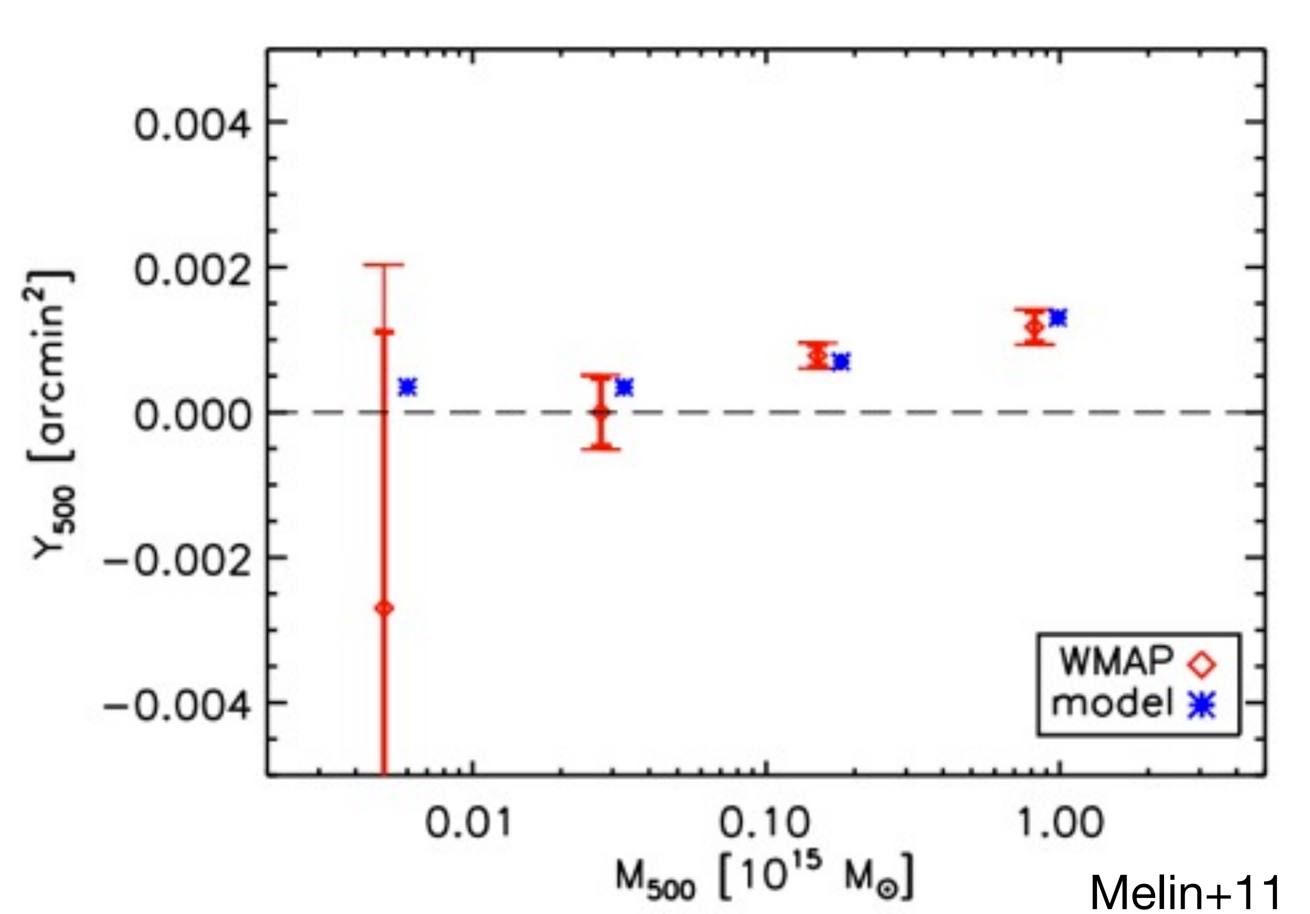
What about cross correlations?



Cross Correlations
aka Stacking



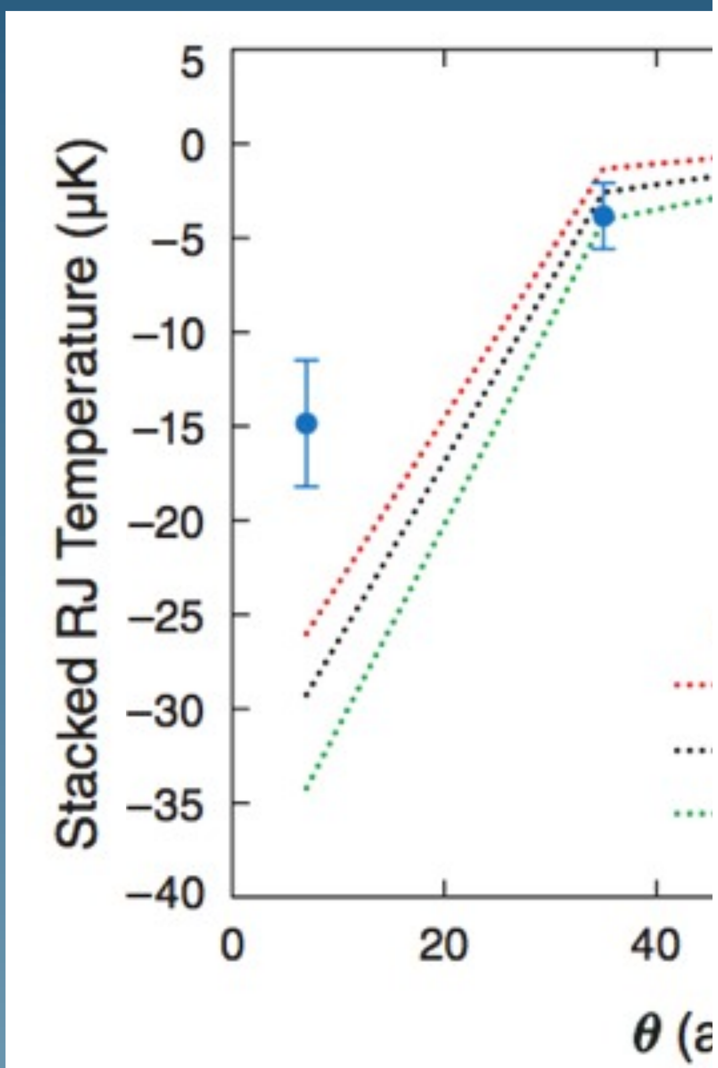
WMAP7+12

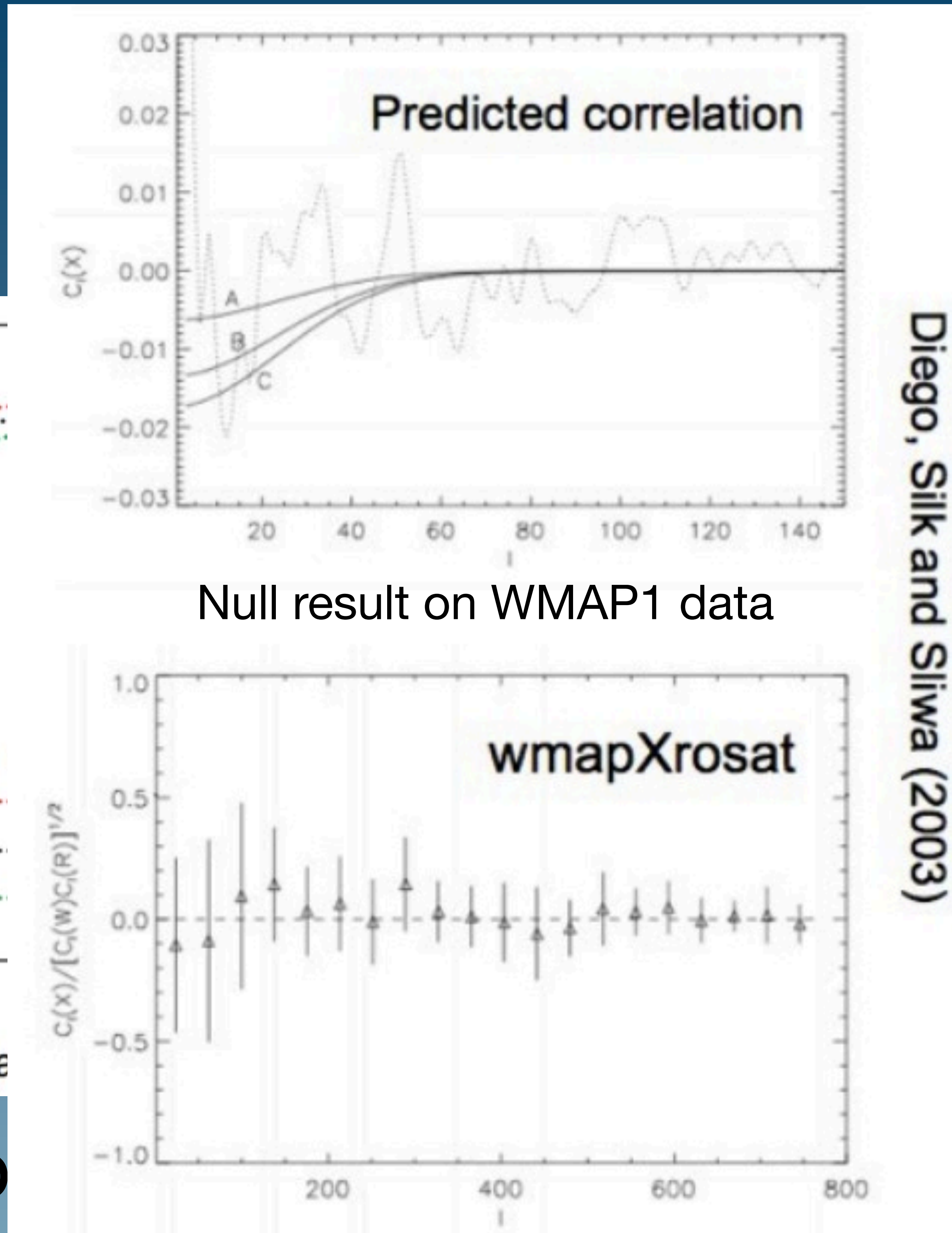


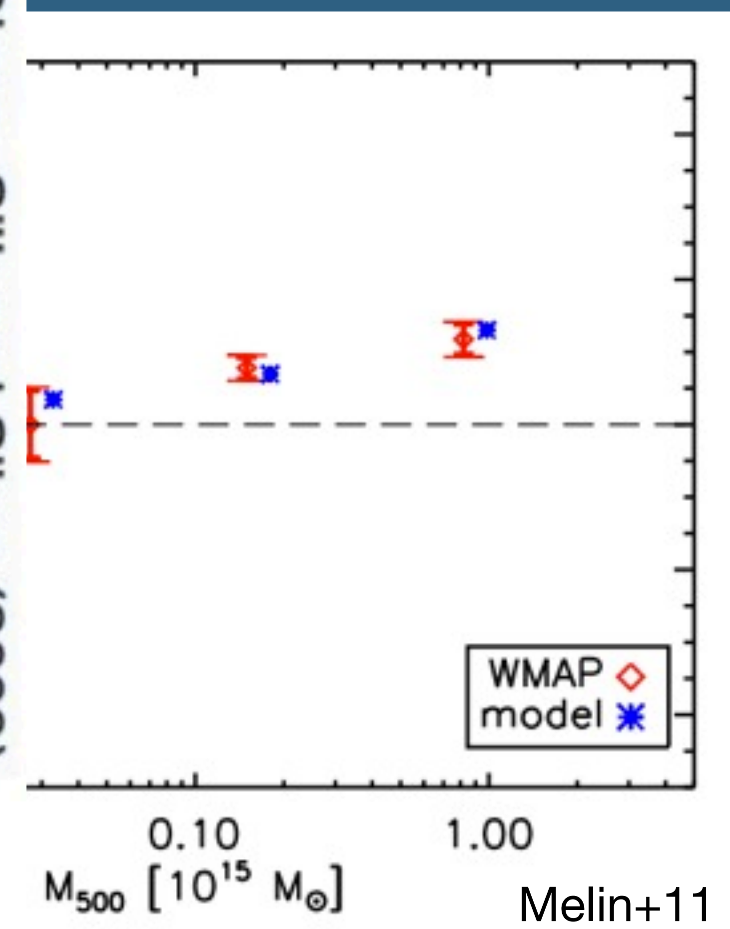
Melin+11

Long history of stacking WMAP data on cluster locations

Cross Correlations

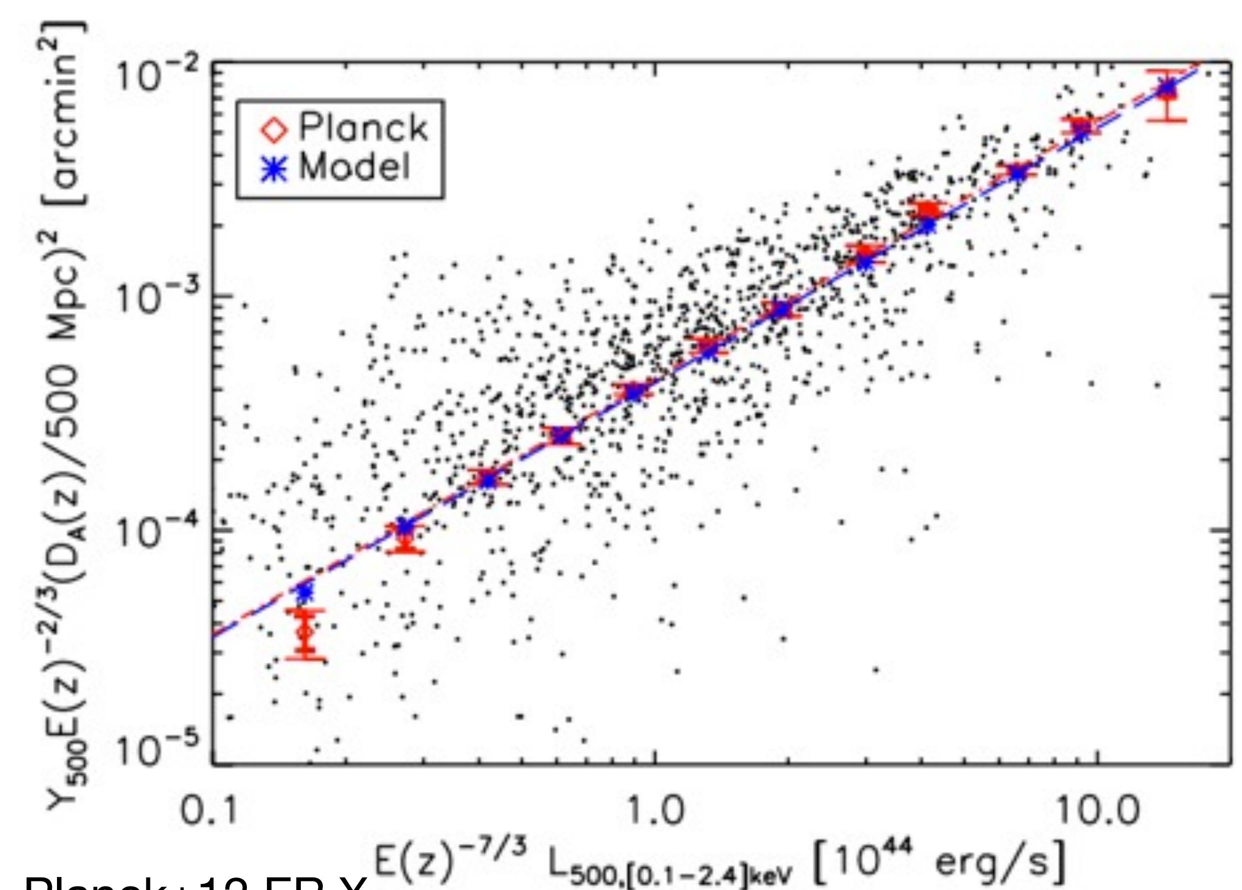






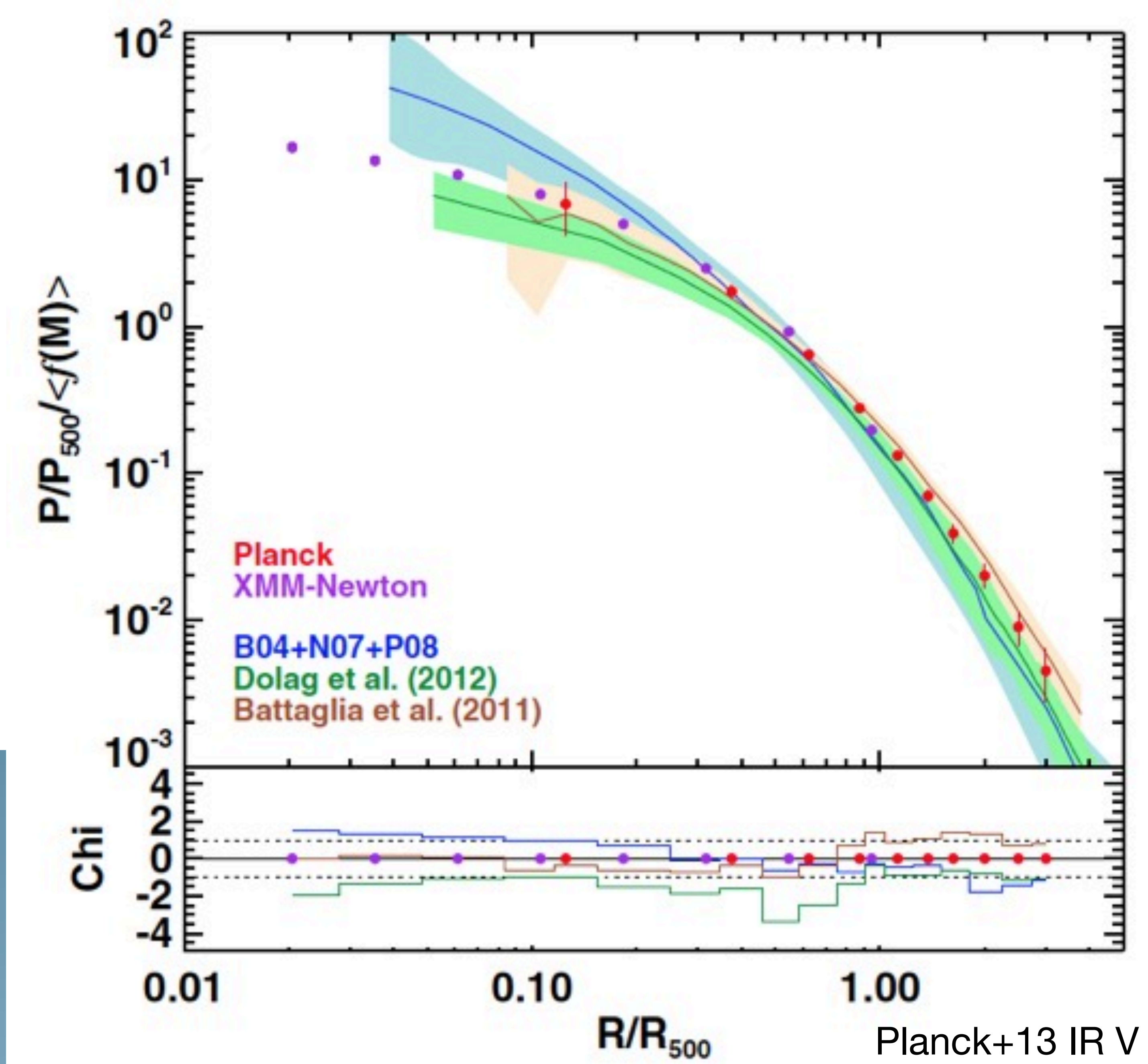
Long histo... a
on cluster locations

Cross Correlations
aka Stacking



Planck+12 ER X

More stacking with Planck



Planck+13 IR V

Cross Correlations

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

$$\otimes$$

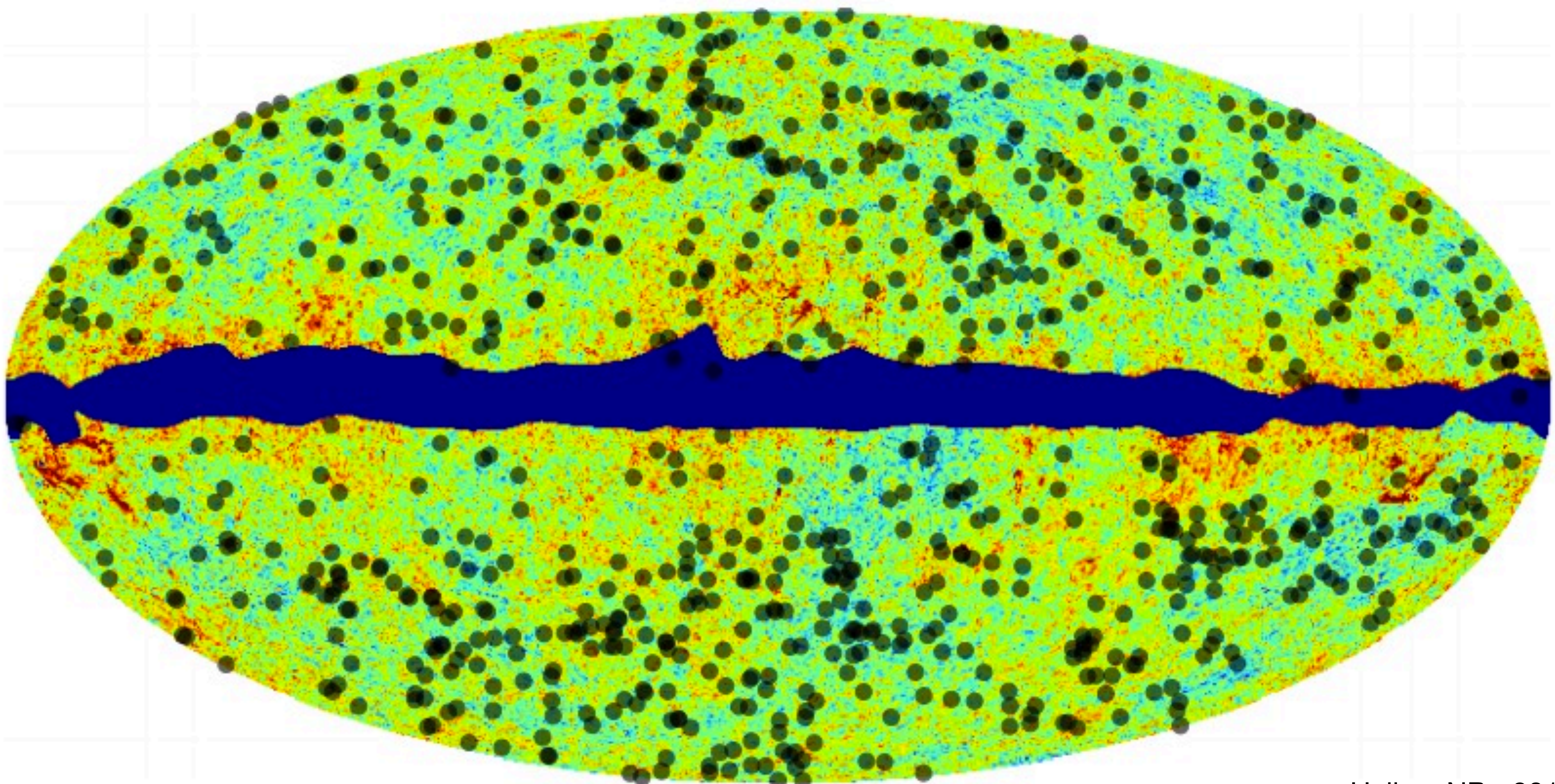
$$\delta_n(\hat{\theta}) = \frac{n(\hat{\theta}) - \bar{n}}{\bar{n}}.$$

n → X-ray cluster catalog

Removes systematics (caution...)

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

Cross Correlations



Hajian, NB+ 2013

Used the raw Planck at 100-857 GHz

Also used the WMAP9 94 GHz

Cluster Catalog

Subsample of the MCXC (flux lim.)

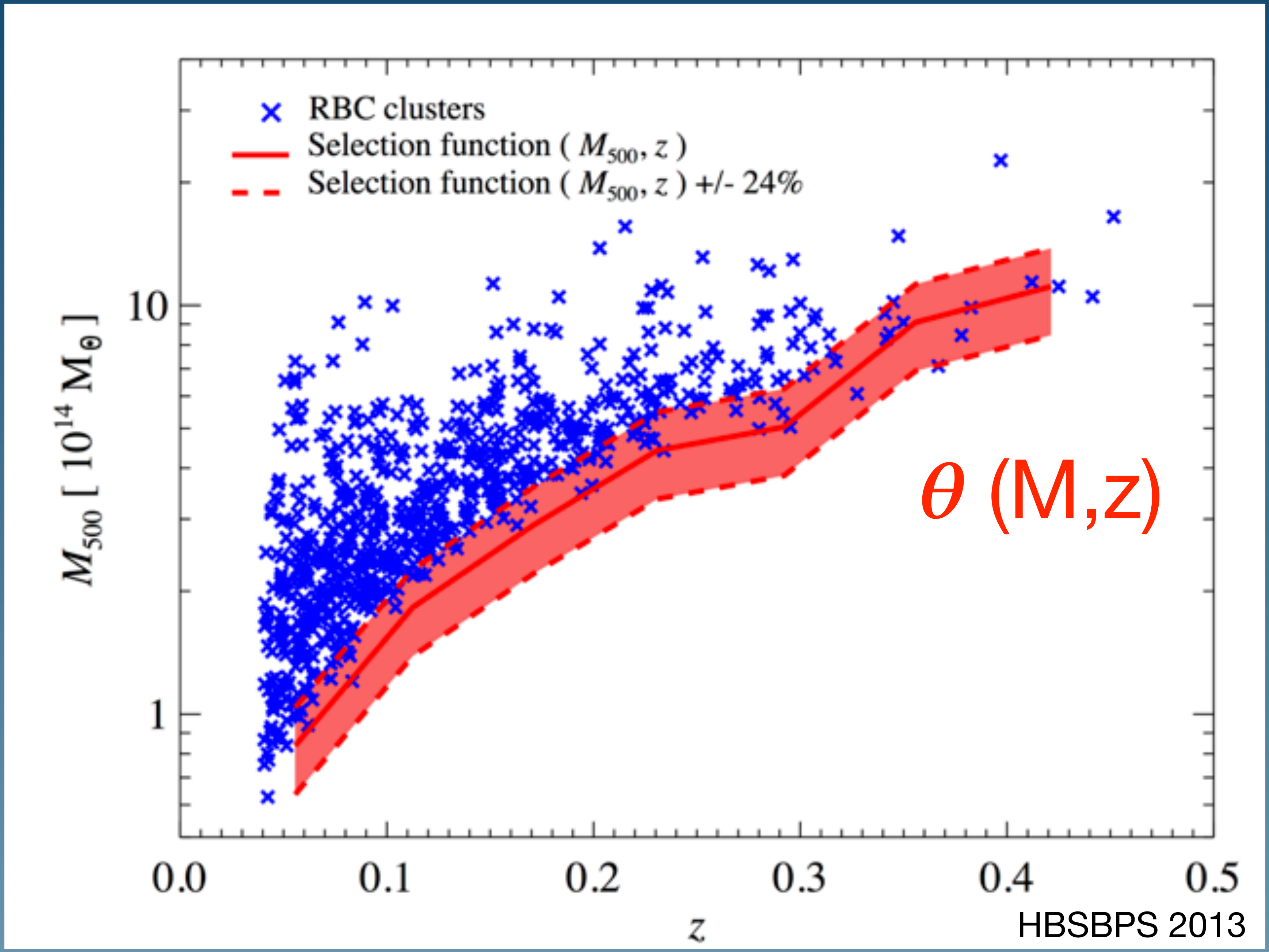
REFLEX

BCS

CIZA

RBC

~800 clusters



M_{500} → L_X - M relation calibrated from the REXCESS sample (not core excised ~24% scat.)

(we include a 20% HSE bias)

Auto & Cross spectra
(ignoring clustering)

tSZ auto power spectrum $A_{tSZ} \propto \sigma_8^{8}$

$$C_l = g_\nu^2 \int_0^{z_{max}} dz \frac{dV}{dz} \int dM \frac{dn(M,z)}{dM} \left|\tilde{y}_l(M,z)\right|^2$$

Gastrophysics

tSZ cross power spectrum

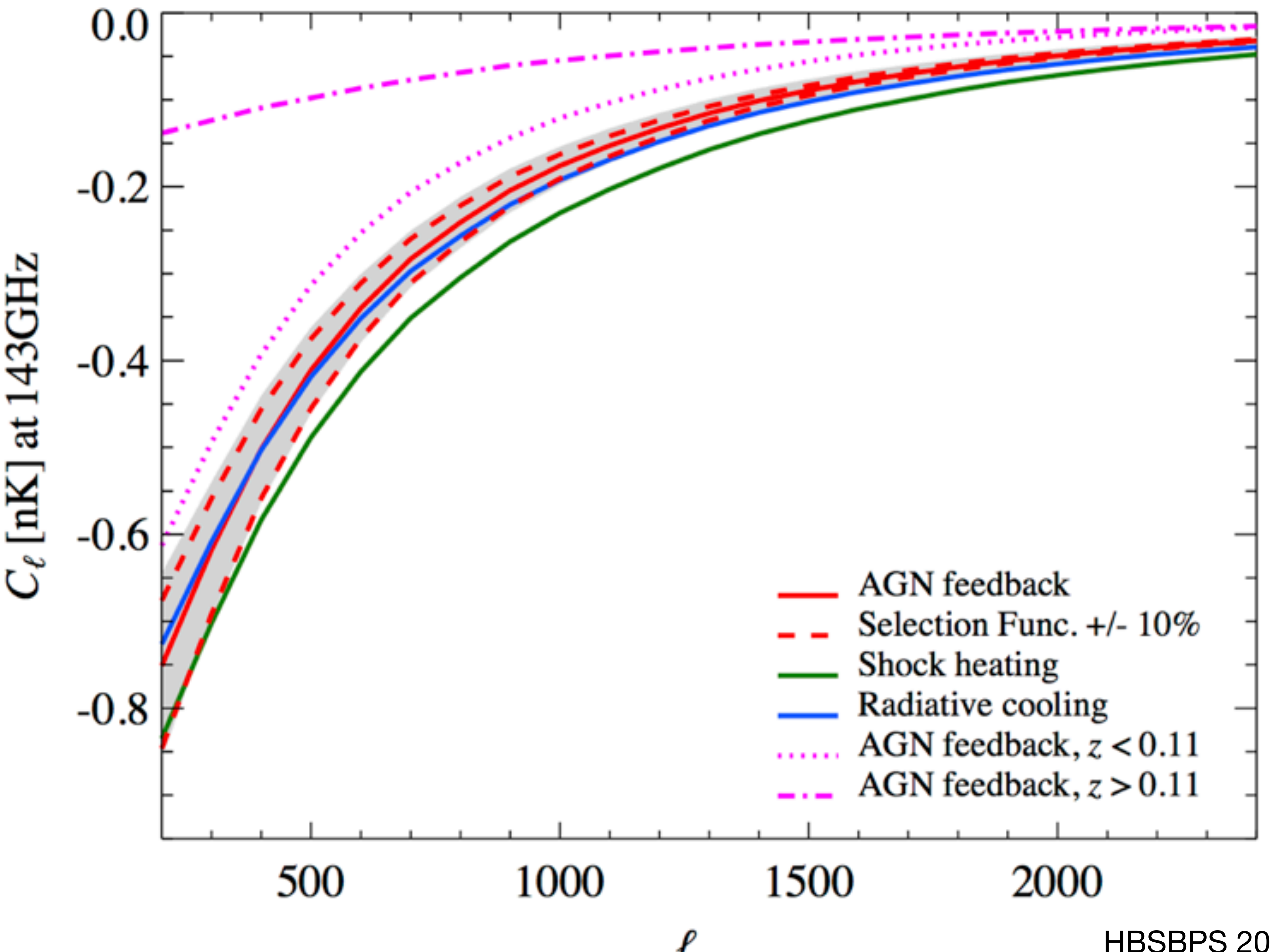
$$C_\ell^{SZ\times n} = f_\nu \int_{0.04}^{\infty} \frac{\mathrm{d}V}{\mathrm{d}z}\mathrm{d}z \int_0^{\infty} \frac{\mathrm{d}n(M,z)}{\mathrm{d}M} \tilde{y}_\ell(M,z)\Theta(M,z)\mathrm{d}M,$$

$A_X \propto \sigma_8^{7.4}\, \Omega_M^{1.9}$

High mass, low redshift clusters

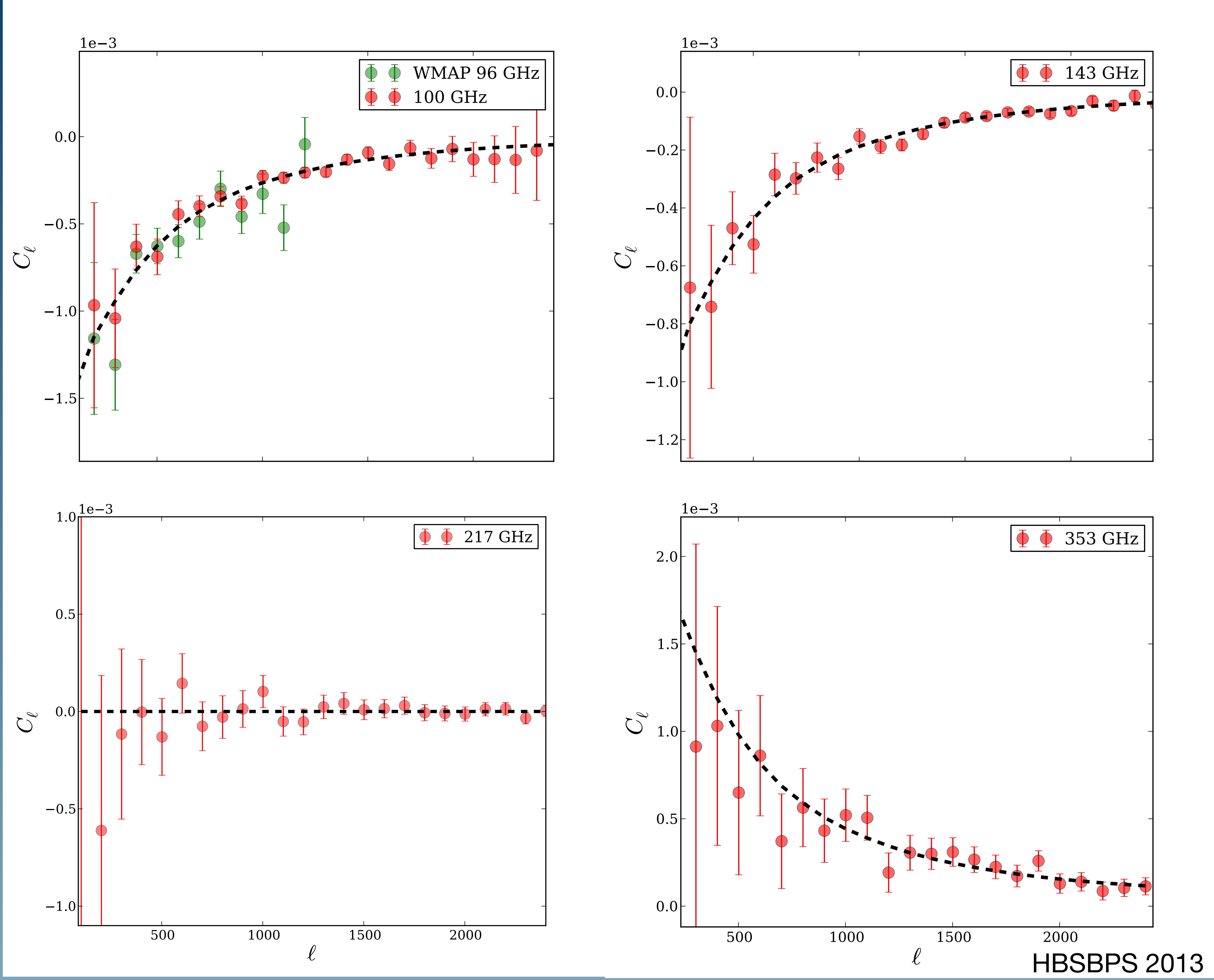
Selection function (Gastrophysics)

Cross spectra theory



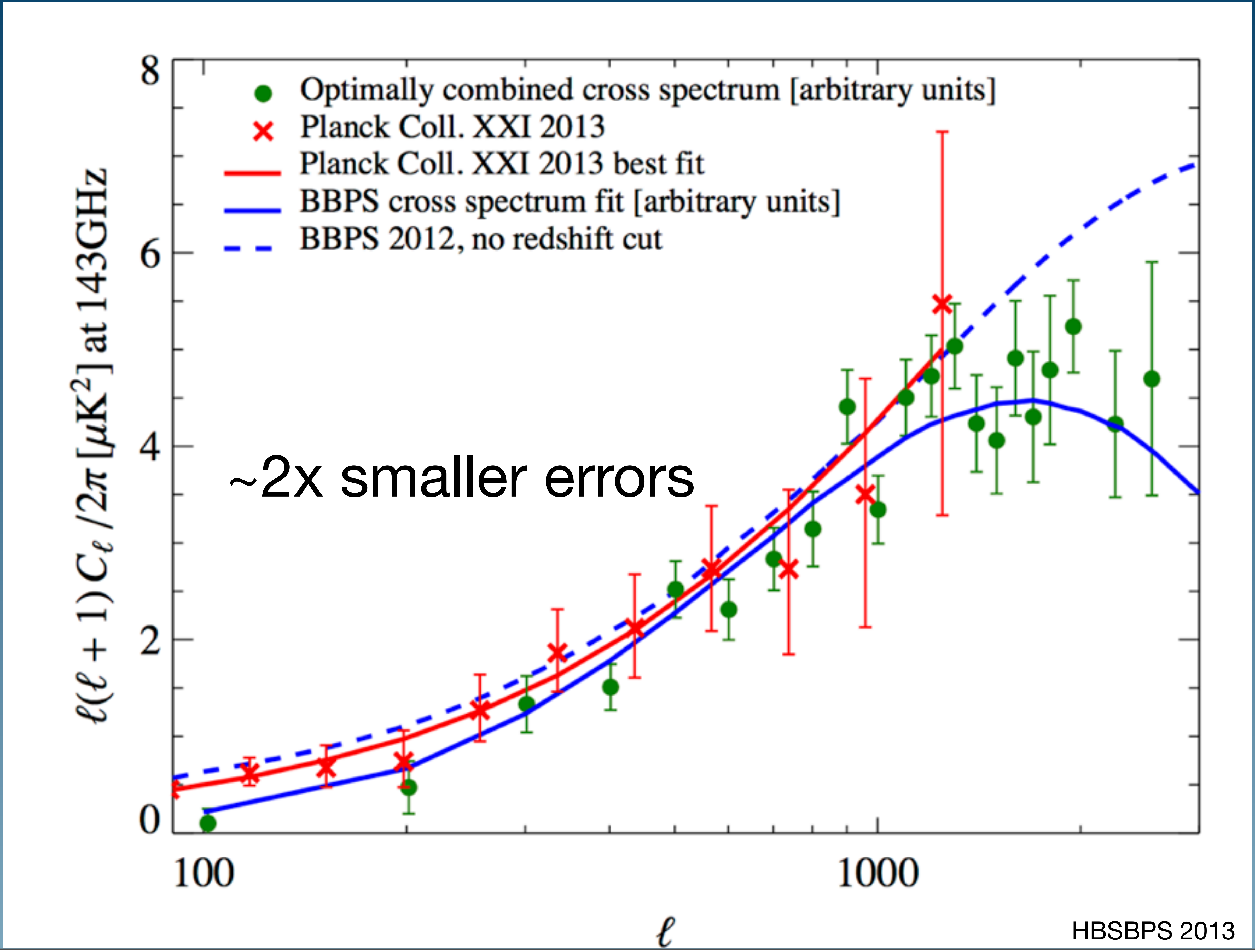
HBSBPS 2013

Cross spectra



HBSBPS 2013

Combined Xspec

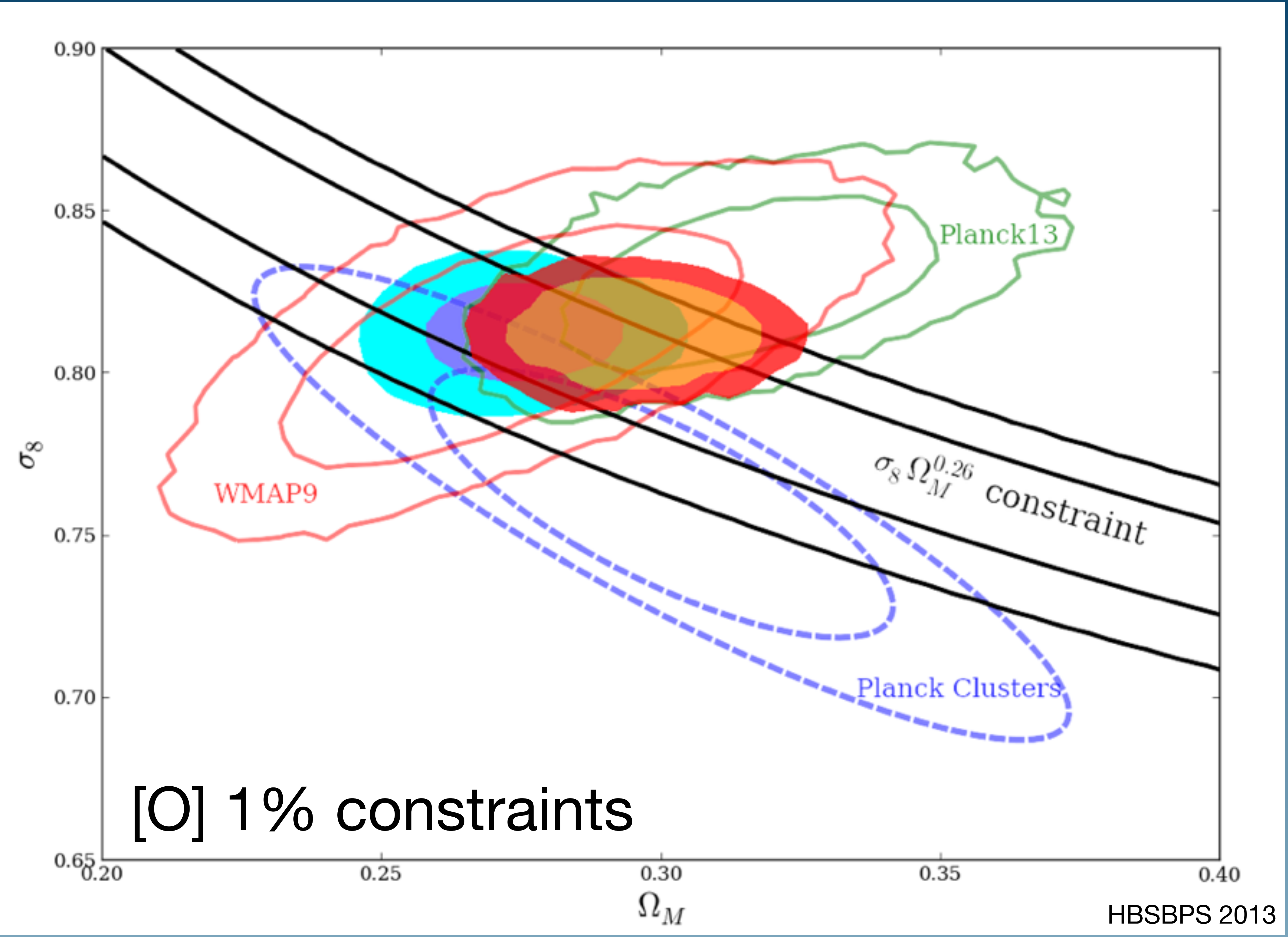


Xspec Results

Model	Spectrum	Fit Parameter	Derived Parameters		
		$A_\times$	$\sigma_8(\Omega_M/0.3)^{0.26}$	σ_8(WMAP9)	σ_8(Planck13)
AGN feedback	overdensity	1.06 ± 0.06	–	–	–
	number-count	1.36 ± 0.14	0.796 ± 0.011	0.812 ± 0.009	0.810 ± 0.007
radiative cooling	overdensity	1.04 ± 0.06	–	–	–
	number-count	1.33 ± 0.14	0.793 ± 0.011	0.811 ± 0.009	0.809 ± 0.007
shock heating	overdensity	0.88 ± 0.05	–	–	–
	number counts	1.12 ± 0.12	0.775 ± 0.011	0.802 ± 0.009	0.801 ± 0.008
AGN feedback **+10%**	overdensity	0.95 ± 0.05	–	–	–
	number-count	1.53 ± 0.15	0.809 ± 0.011	0.819 ± 0.009	0.815 ± 0.007
AGN feedback **-10%**	overdensity	1.16 ± 0.07	–	–	–
	number-count	1.25 ± 0.13	0.787 ± 0.010	0.808 ± 0.009	0.805 ± 0.007
AGN feedback **all**	number-count	1.38 ± 0.19	0.797 ± 0.015	0.812 ± 0.010	0.812 ± 0.008

Rule out an extreme ICM model (shock heating)
Include scaling relation uncertainties by combining the posterior probabilities

Constraints



Can we do better?

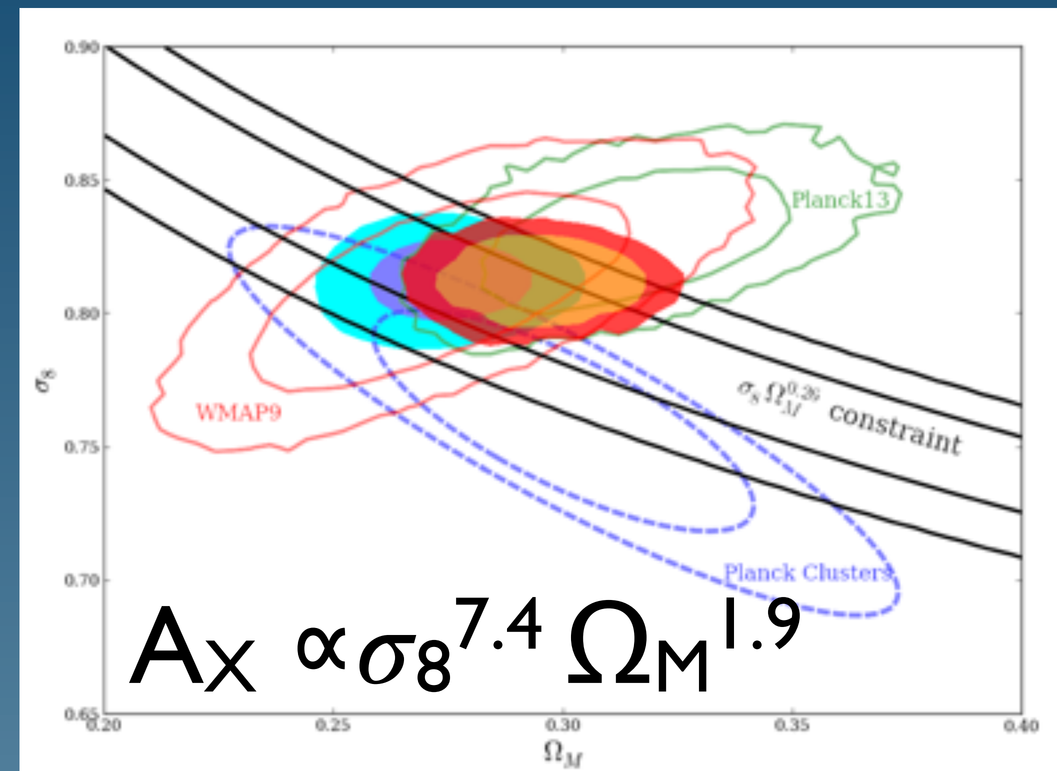
Yes we can!

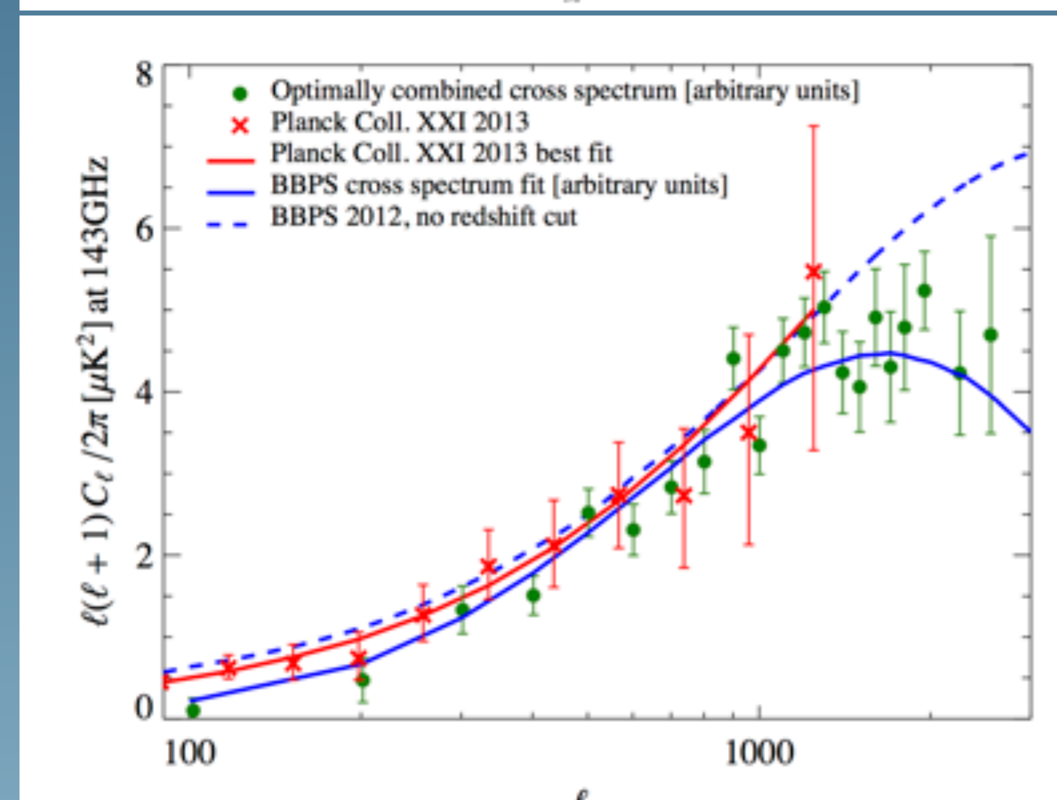
Planck ⊗ X-ray catalogs constrains “Gastrophysics” and cosmology

2x smaller measurement errors than the Planck y spectra

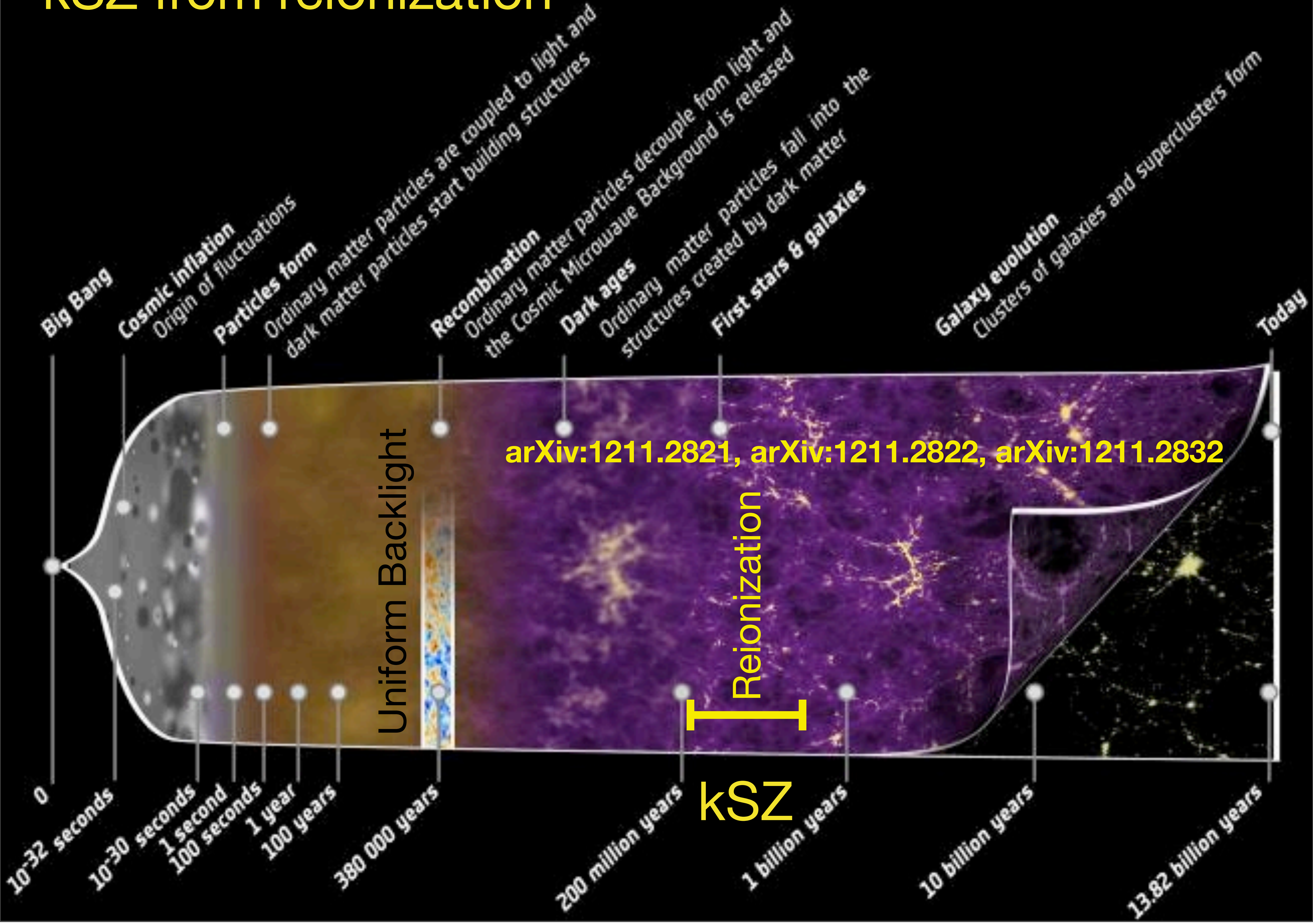
Constrain “contaminants” to the tSZ signal

eRosita will be even better!



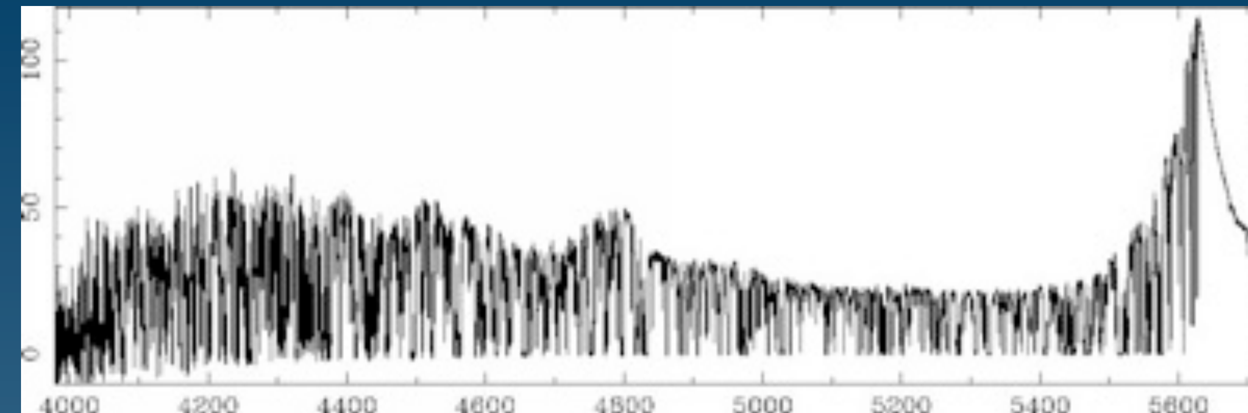


kSZ from reionization



21cm signal

Lyα absorption in QSO spec

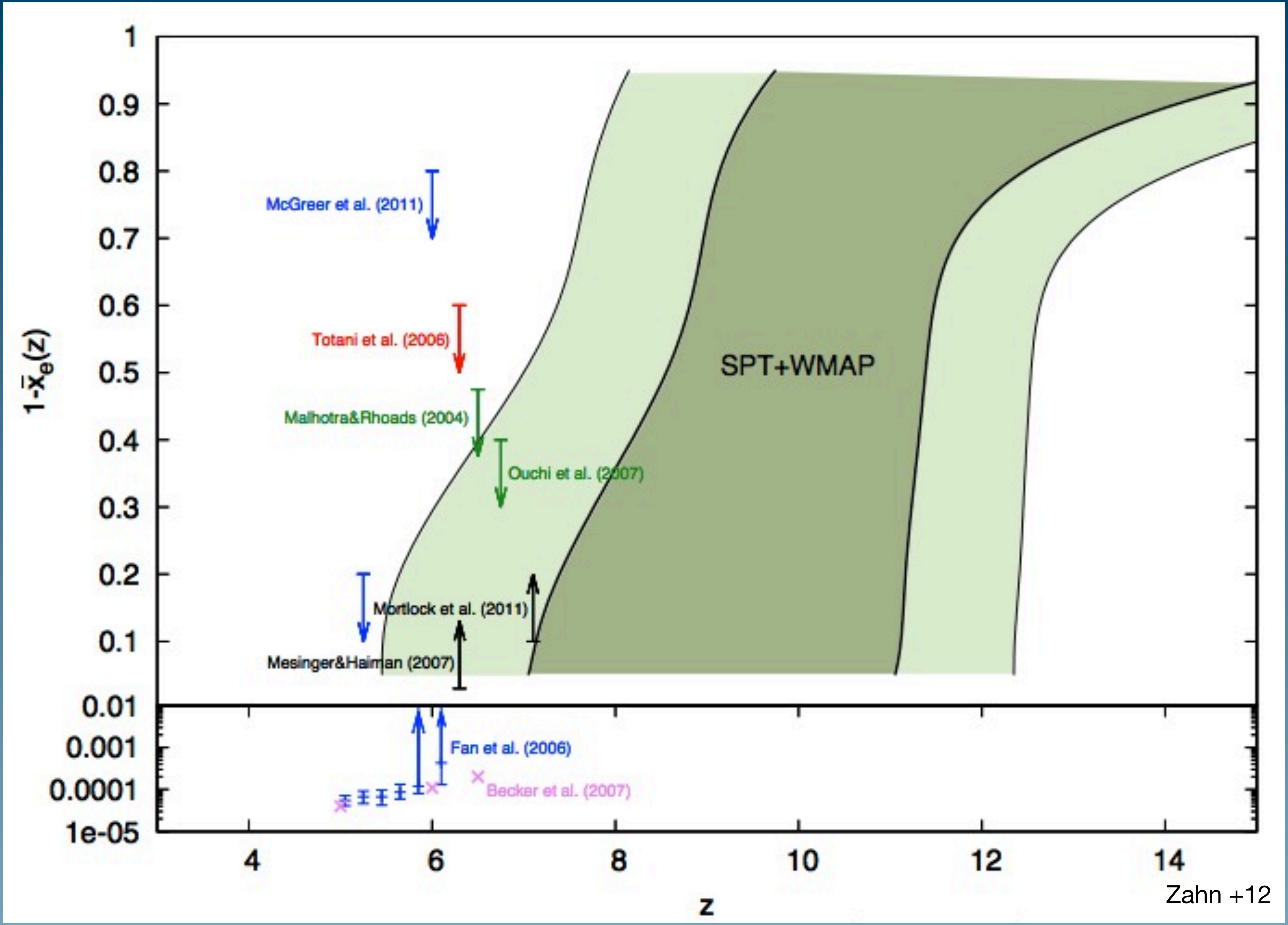


hydrogen + radiation → proton + electron + heat

γ first galaxies, QSOs

Thomson scattering → CMB

Current constraints



Big Questions

Understand these first sources: stars, galaxies and quasars

Mean redshift ($\bar{z}$) Duration (Δ_z)

How much can the kSZ tell us?

Theoretical predictions

- Semi-analytic approach:
  Excursion set (Bond+91)

Barkana & Loeb 01
Furlanetto+04; Zahn+05,07; Mesinger & Furlanetto 07; Geil & Wyithe 08; Alvarez+09; Thomas+09; Choudhury+09; Santos+10; Mesinger+11

$$\zeta F_{\rm coll} \geq 1$$

- Simulations approach:
  Radiative Transfer + Hydro

Gnedin &Abel 01; Ciardi+01; Maselli+03; Alvarez+06; Mellema+06; Iliev+06; Trac &Cen07; McQuinn+07; Trac+08; Aubert& Teyssier 2008; Altay +08; Croft & Altay 08; Finlato+09; Petkova & Springel 2009

Difficult to directly compare semi-analytic method to simulations

Direct simulations of large cosmological volumes are not possible

Our Simulations

Model	L (Mpc/h)	DM	Gas	Rays	Comments
L100N	100	29 Billion			N-body only
L100A	100	2048^3	2048^3	17 Billion	Late reionization $\bar{z} \sim 8$
L100B	100	2048^3	2048^3	17 Billion	Early reionization $\bar{z} \sim 10$

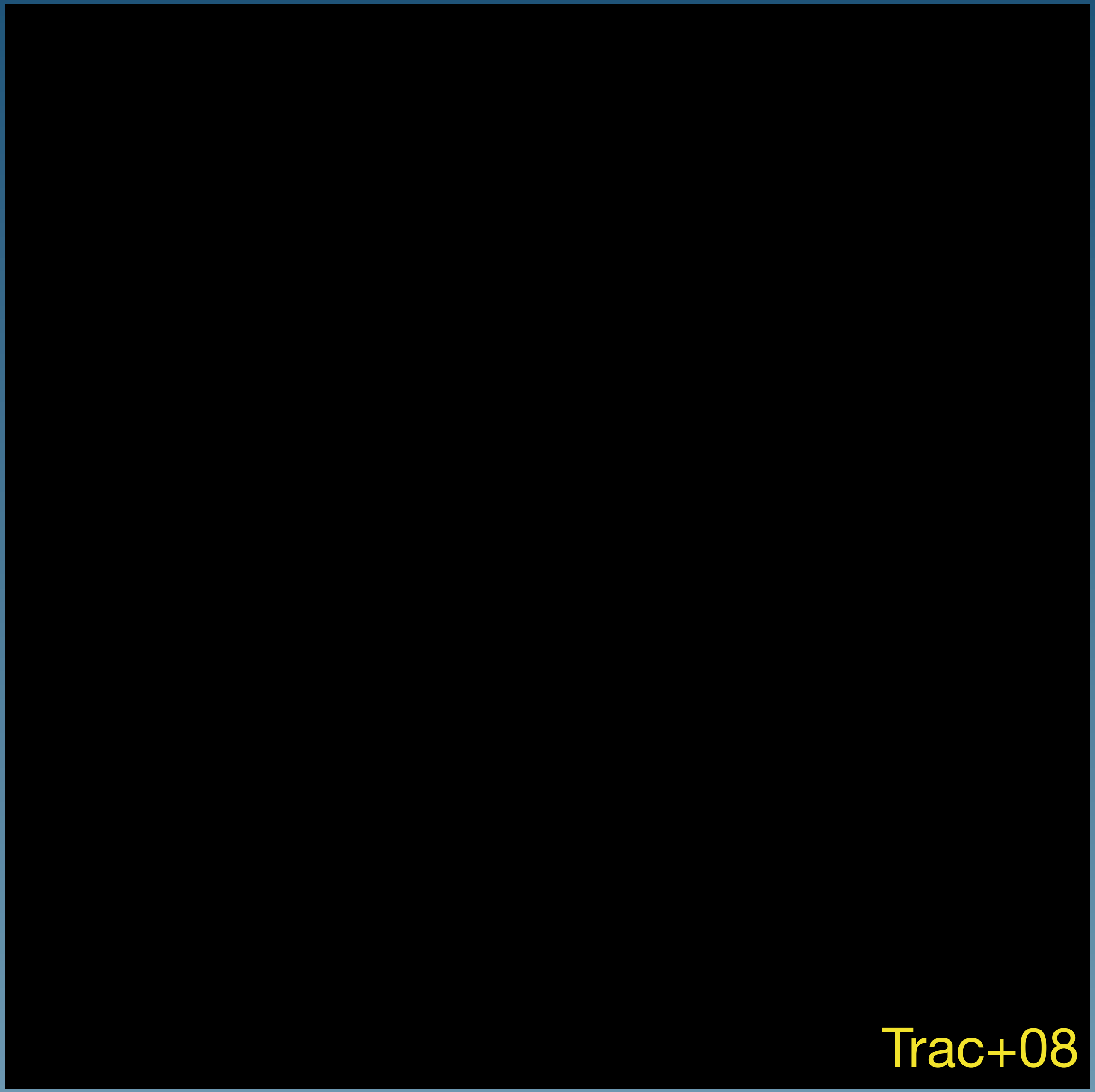
Hybrid approach (Trac+08)

High-res N-body → radiation sources ($\sim 10^8\ M_\odot$)

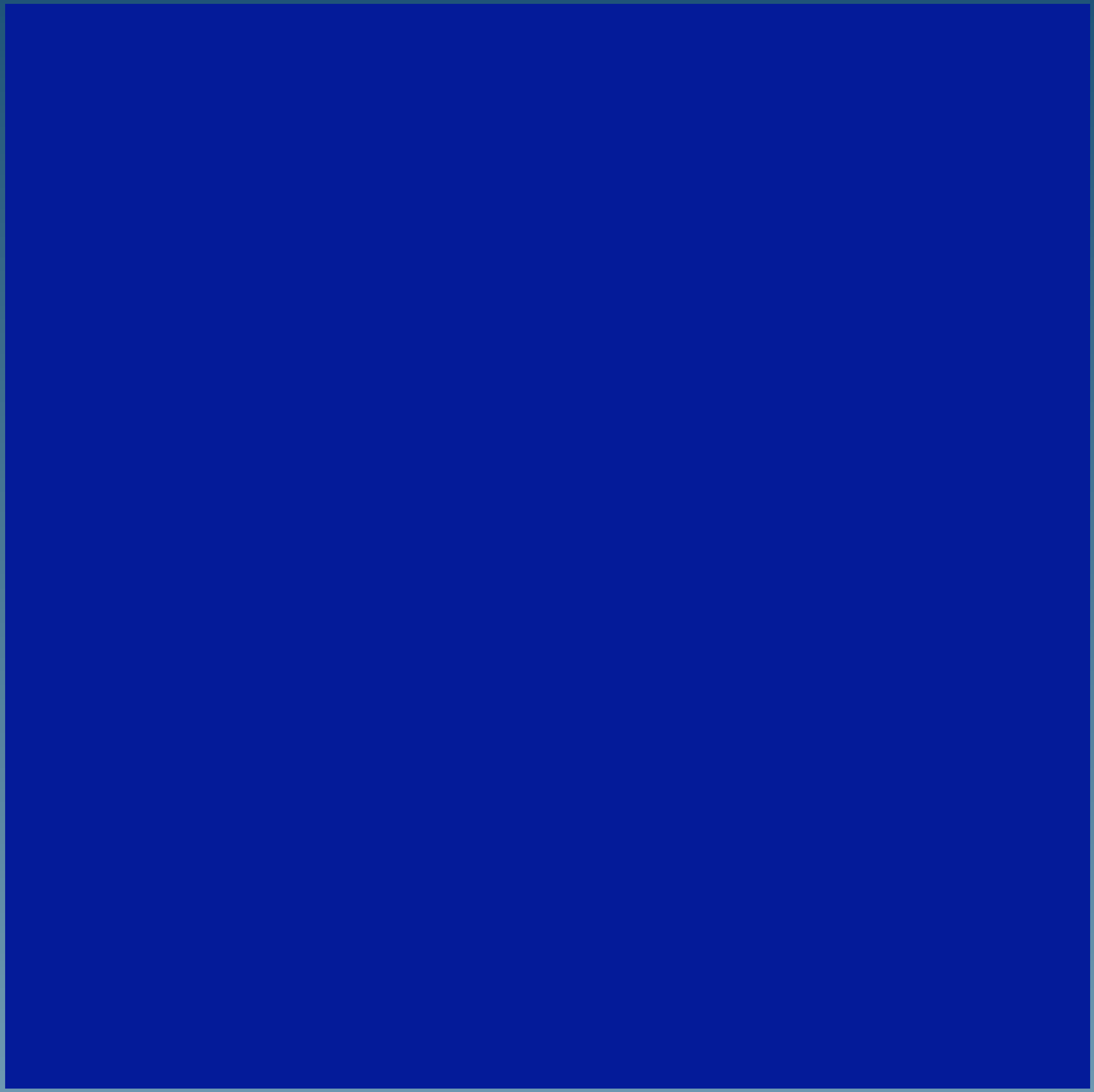
RadHydro →N-body, Hydro, RT

$N_\gamma(M,z)$ Halo model (Trac & Cen 07, BTCL 2013)

Simulations



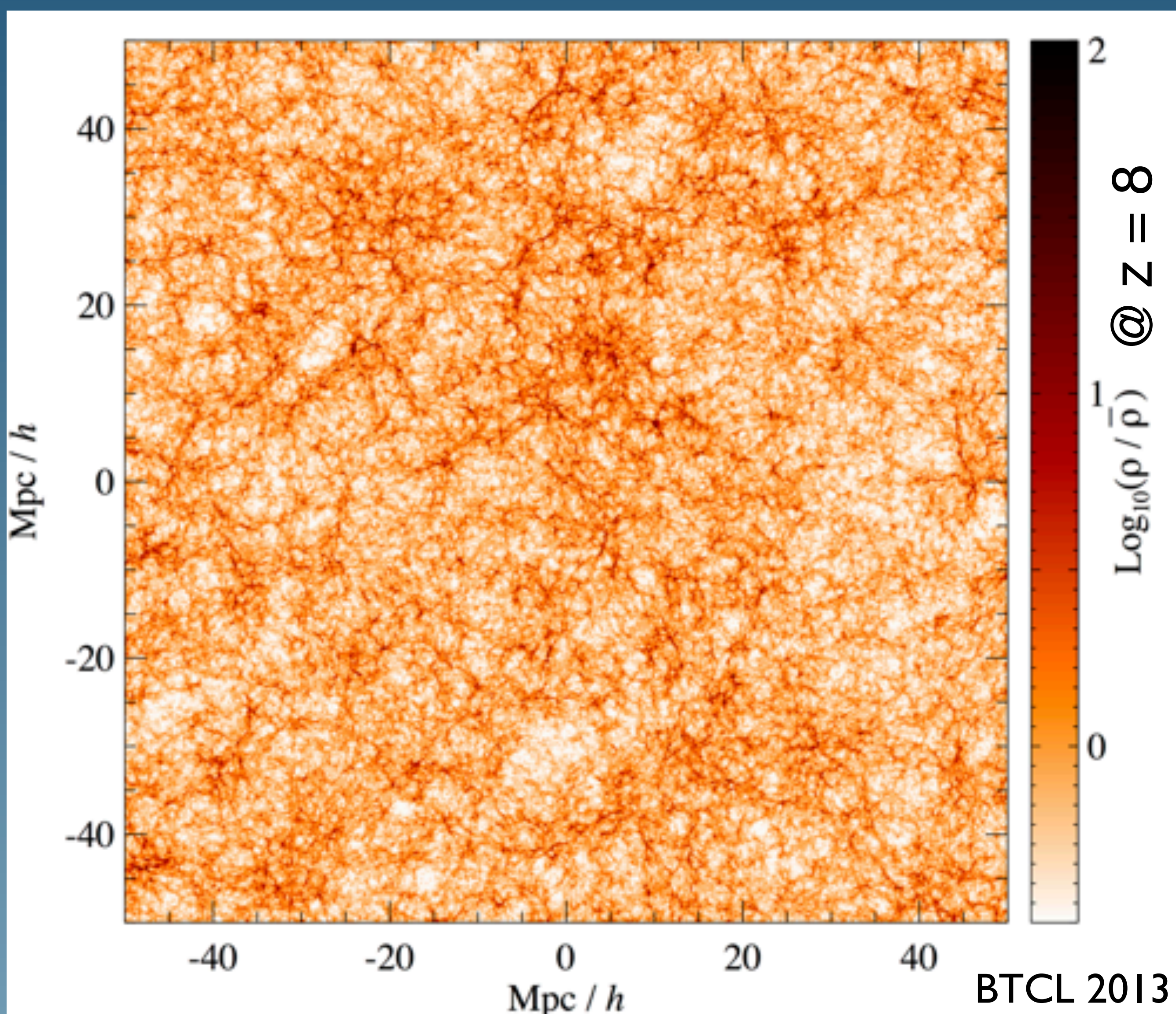
ionized density

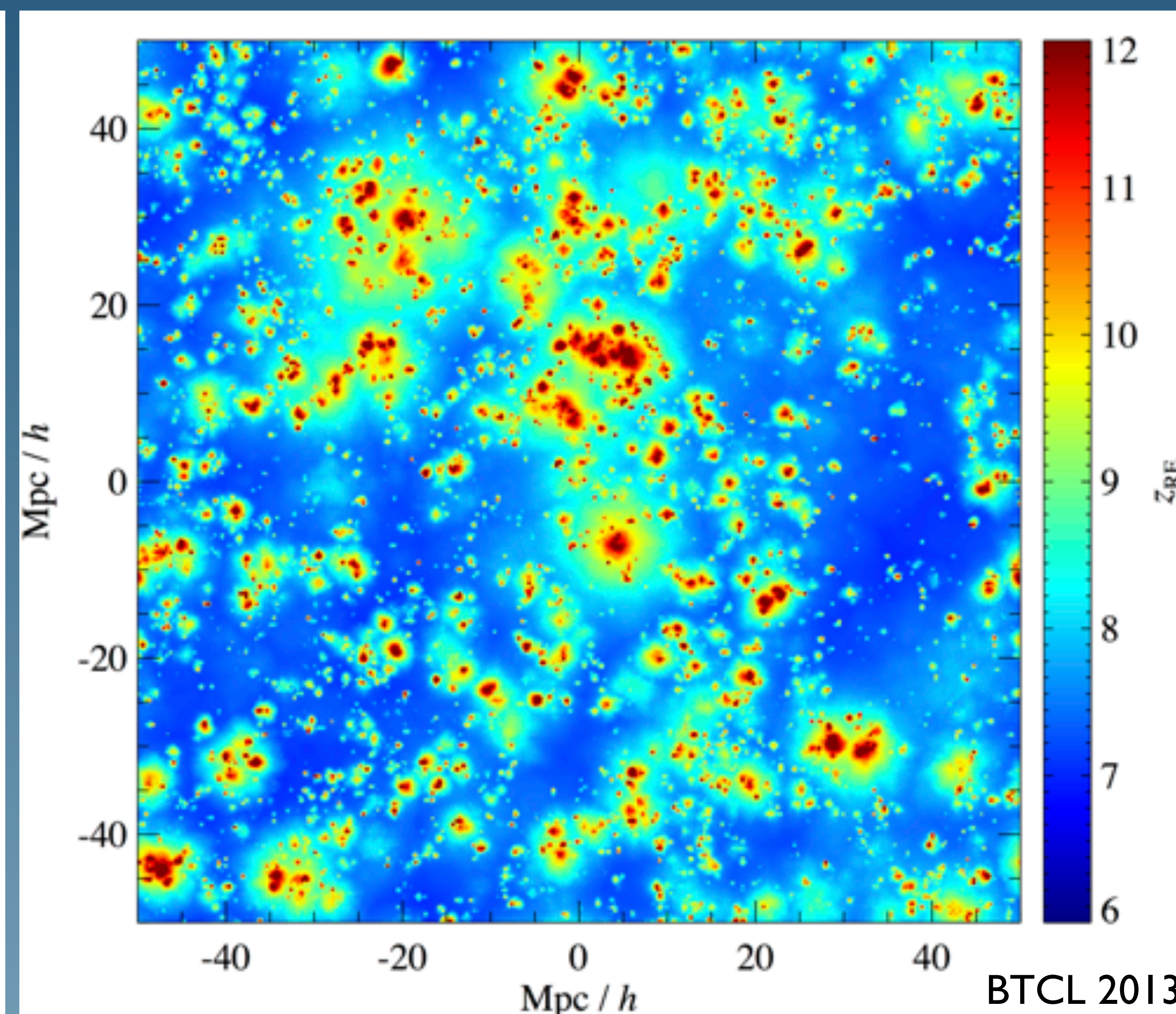


z reionization field

Model Motivation

constructed field z_{RE} → 90% ionized





Correlation between density and z_{RE}

Correlation + Bias

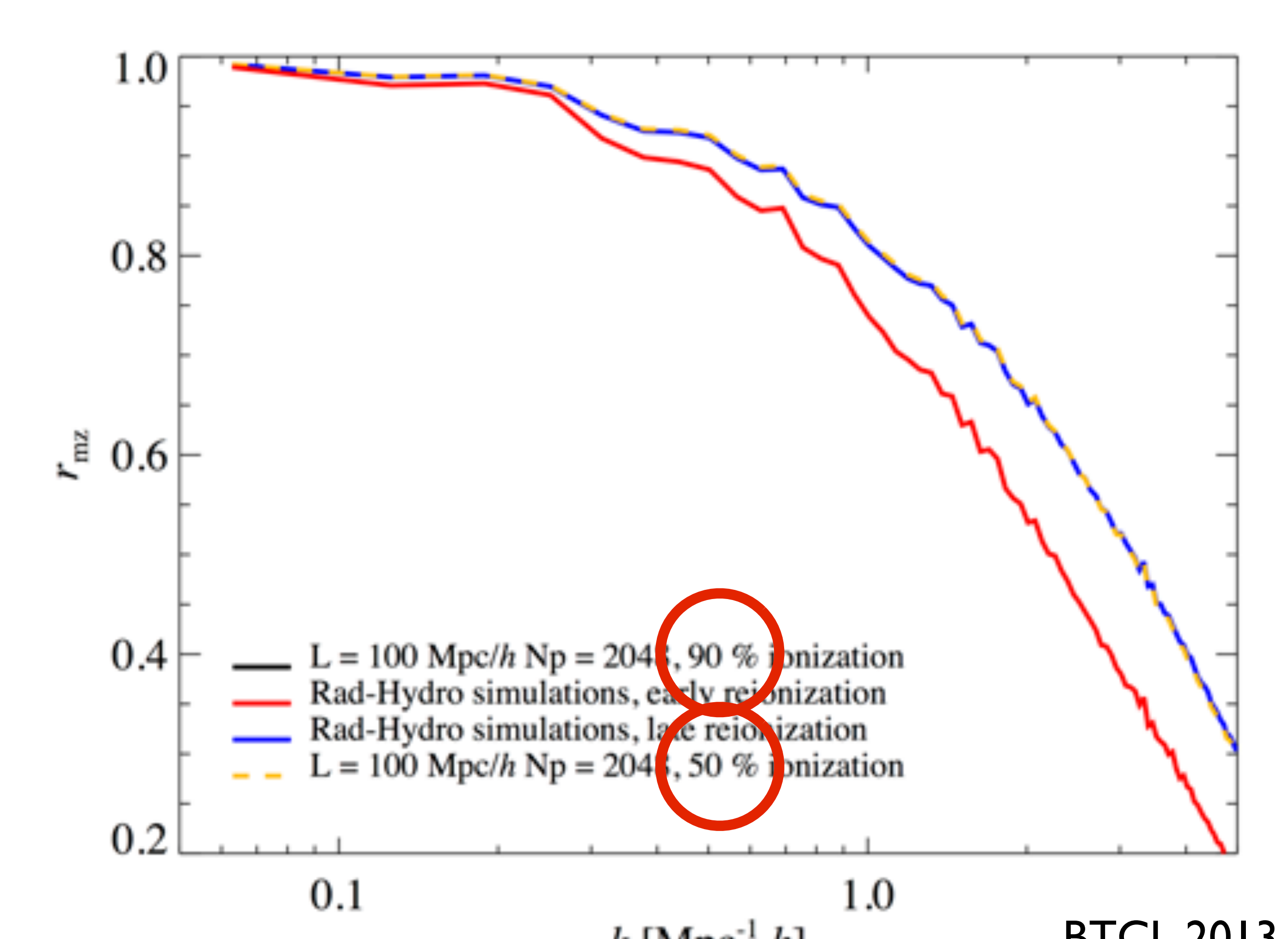
Construct

$$\delta_{\rm m}({\bf x}) \equiv \frac{\rho({\bf x}) - \bar{\rho}}{\bar{\rho}},$$

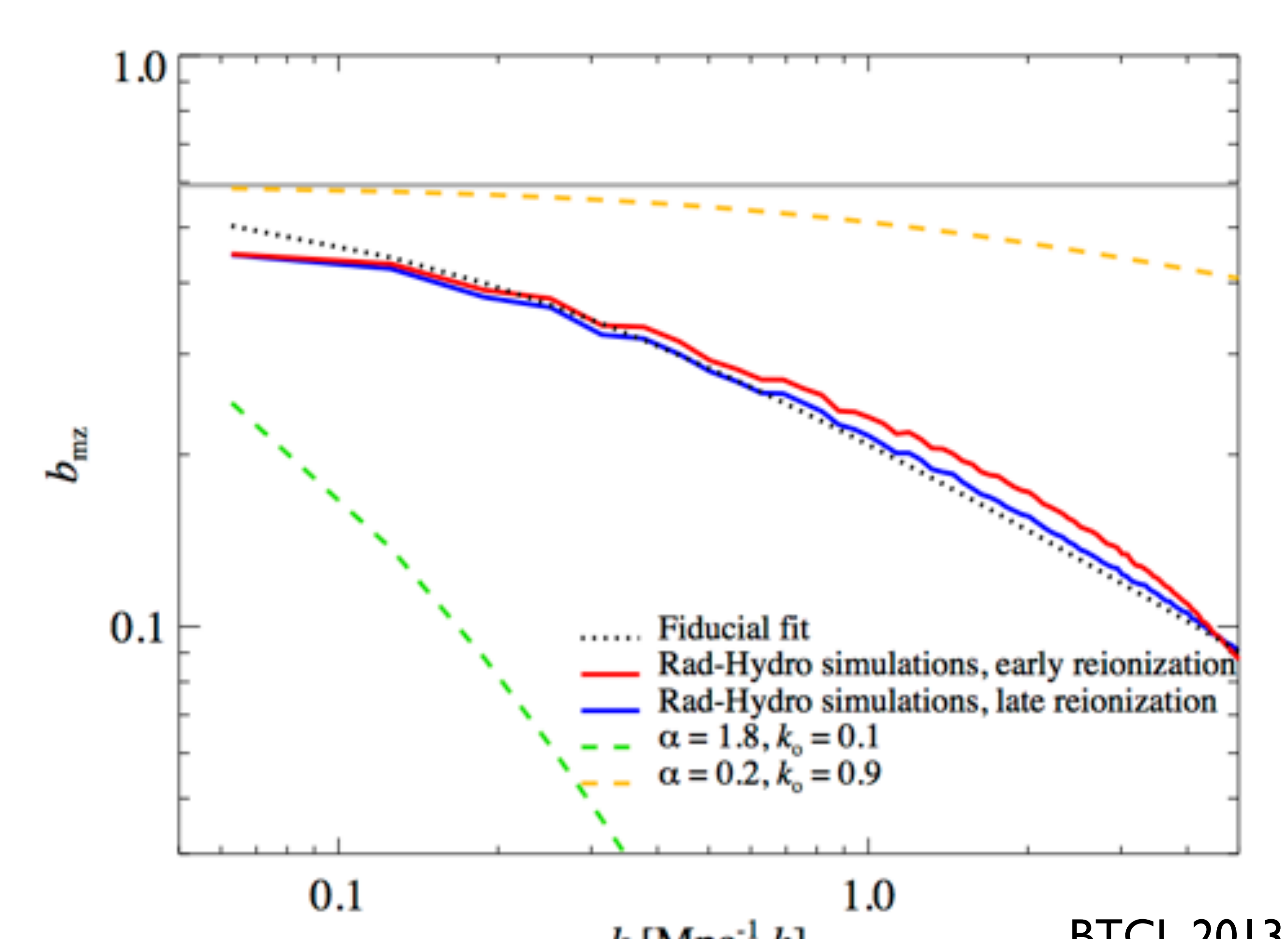
$$\delta_{\rm z}({\bf x}) \equiv \frac{[1 + z_{\rm RE}({\bf x})] - [1 + \bar{z}]}{1 + \bar{z}}$$

Functional Form

$$b_{\rm mz}(k) = \frac{b_{\rm o}}{(1 + k/k_{\rm o})^{\alpha}}$$



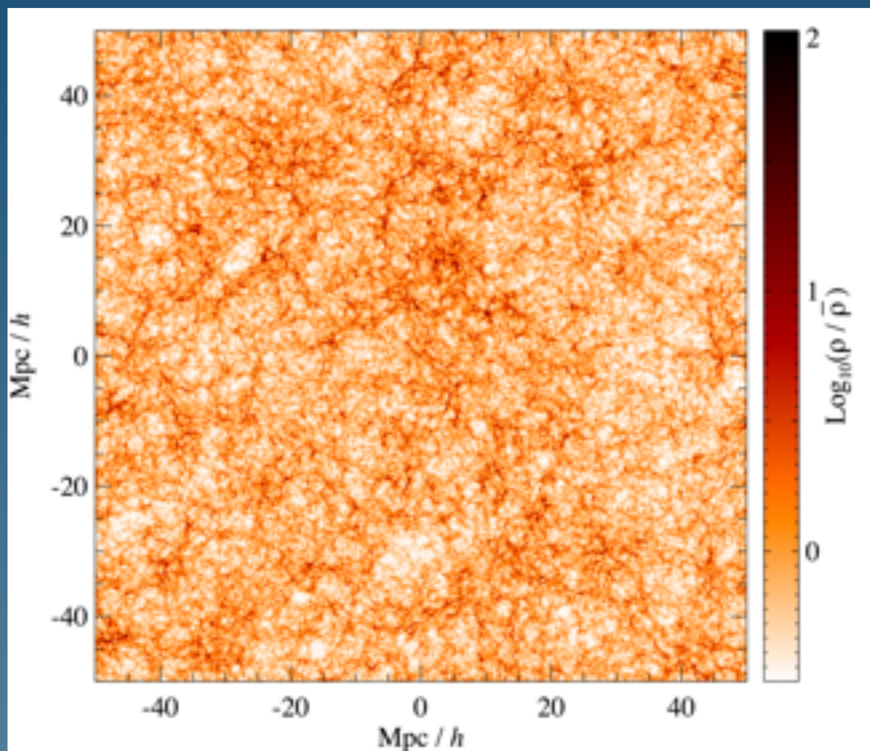
BTCL 2013



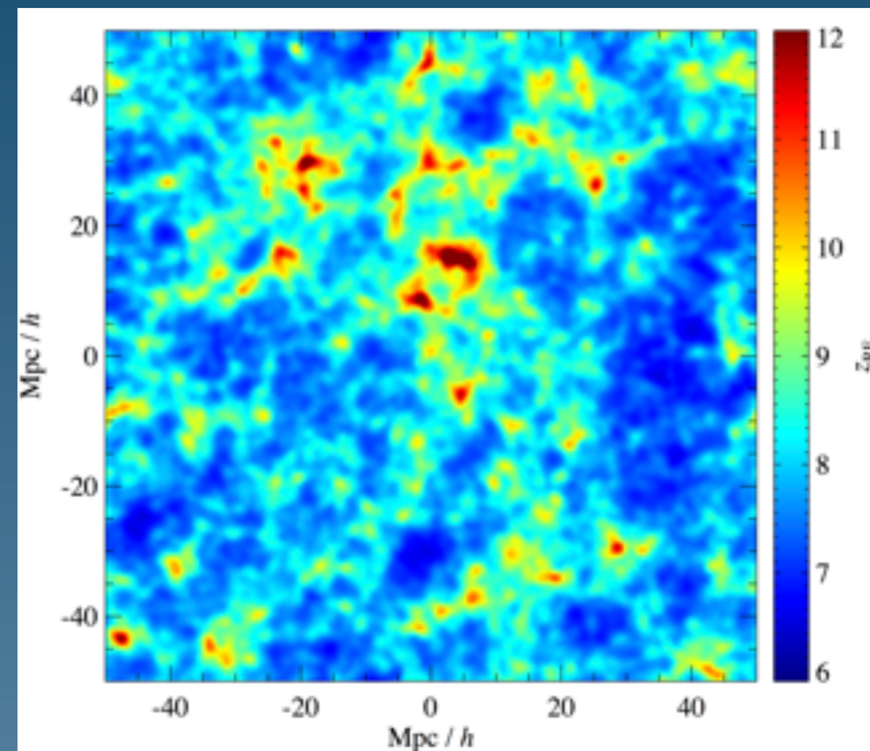
BTCL 2013

Wednesday, October 23, 13

The Model



$\otimes\ W_z \rightarrow$

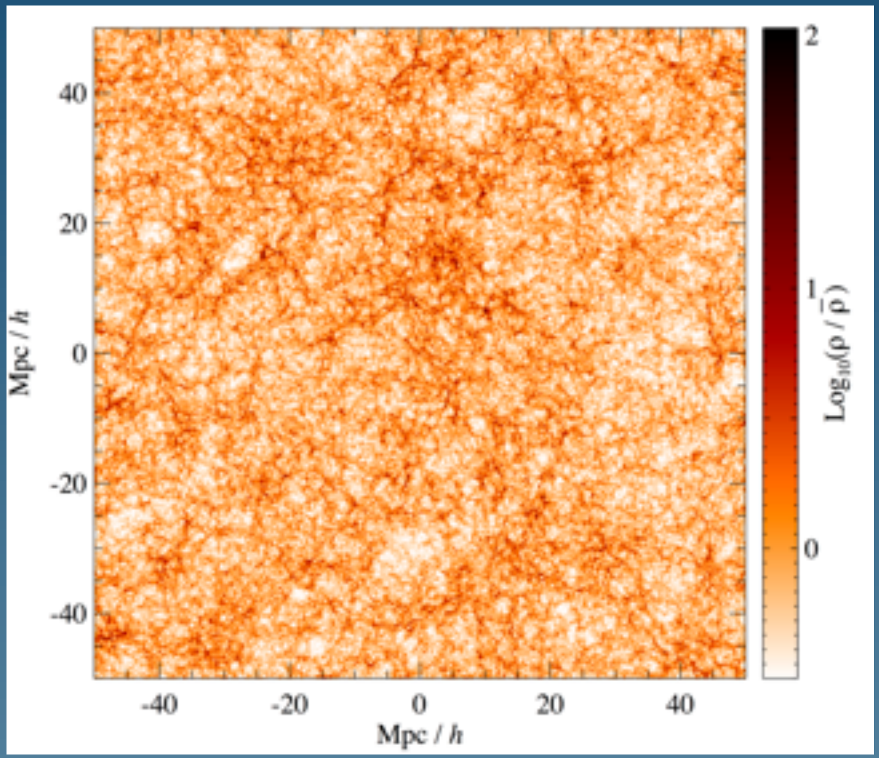


Built off of RadHydro

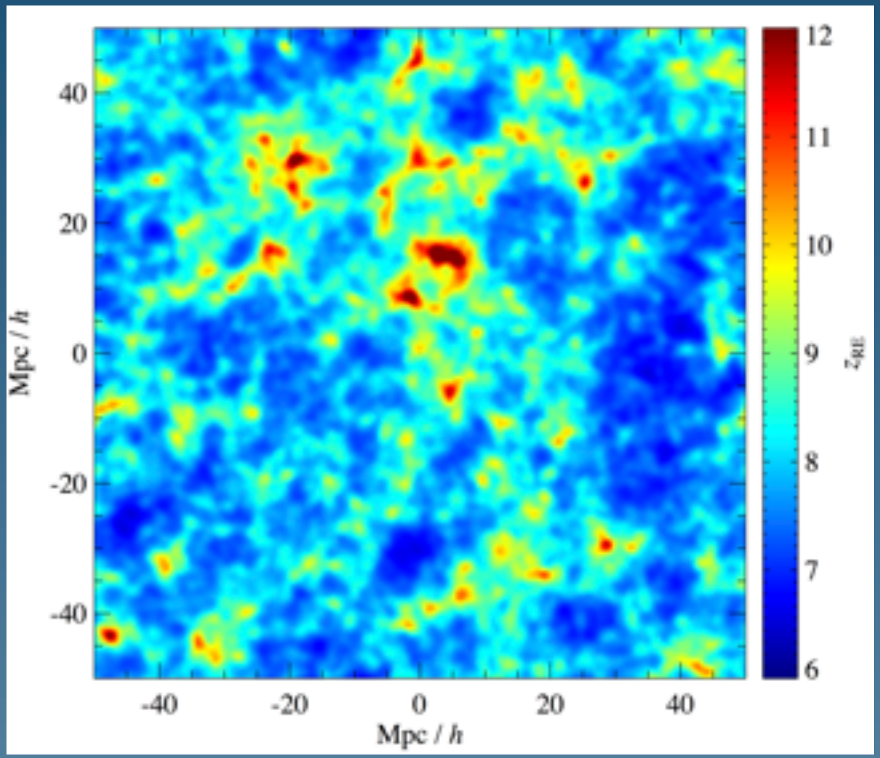
$$W_z(k) \equiv \frac{b_{mz}(k)\Theta(k)}{\Xi(k)}$$

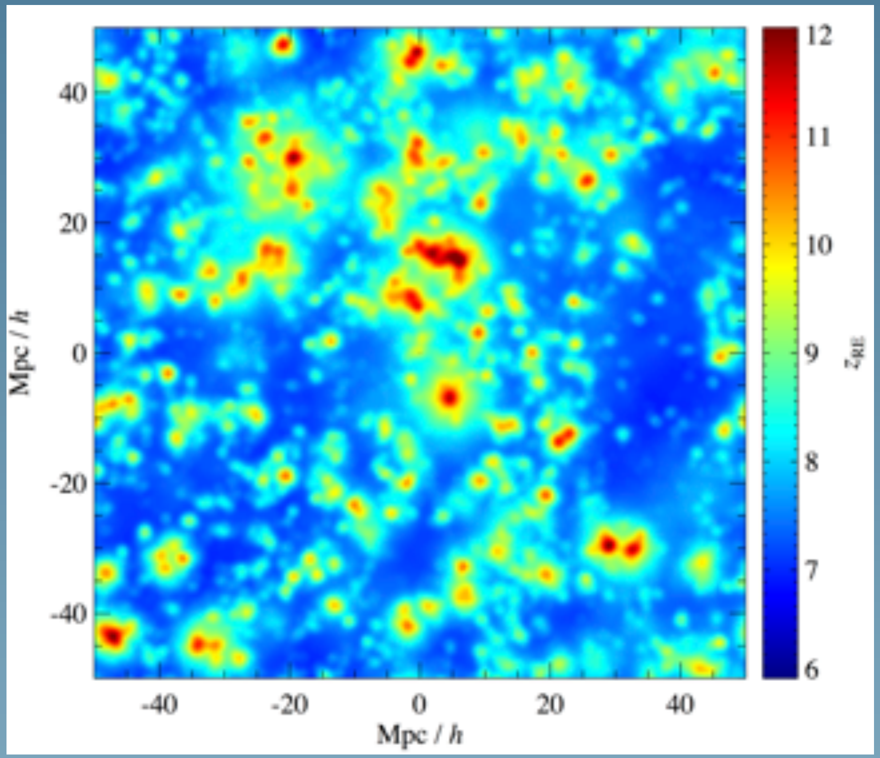
- Apply filter $W_z \rightarrow$
- Applicable to Large N-body
- Fast (just FFT)
- Parameter space exploration
- 3 parameters ($\bar{z}, k_o, \alpha$)

The Model



$\otimes W_z \rightarrow$





Built off of RadHydro

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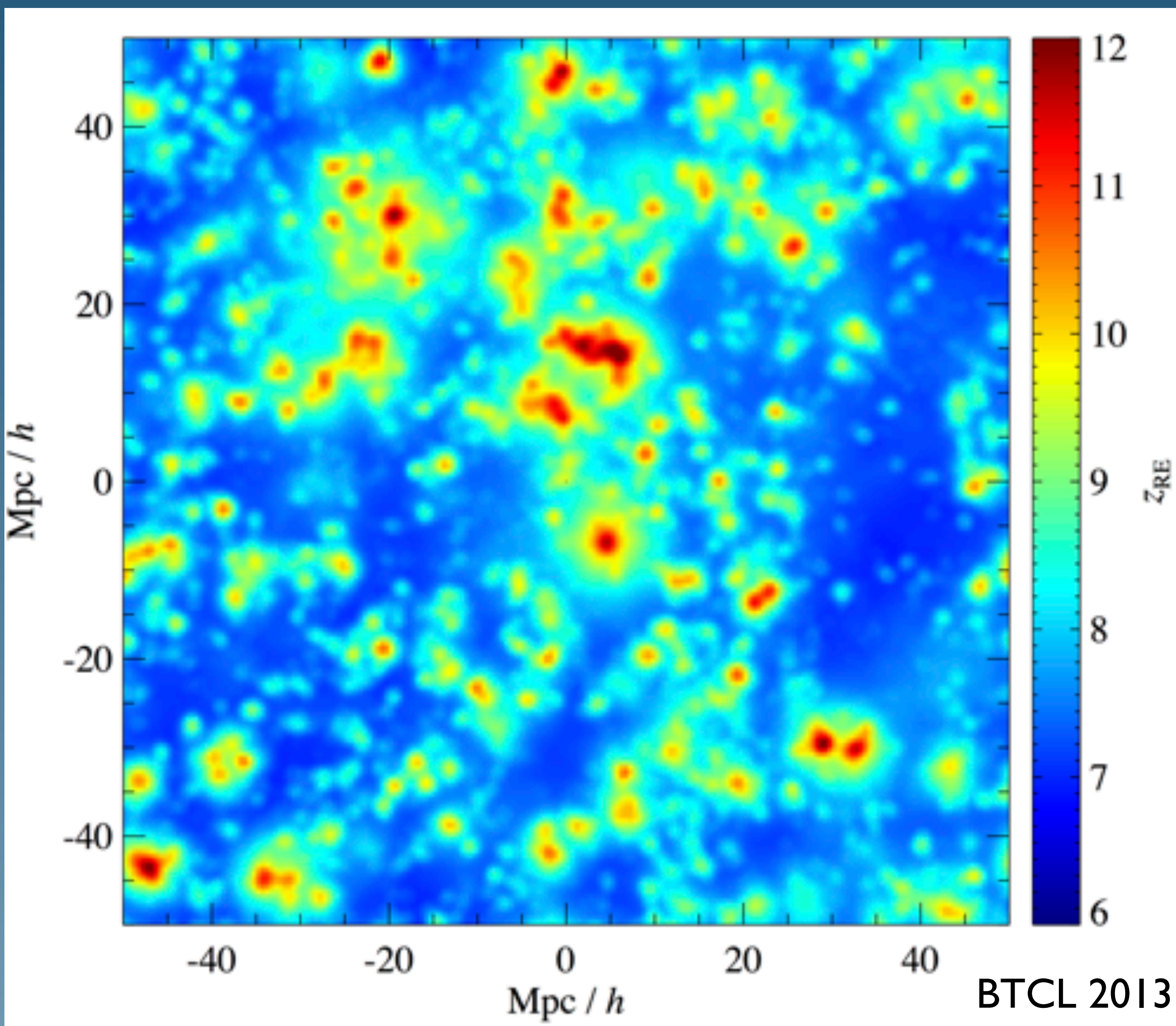
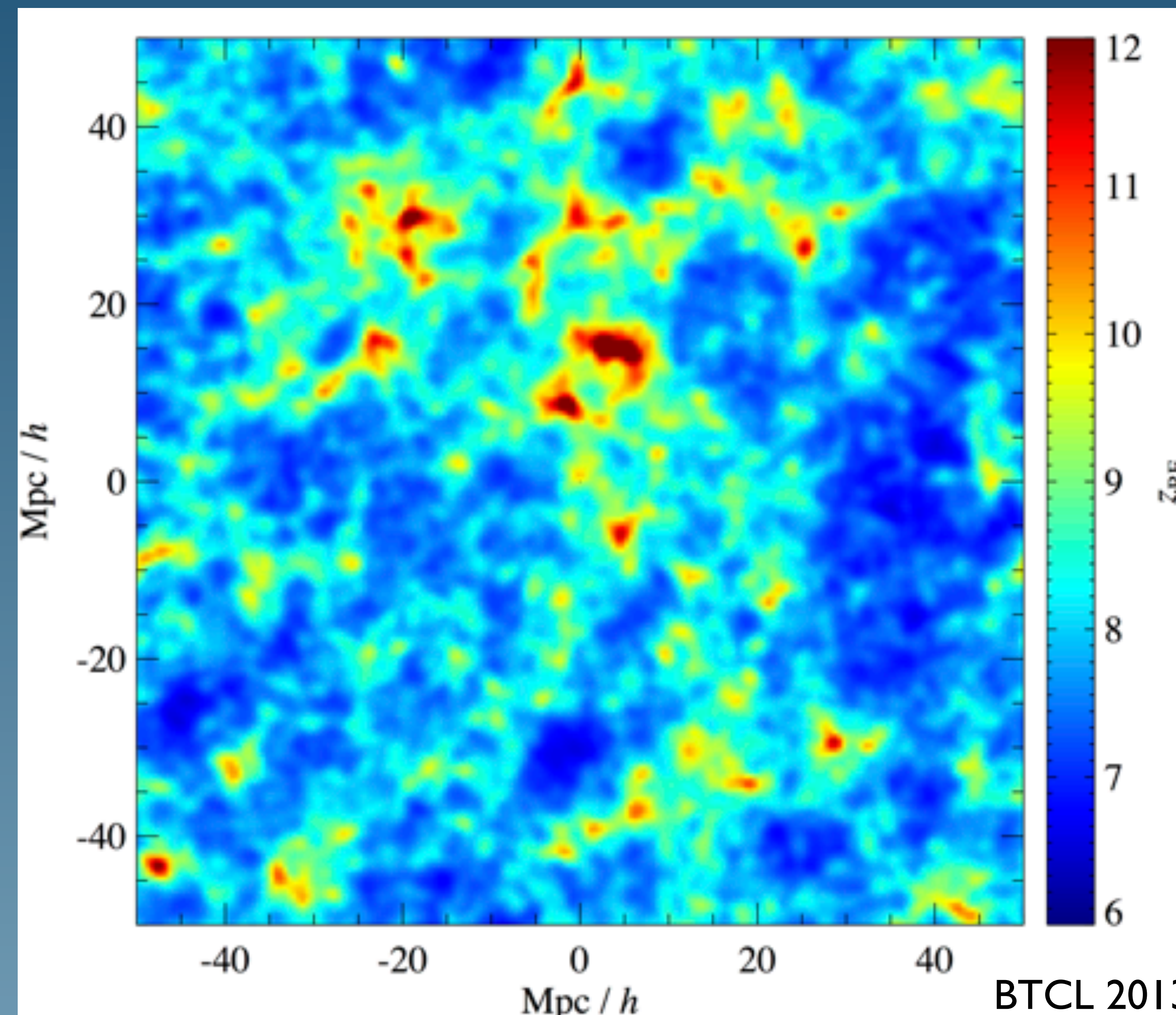
Model comparison



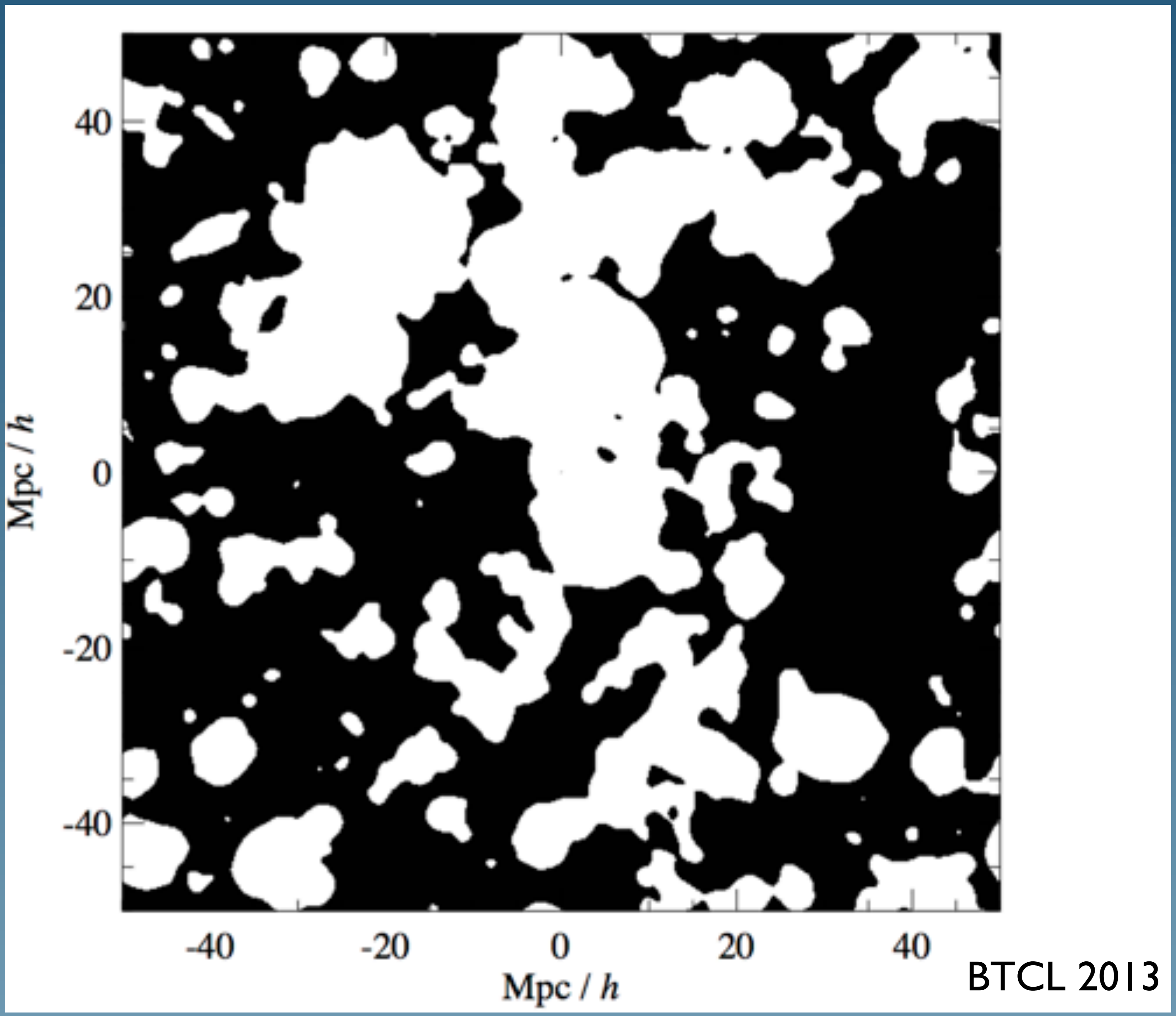
Simulation



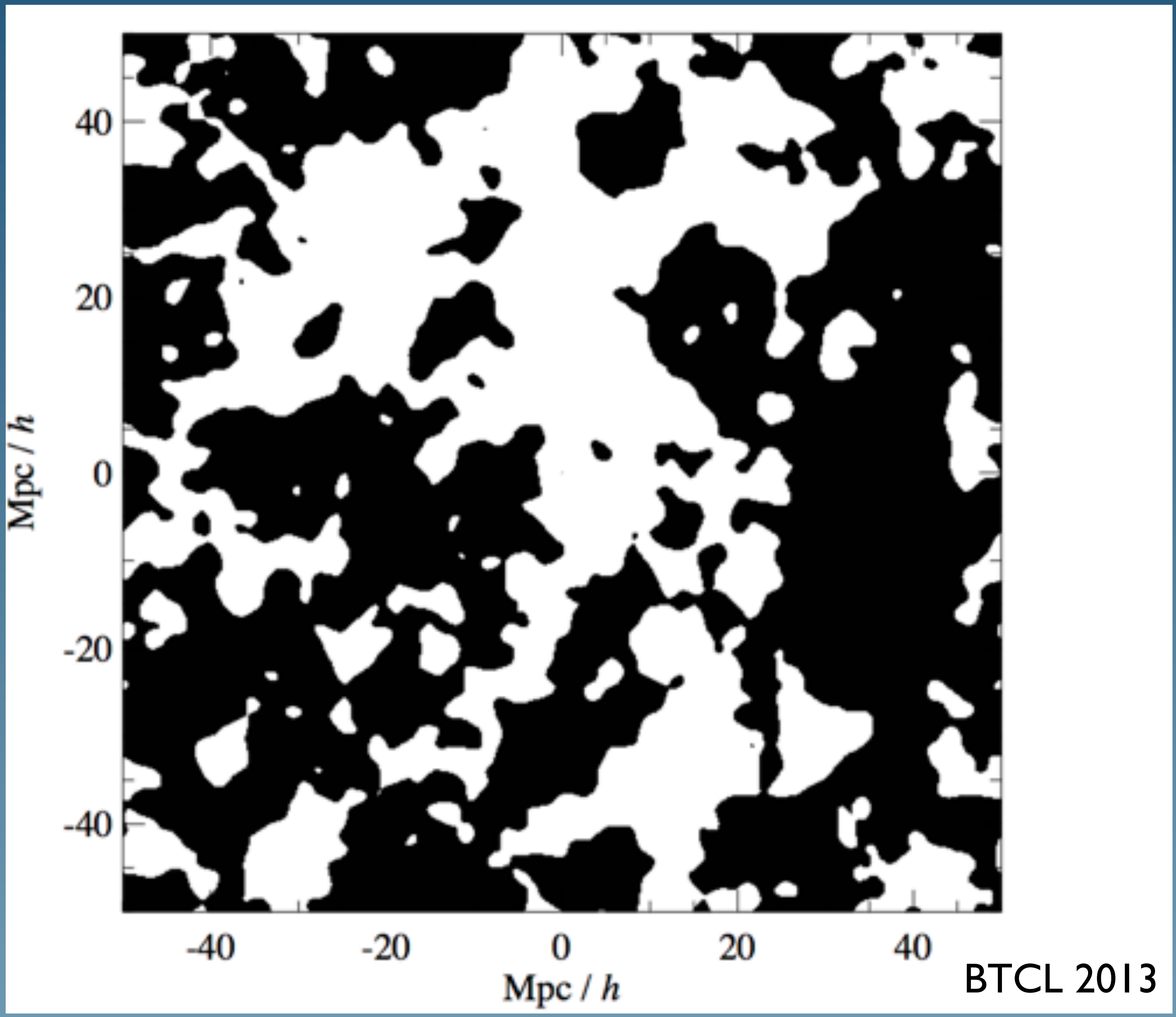
Model

Model comparison

Simulation

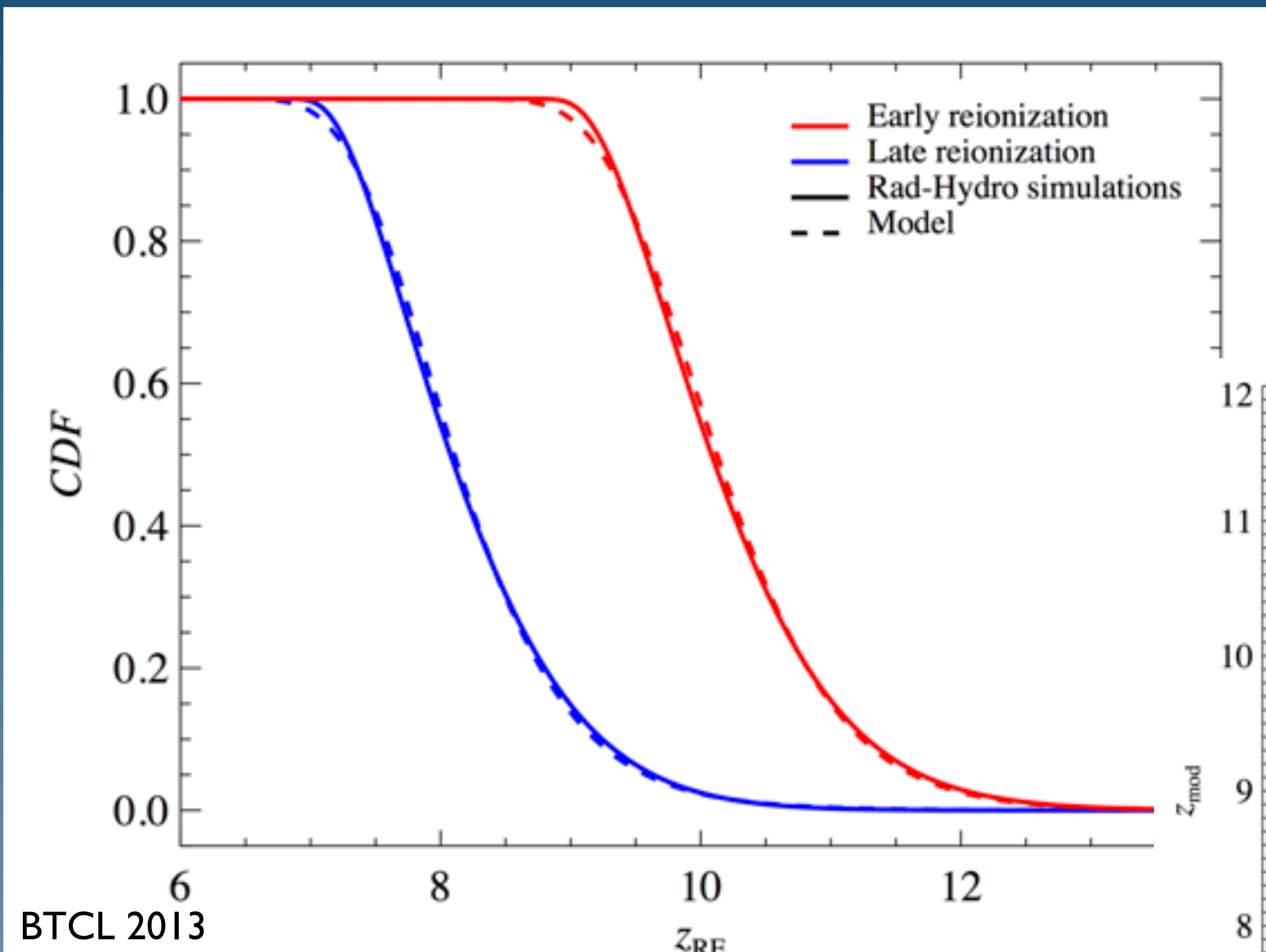


Model

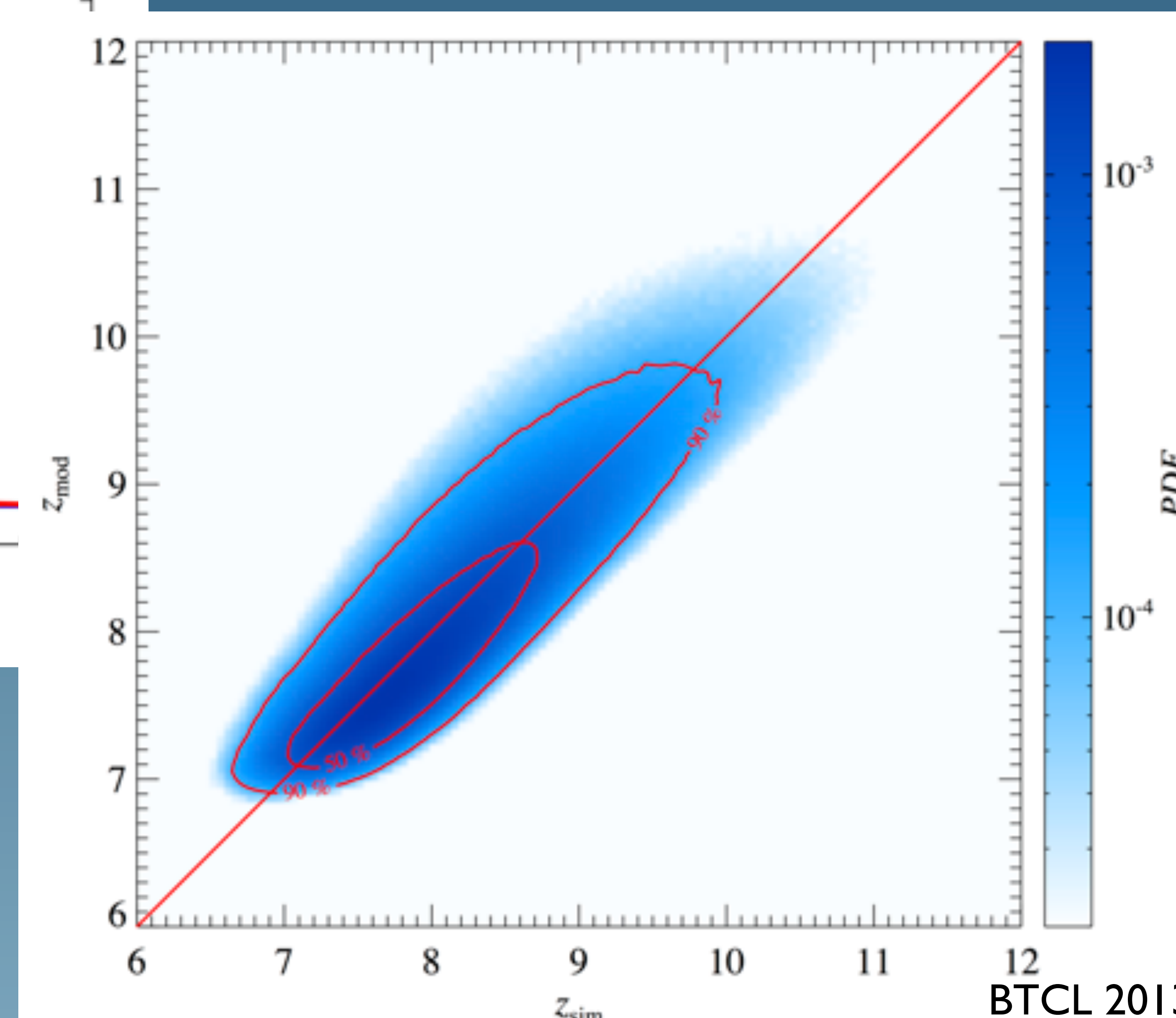


x_e (z = 8.1) ~ 50 % ionized

Model comparison

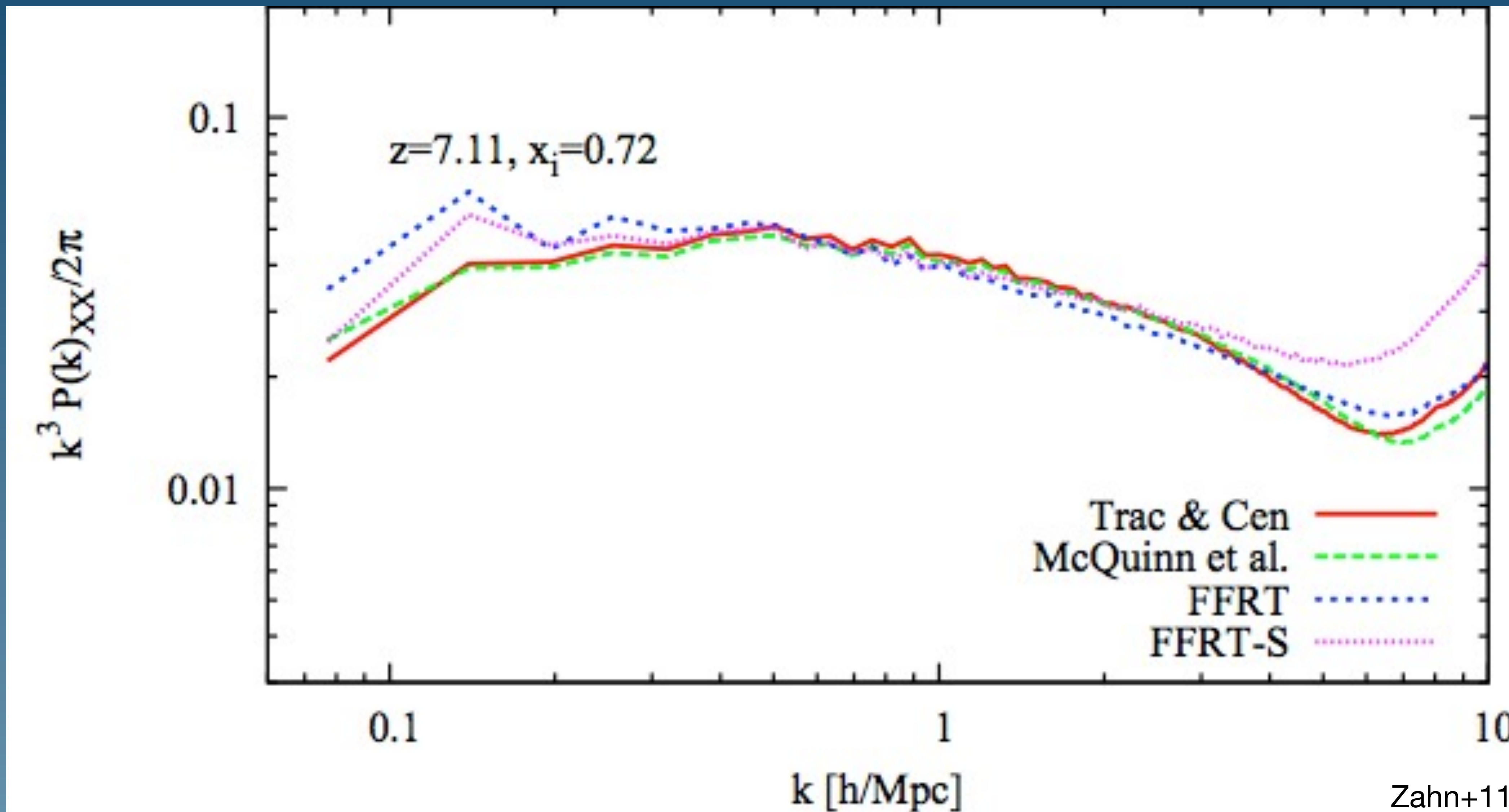


PDF & CDF



Matches well!

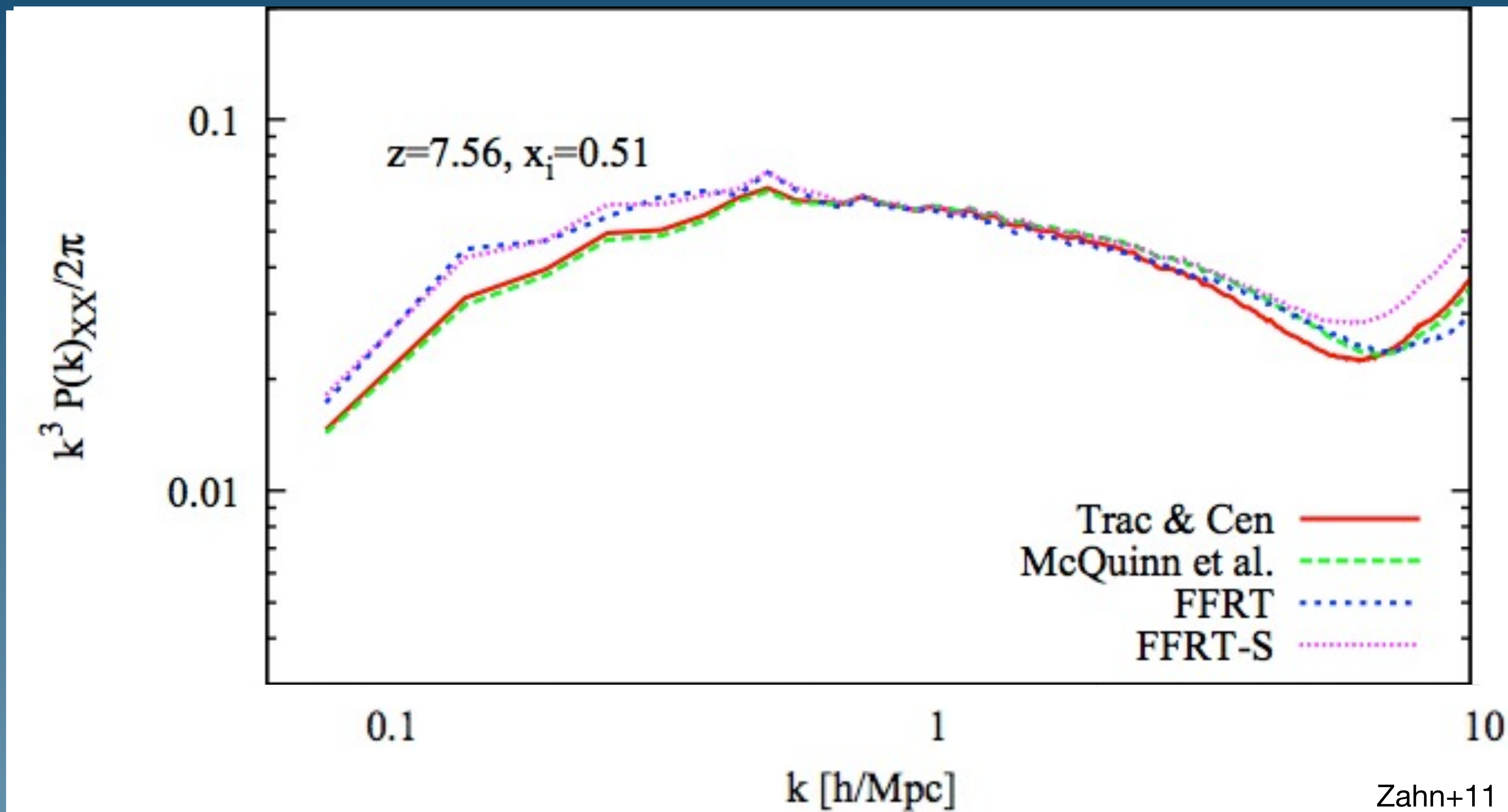
Model comparison



Statistical comparison of x_i fields

Fine tuned to match simulations...

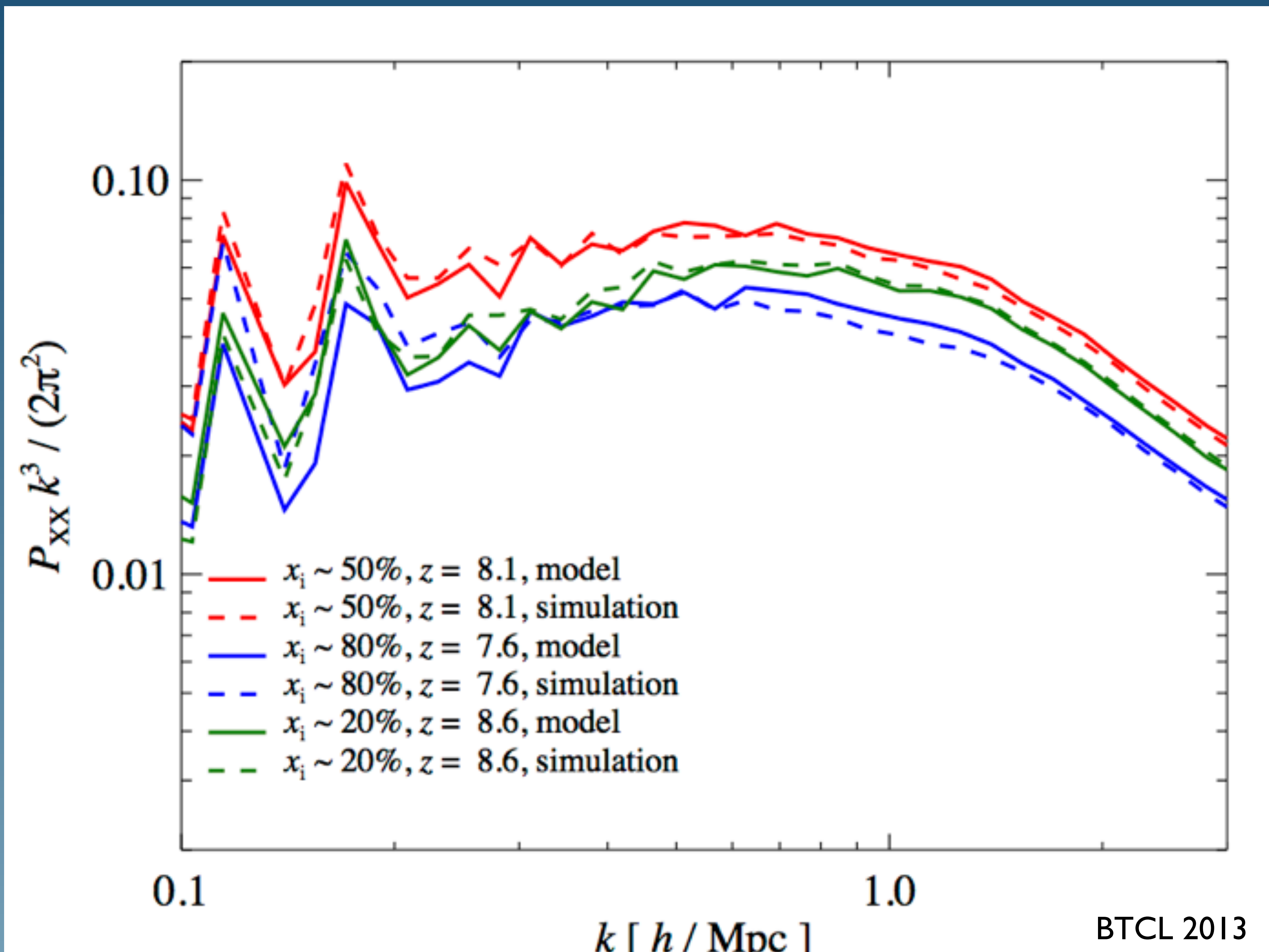
Model comparison



Statistical comparison of x_i fields

Fine tuned to match simulations...

Model comparison

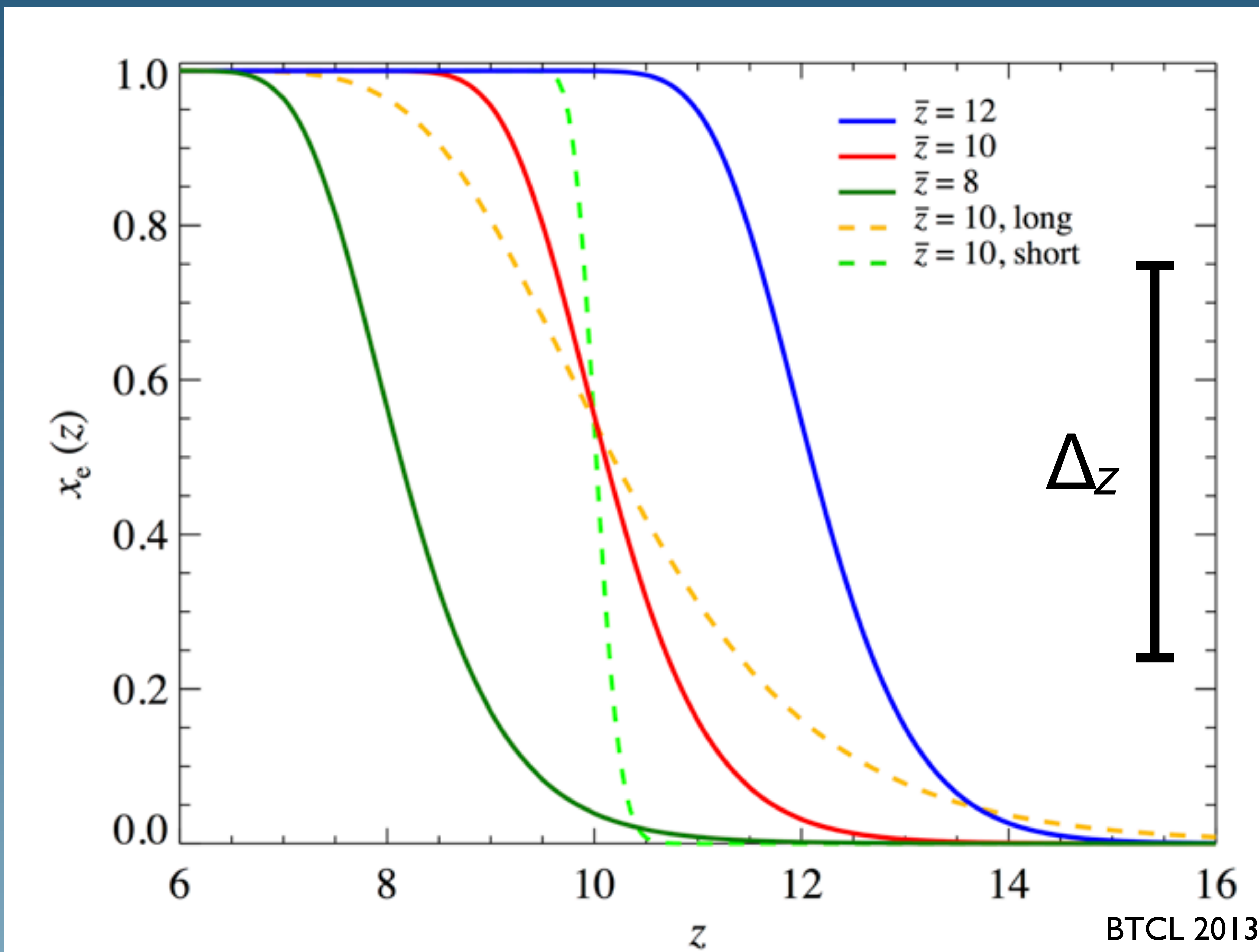


Matches well!

Without tuning!

Results - x_i (z)

Ionization history for all cells



5 models shown

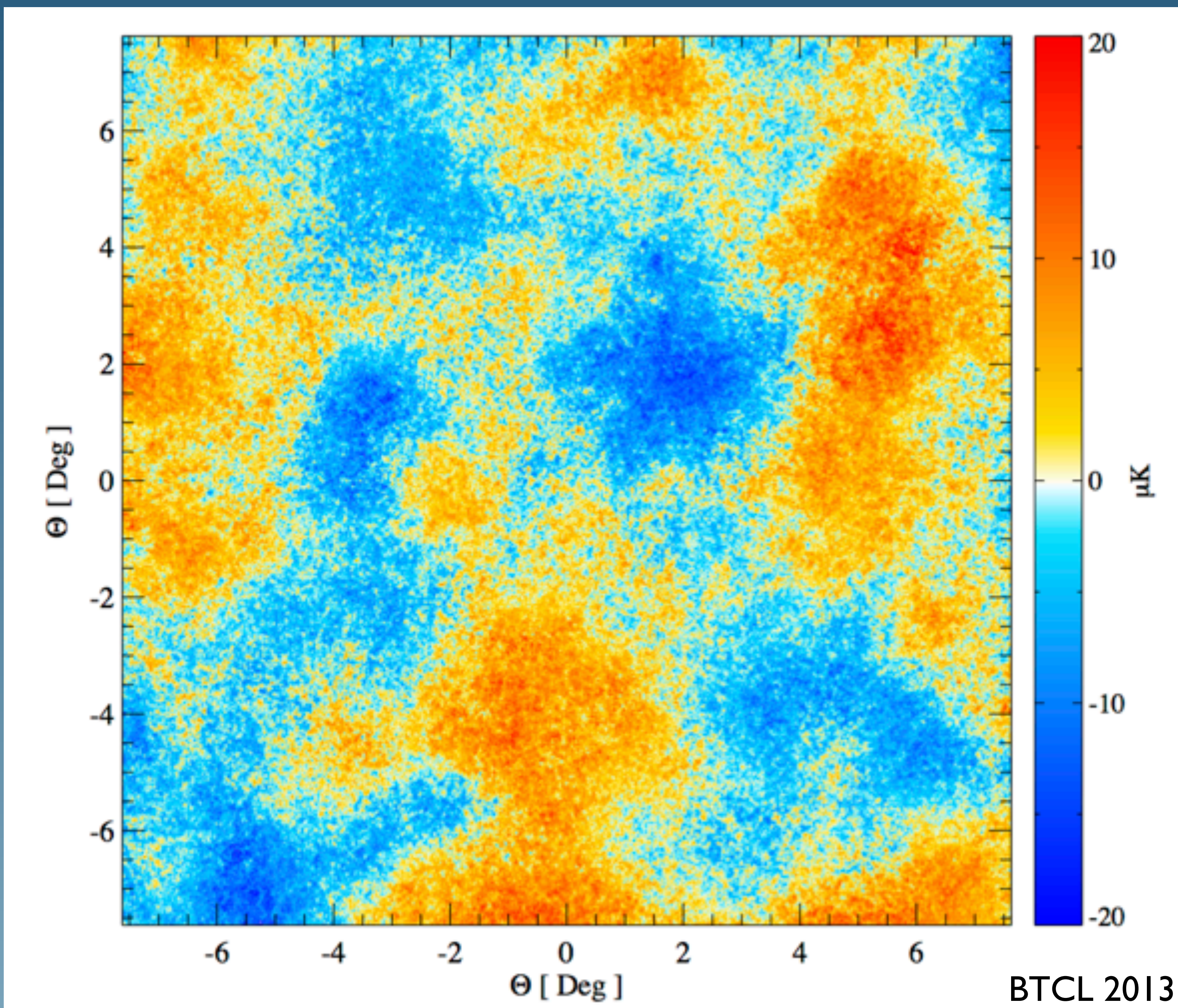
1. Fiducial
2. Long duration
3. Short duration

vary $\bar{z}$

$$b_{\mathrm{mz}}(k) = \frac{b_o}{(1 + k/k_o)^{\alpha}}$$

kSZ Observables

Integrated maps, e.g. kSZ



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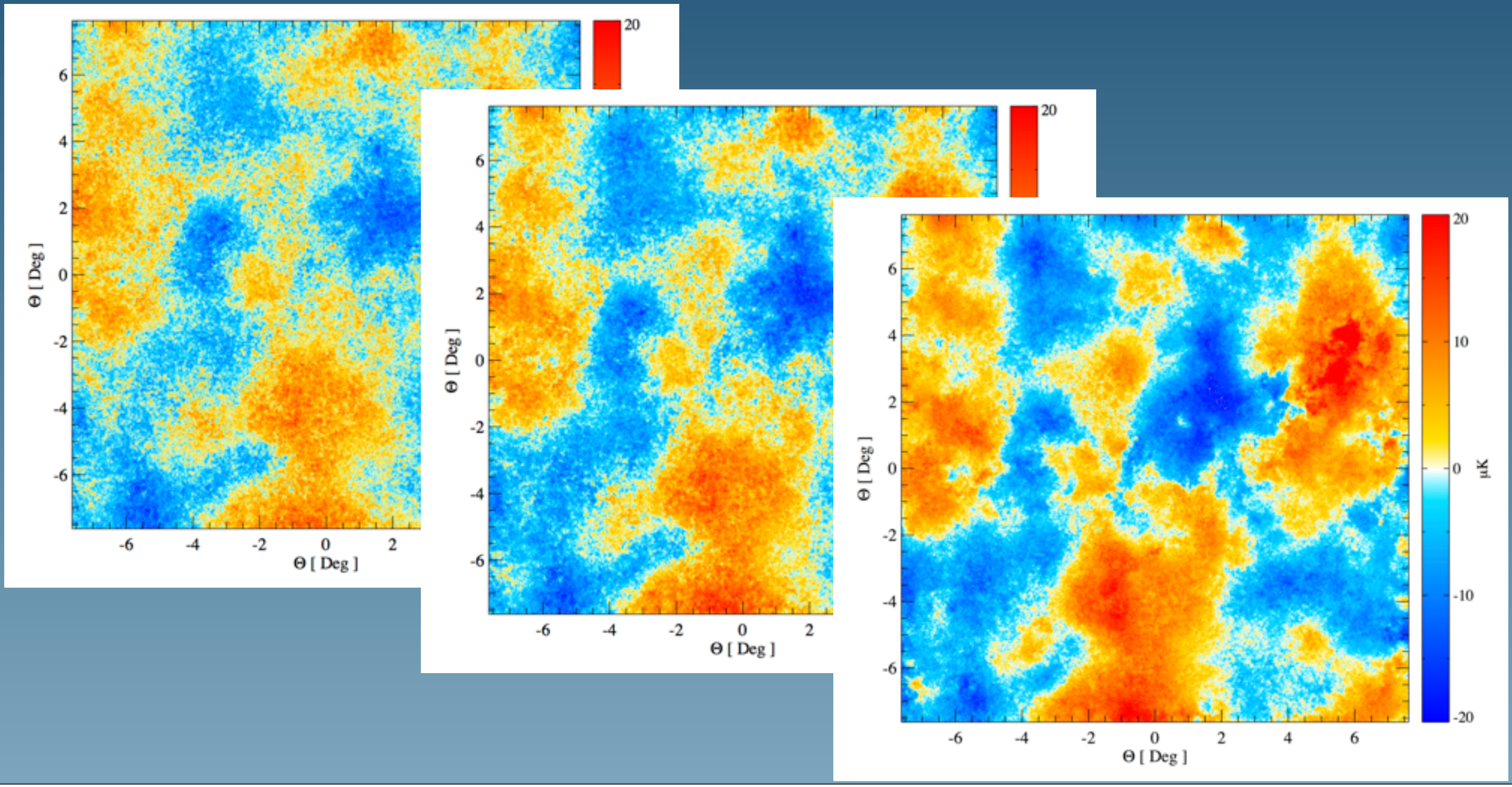
Construct “proper” light cones

3 realizations per model

integrate from $z > 5.5$

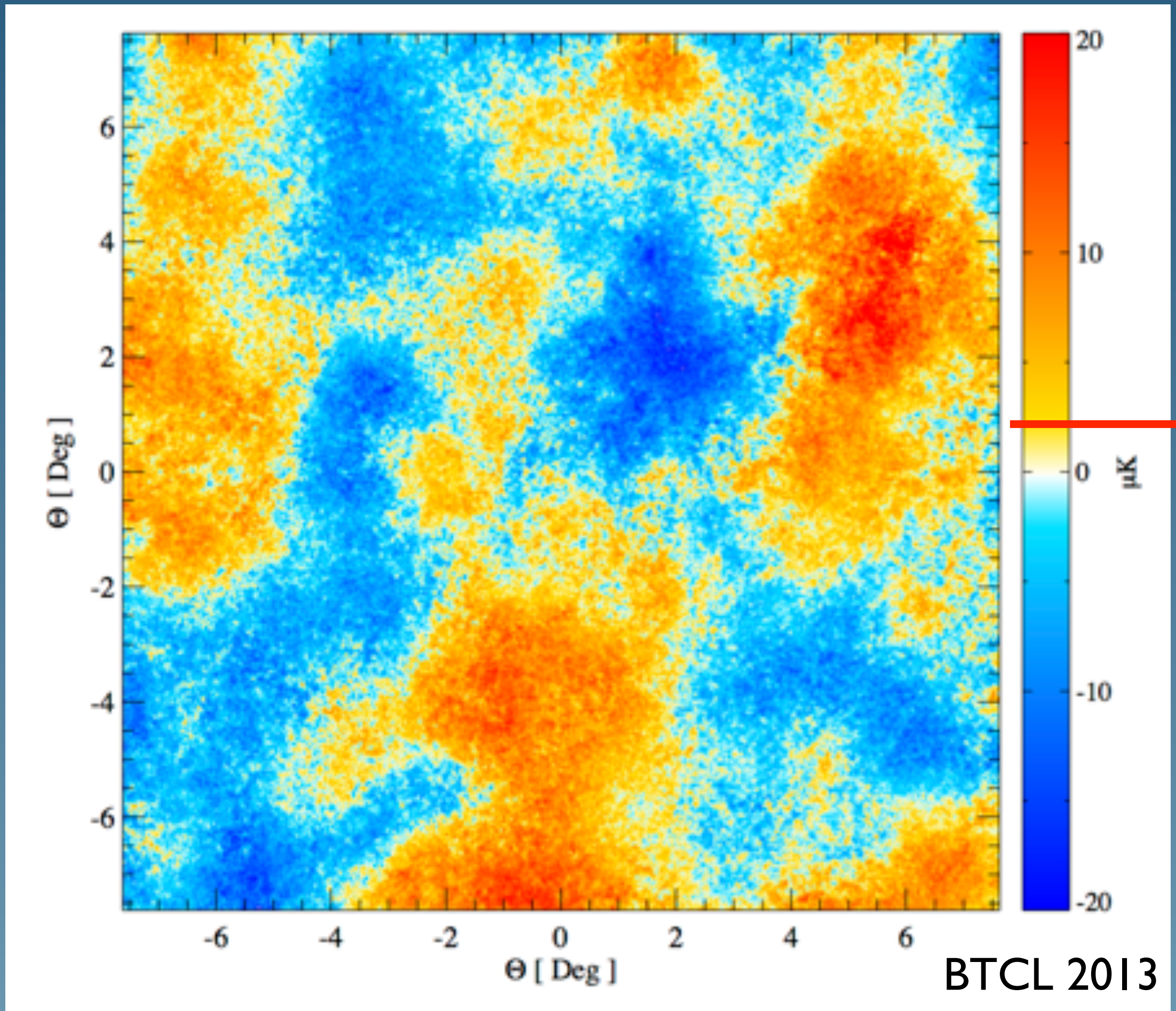
kSZ Observables

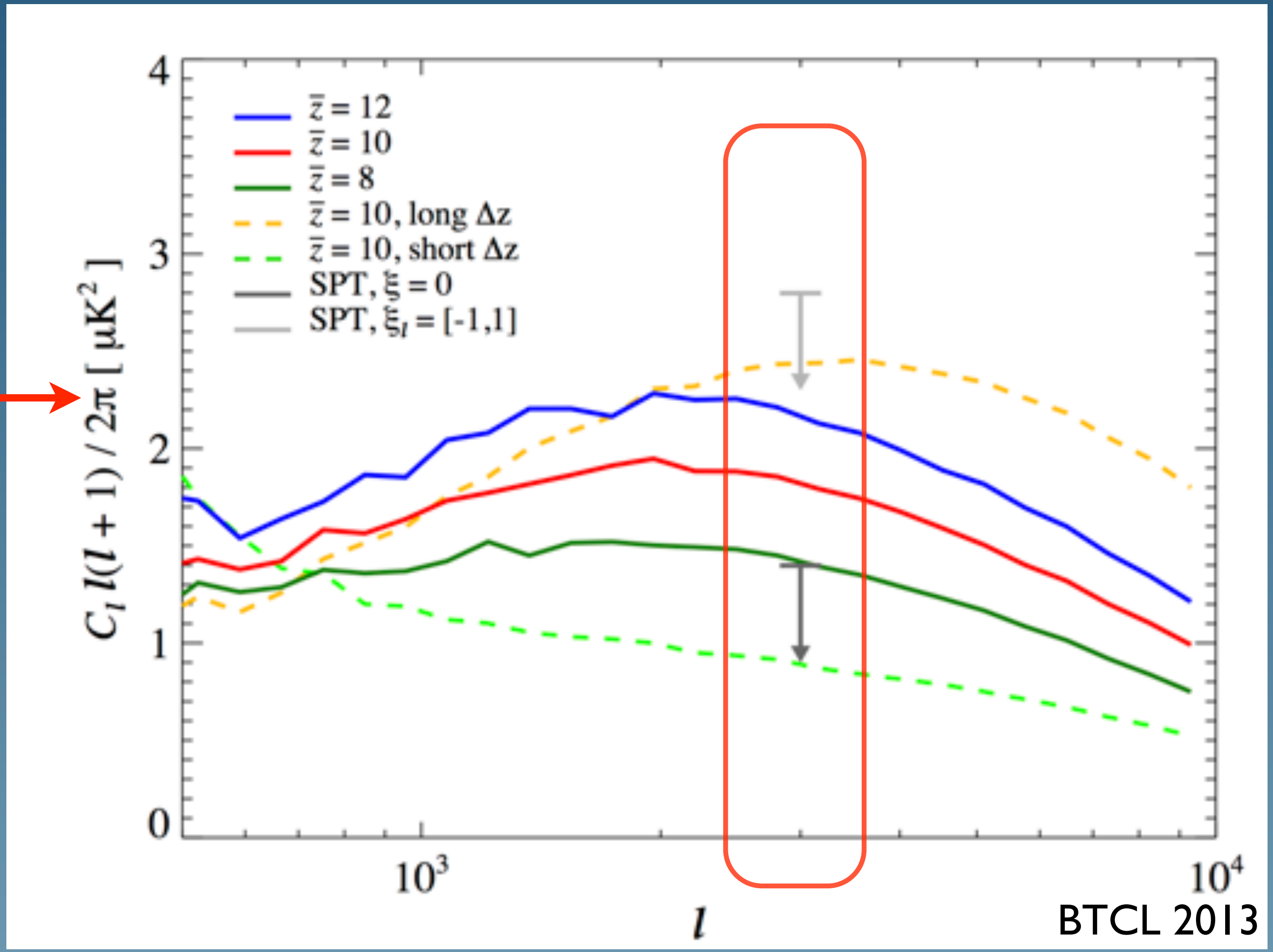
Integrated maps, e.g. kSZ



kSZ Observables

Integrated maps, e.g. kSZ





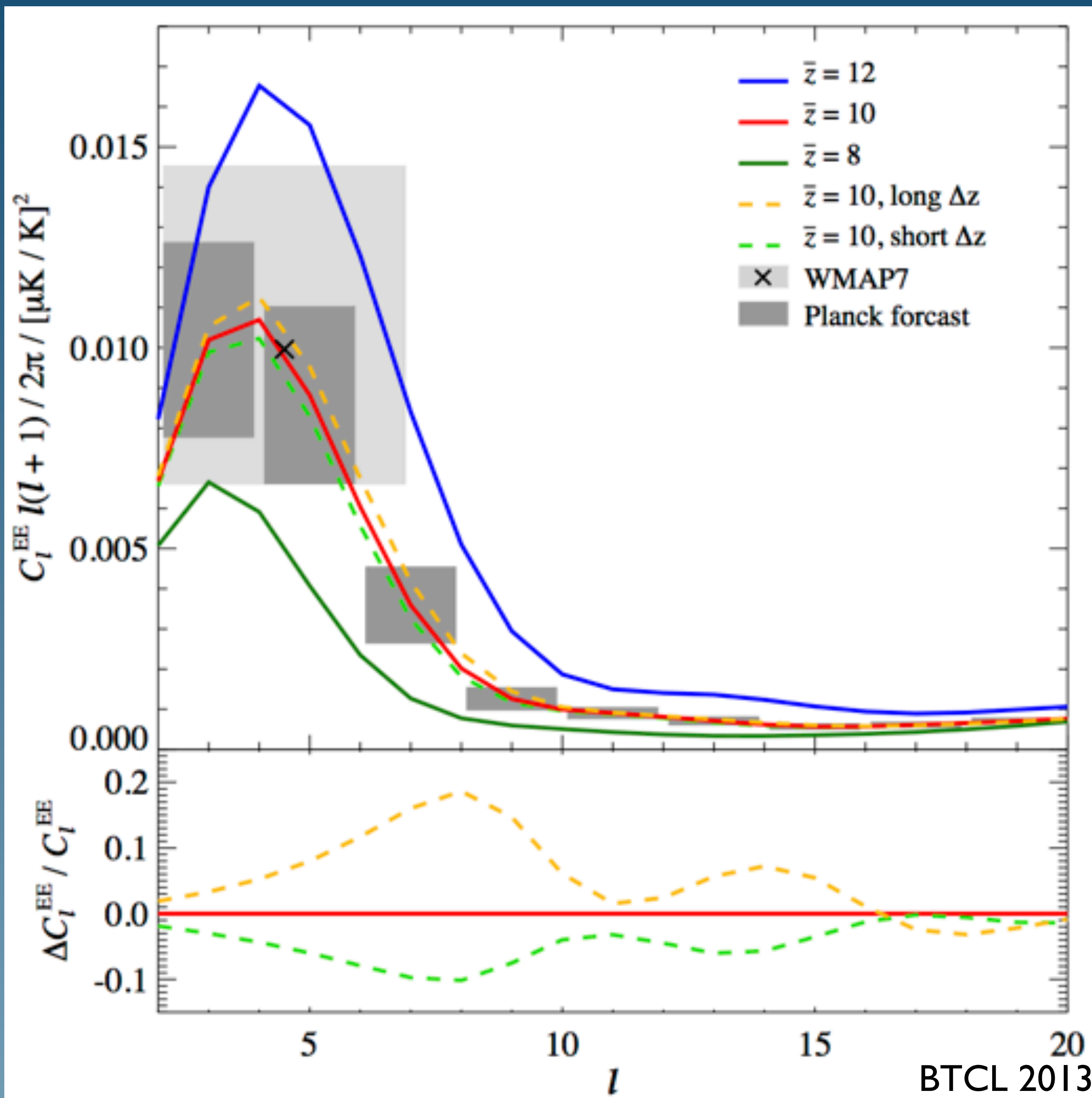
patchy kSZ power spectrum

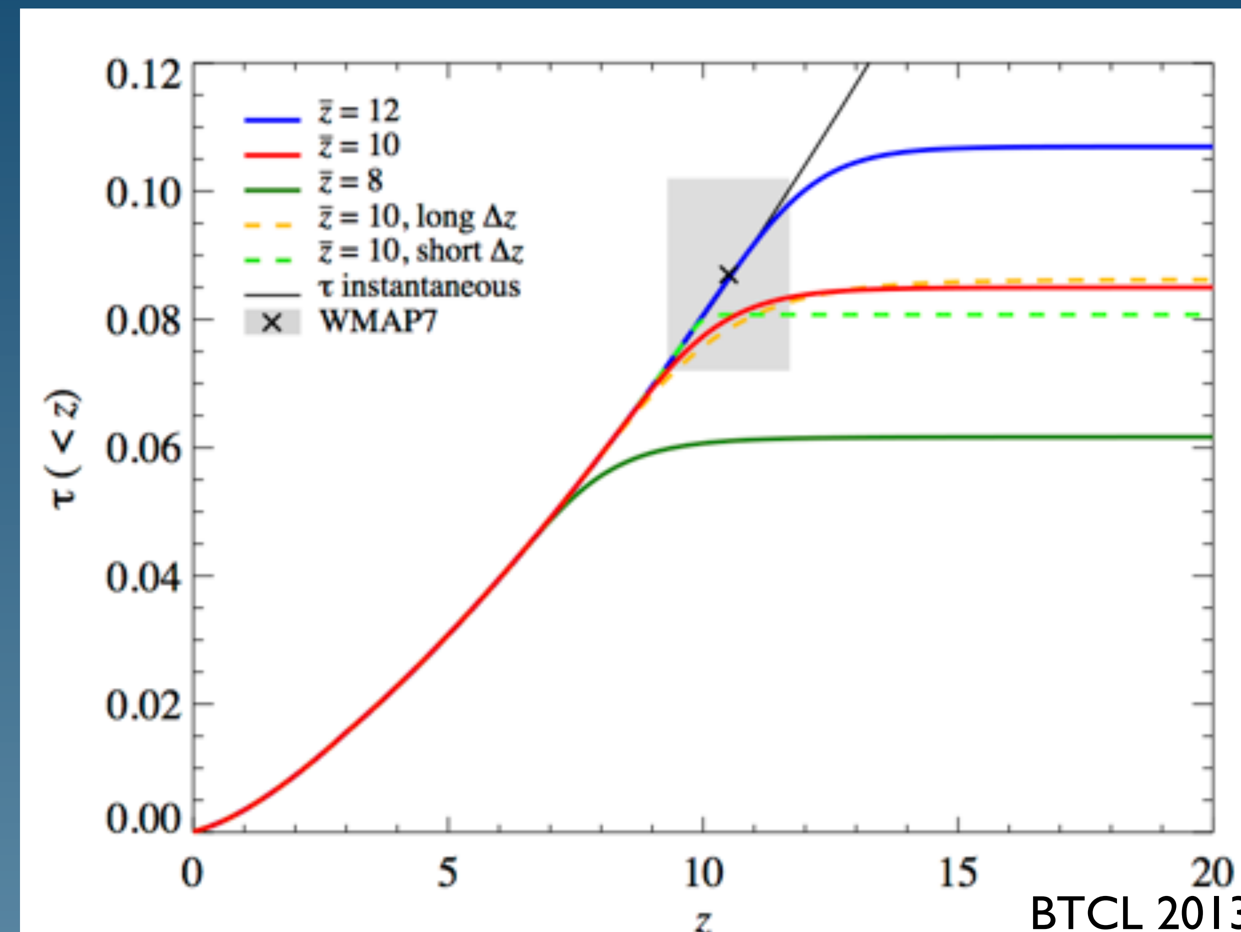
typical power ~1-2 μK^2

sensitive to both $\overline{z}$ and Δ_z

(Zhan+12; Messinger+12)

CMB polarization





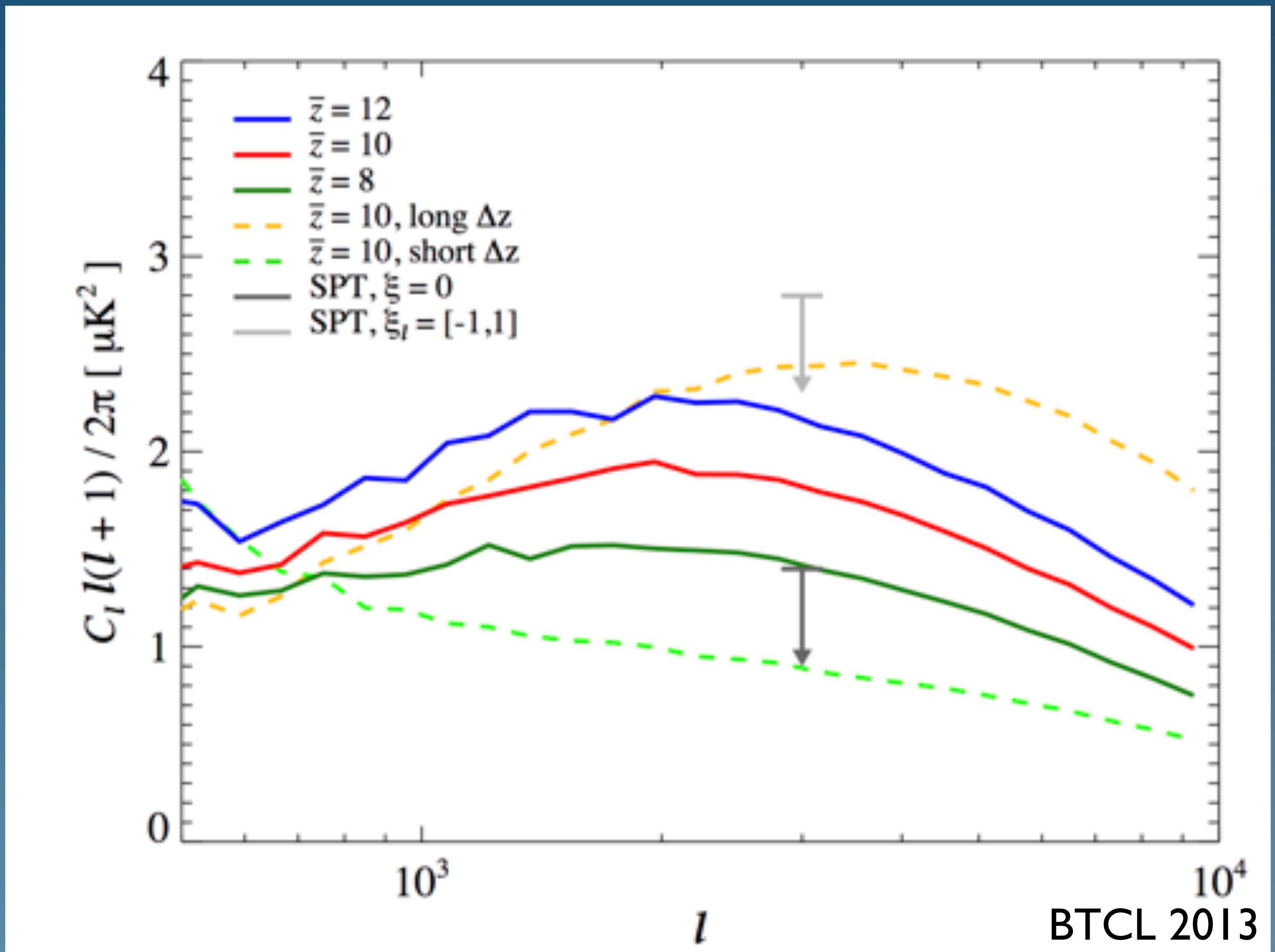
Scattering of CMB γ

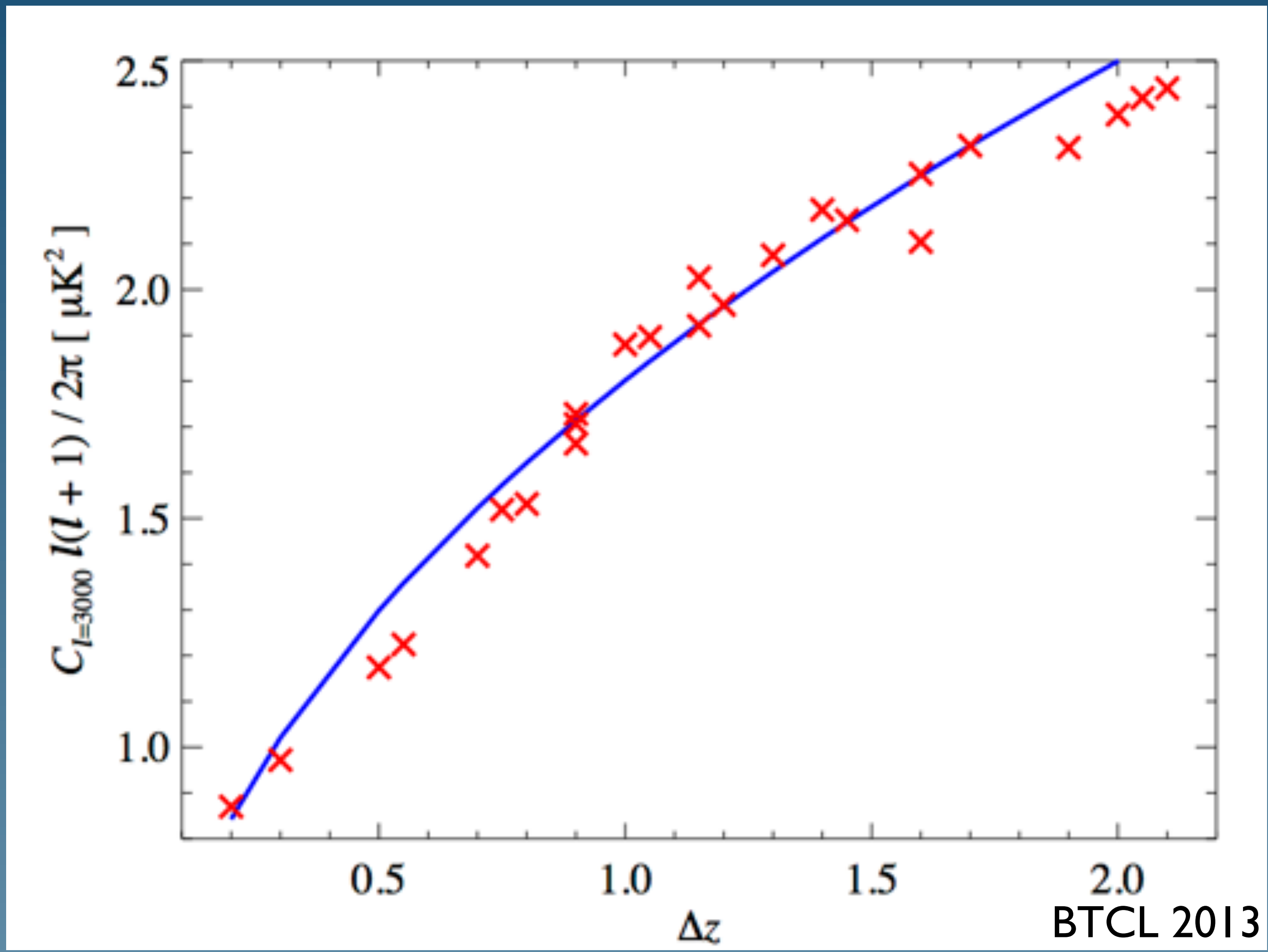
τ & EE power spectrum

sensitive to $\bar{z}$, not to Δ_z

Modify CAMB (Mortonson & Hu 10)

kSZ Fitting Function





$$D^{\rm kSZ}_{\ell=3000} \simeq 2.02\mu{\rm K}^2 \left[\left(\frac{1+\bar{z}}{11}\right) - 0.12\right]\left(\frac{\Delta_z}{1.05}\right)^{0.47}$$

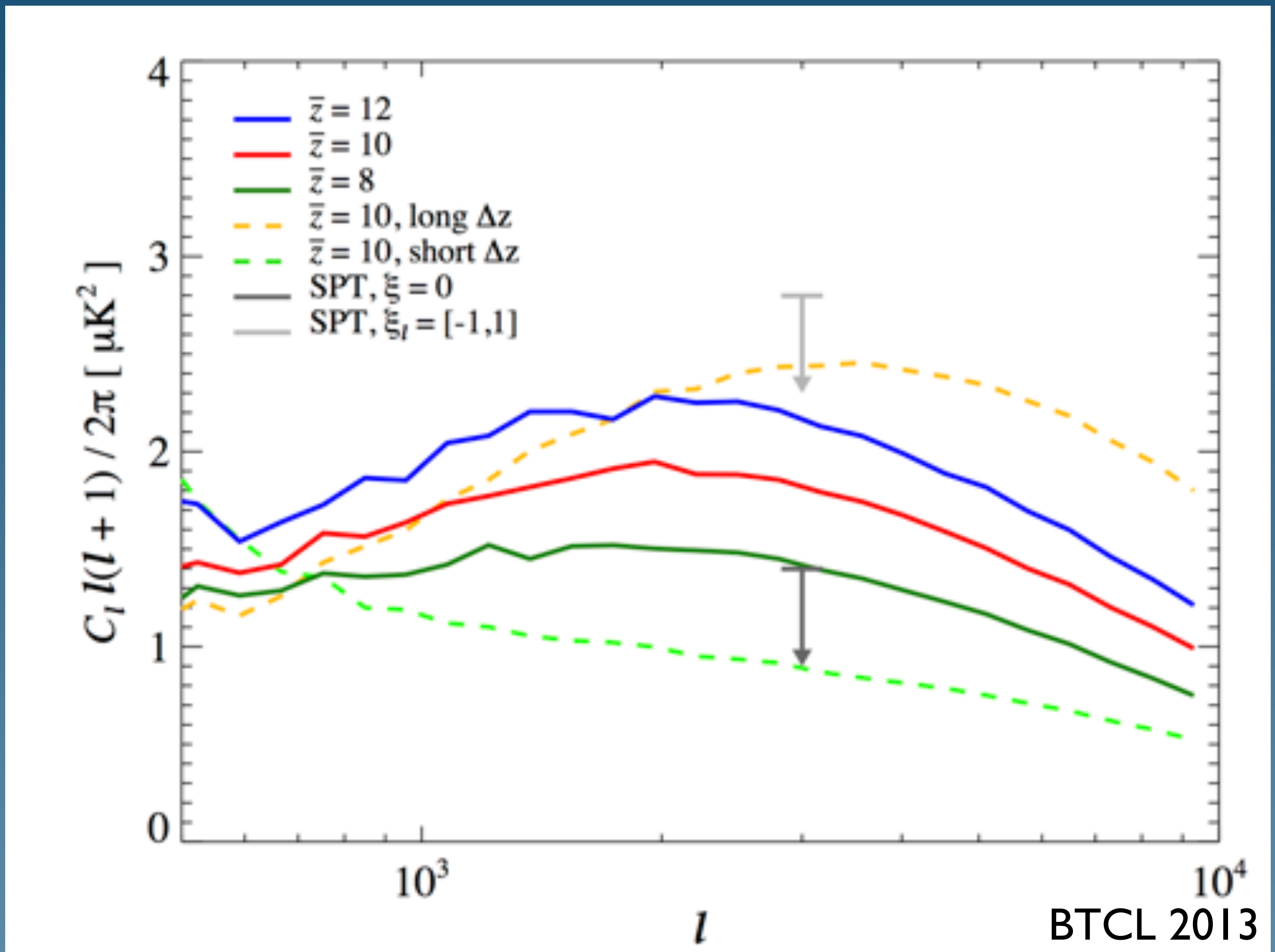
- Recent constraints from ACT & SPT

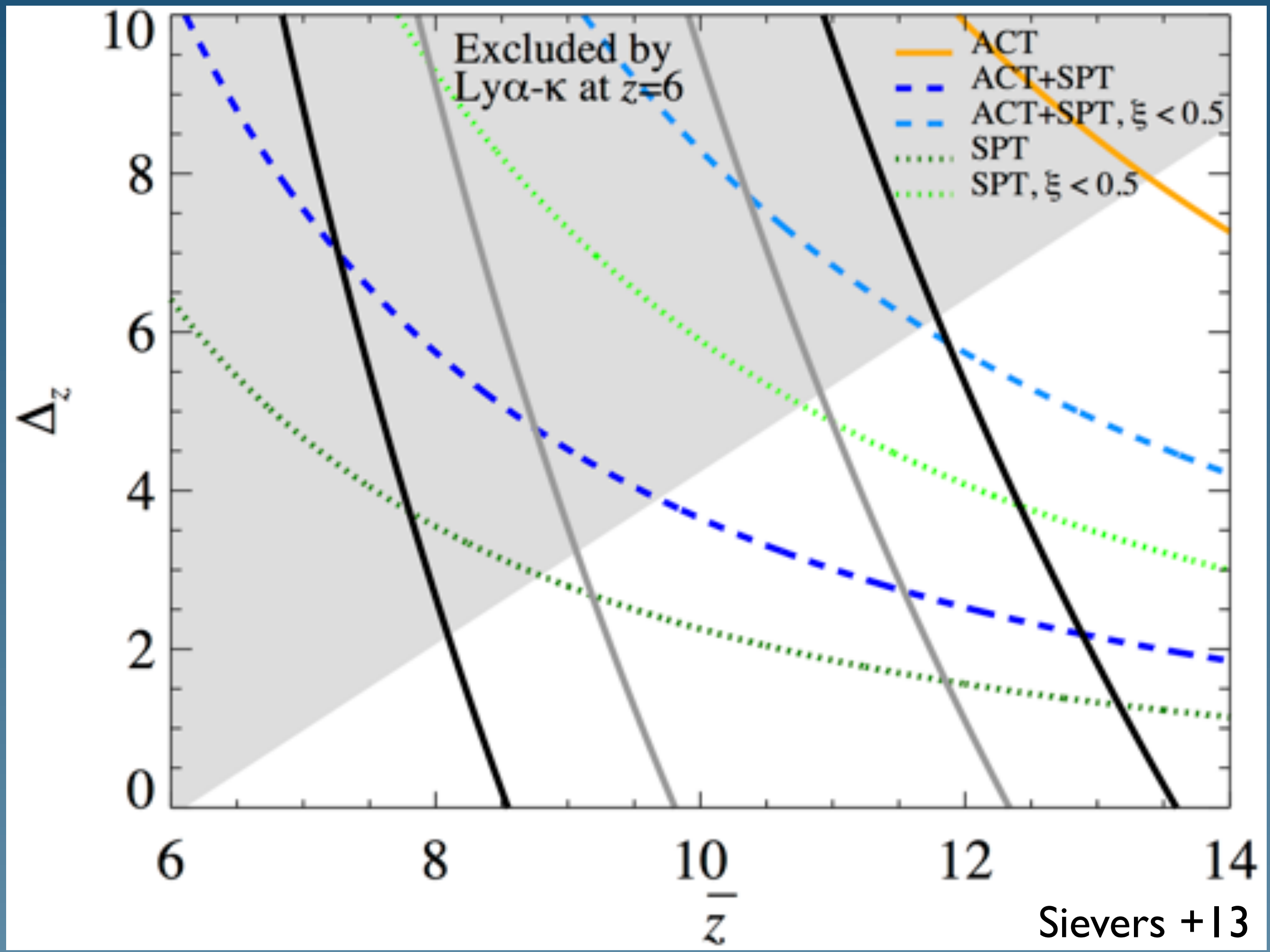
(Sievers +13, Zahn +12)

Caveats...

(Park+13)

kSZ constraints



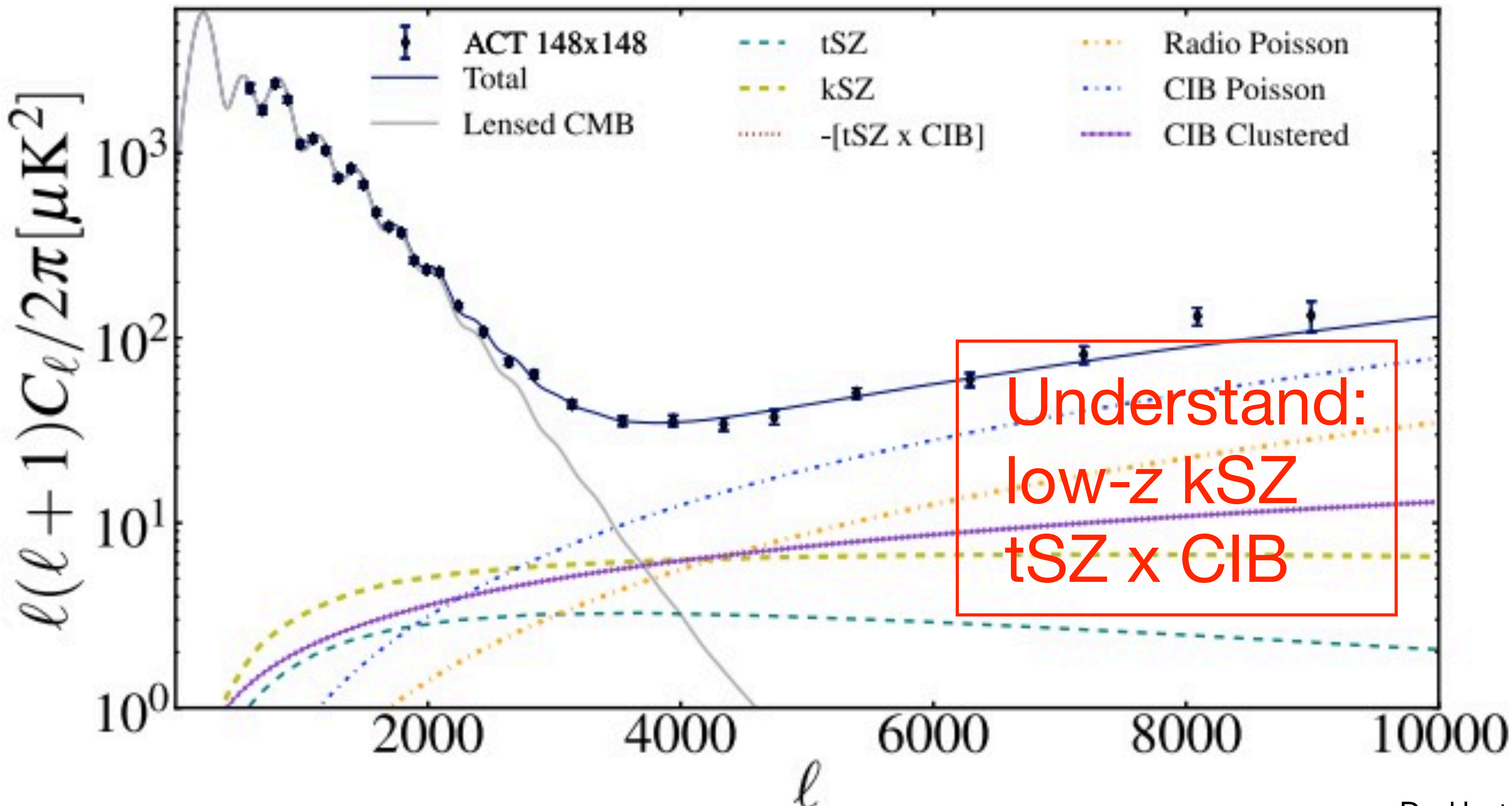


- Recent constraints from ACT & SPT

(Sievers +13, Zahn +12)

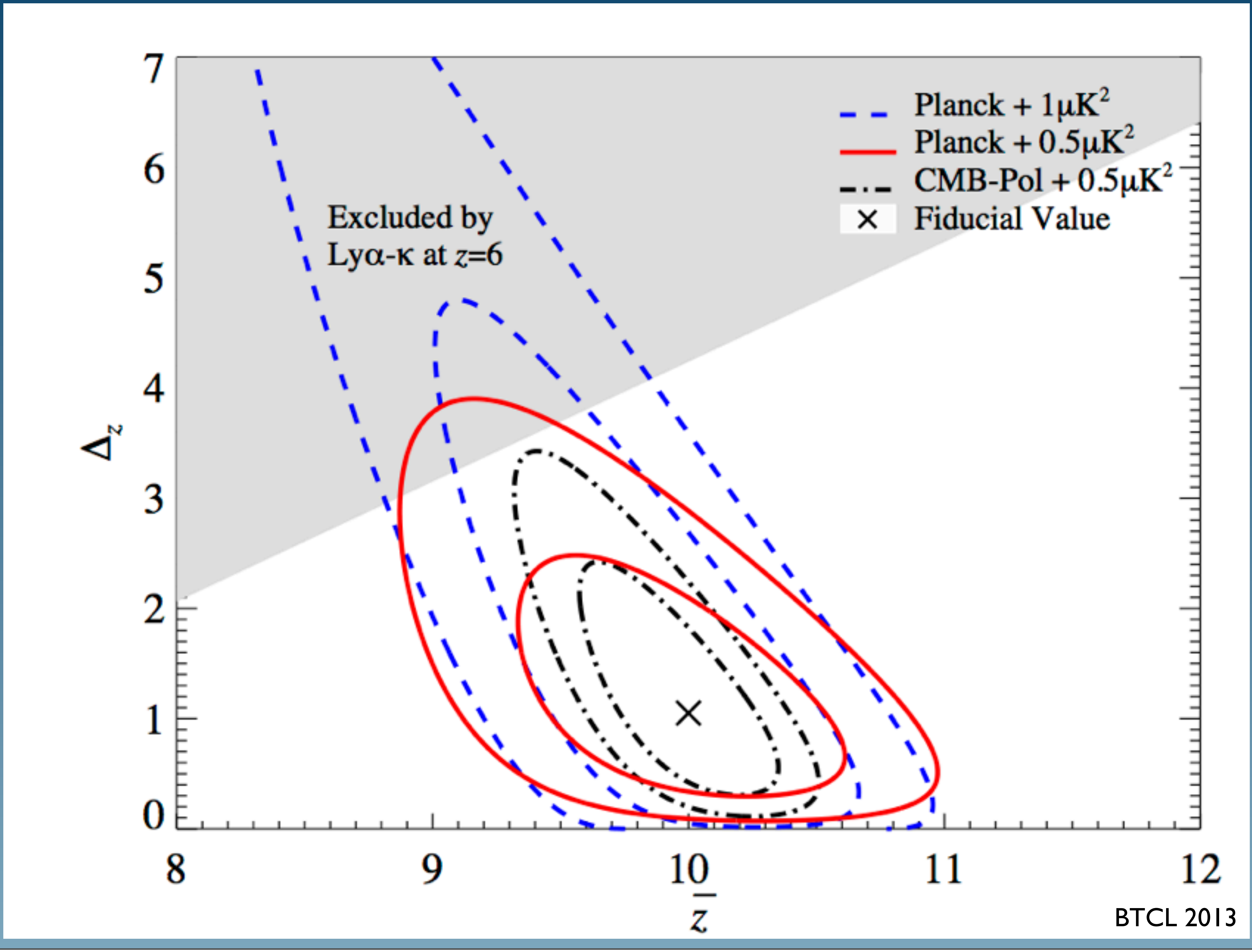
Understand:
low-z kSZ
tSZ x CIB

kSZ constraints

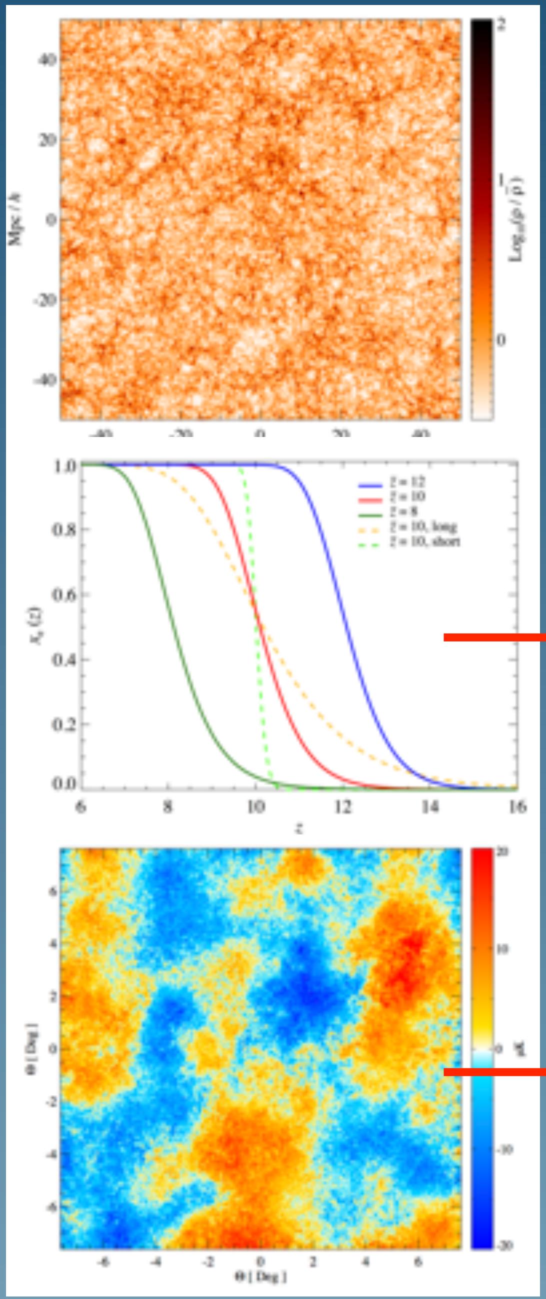


Dunkley+13

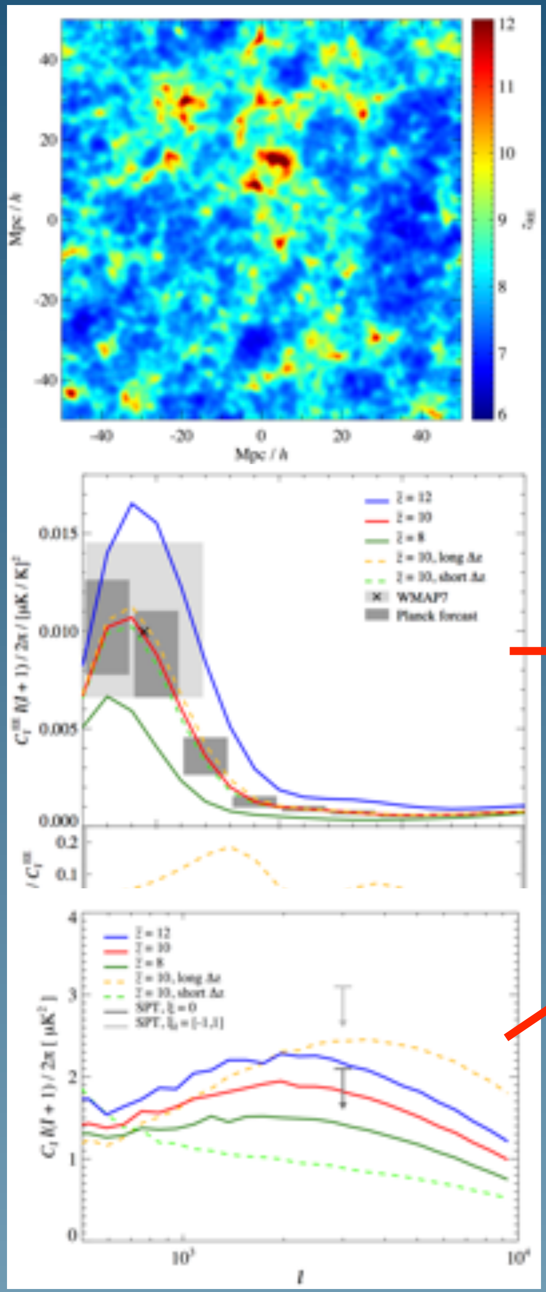
Planck + ACTPol + SPT-POL + ...



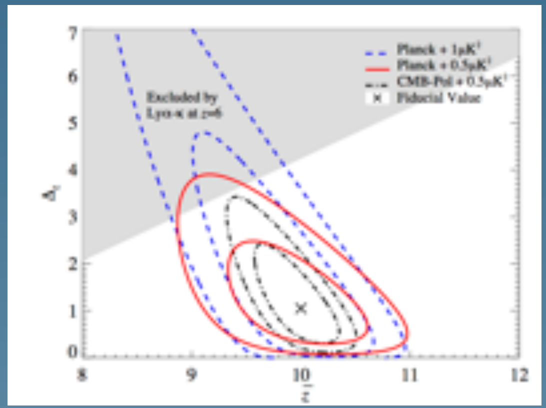
kSZ Summary



$\otimes\, W_z \rightarrow$



Fiducial source model for reionization



Reionization constraints on $\bar{z}$ and Δ_z

Future: 21cm (La Plante+13), non-linear bias...

Final thoughts

Secondary anisotropies are full of information!

- Growth of structure - Astrophysics - Reioniaztion

There's already a plethora of observations of CMB secondaries (and more are coming)

Both simulations and semi-analytic methods are required to extract this information

Data driving the theory...

Thank you!