SZ clusters as cosmological probes

Jean-Baptiste Melin
CEA Saclay, France

SZ cosmology from cluster counts

SZ power spectrum, kinetic SZ,
CMB data as a probe of the LSS

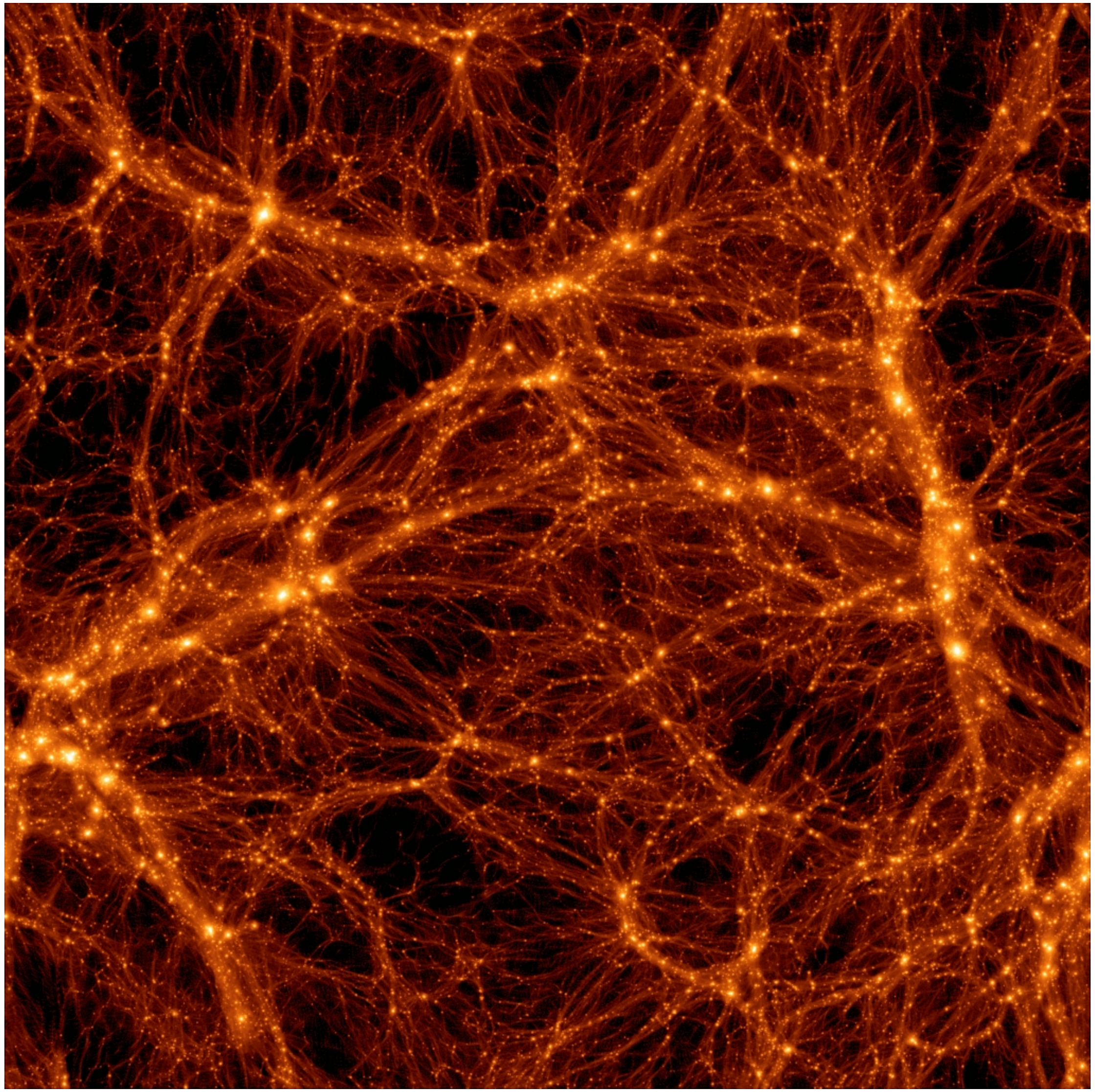
Outline

- Galaxy clusters, the Sunyaev-Zel’dovich (SZ) effect, blind SZ catalogues

- Cosmology from SZ cluster counts

- Solutions to the tension?

Galaxy clusters

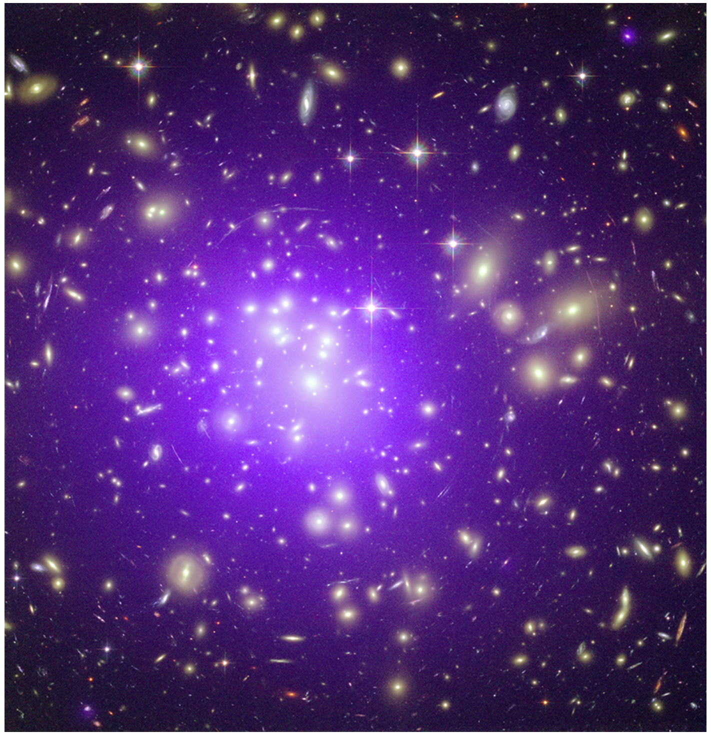


http://www.projet-horizon.fr/rubrique38.html

Galaxy clusters

- **Galaxies**
  - 10-1000 per cluster
  - **M_{gal} ~ 0.02 $M_{cluster}$**
- **Gas**
  - Hydrogen, helium
  - $T_{gas} \sim 10^{7\text{-}8}$ K, 1-10 keV
  - **M_{gas} ~ 0.1 $M_{cluster}$**
- **Dark matter**
  - $R_{cluster} \sim 1$ Mpc
  - **$M_{cluster} \sim 10^{14} – 10^{15}\ M_{\odot}$**

Abell 1689



http://chandra.harvard.edu/photo/2008/a1689/

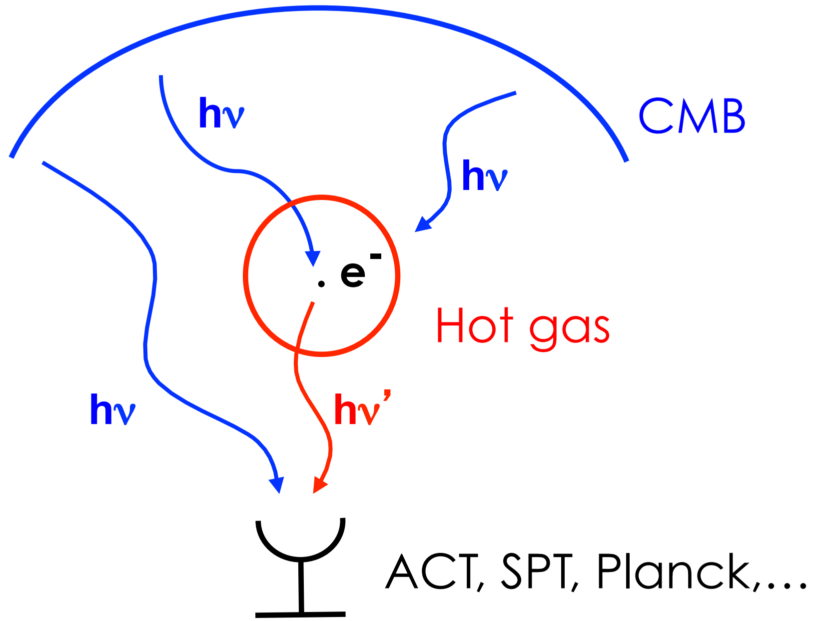
Galaxy clusters

- **Galaxies [optical]**
  - 10-1000 per cluster
  - **M_{gal} ~ 0.02 $M_{cluster}$**
- **Gas [X-ray, SZ effect]**
  - Hydrogen, helium
  - T_{gas} ~ $10^{7\text{-}8}$ K, 1-10 keV
  - **M_{gas} ~ 0.1 $M_{cluster}$**
- **Dark matter [lensing]**
  - $R_{cluster}$ ~ 1 Mpc
  - **$M_{cluster}$ ~ 10^{14} – 10^{15} $M_\odot$**

http://enfantvege.canalblog.com/archives2012/05/21/24294587.html

Detecting the hot gas in halos with the SZ effect

Sunyaev and Zeldovich 1970,1972



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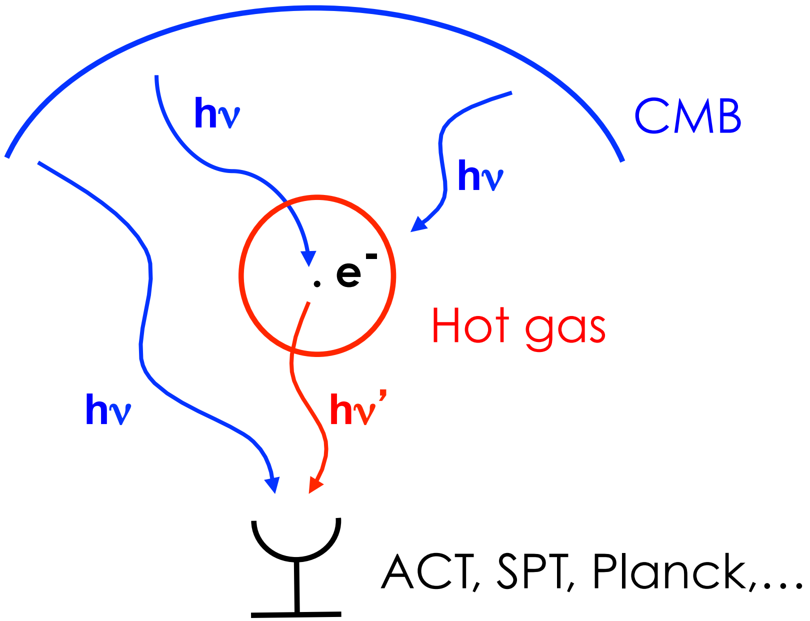

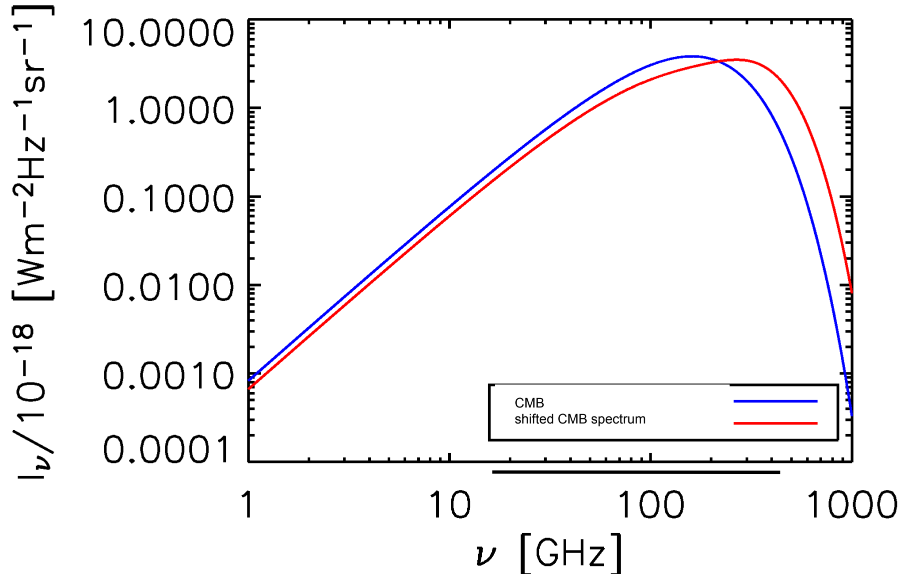

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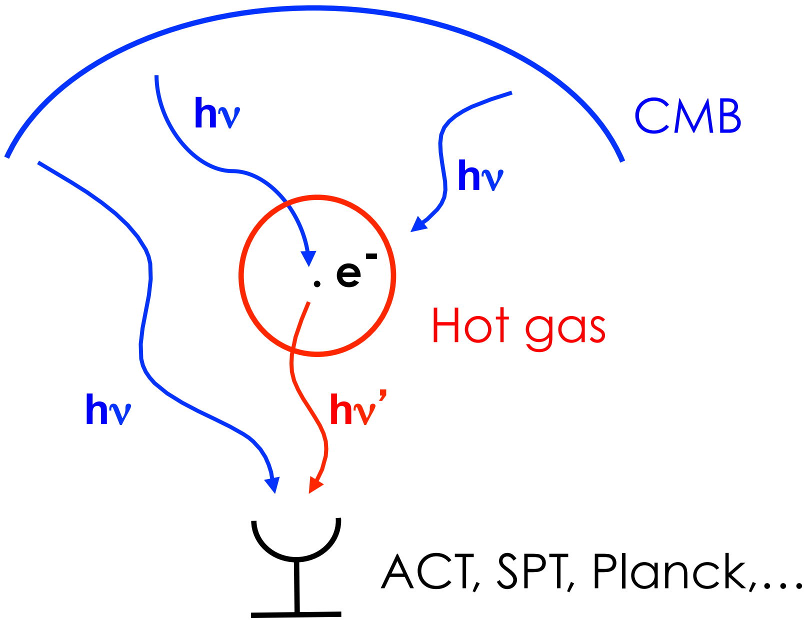

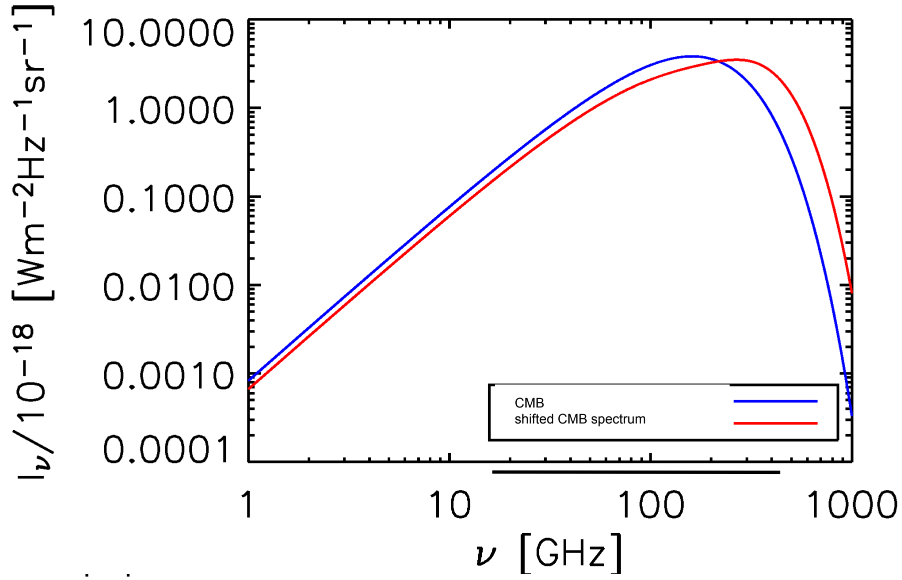

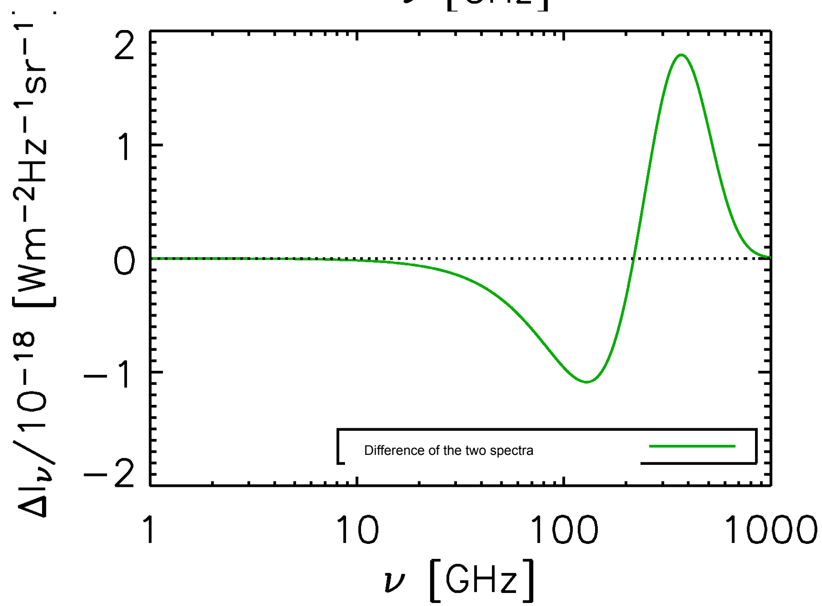

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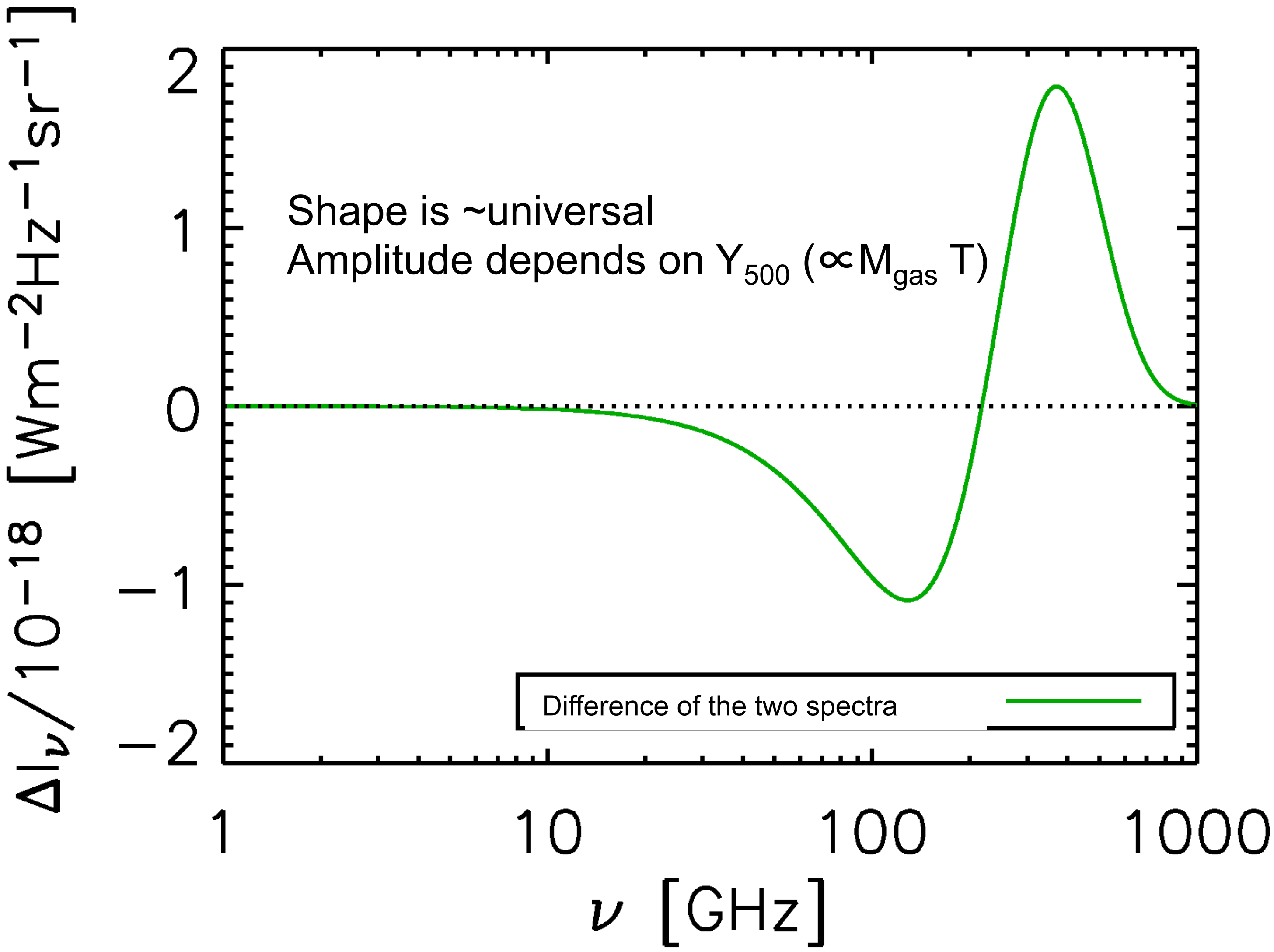

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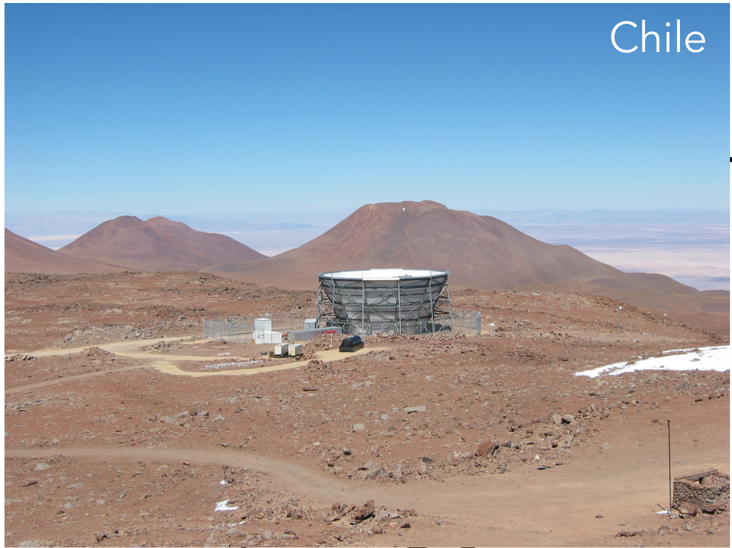
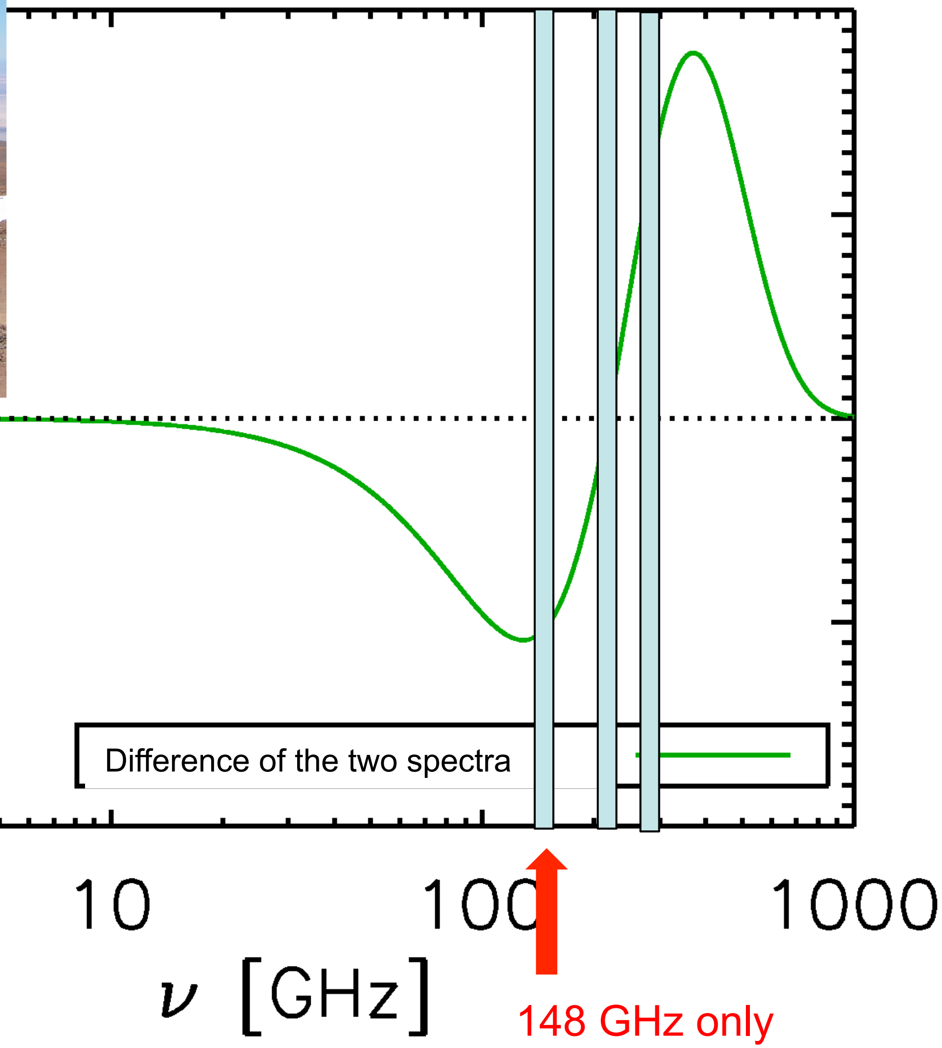


Credit: ACT

3 **ACT** frequencies

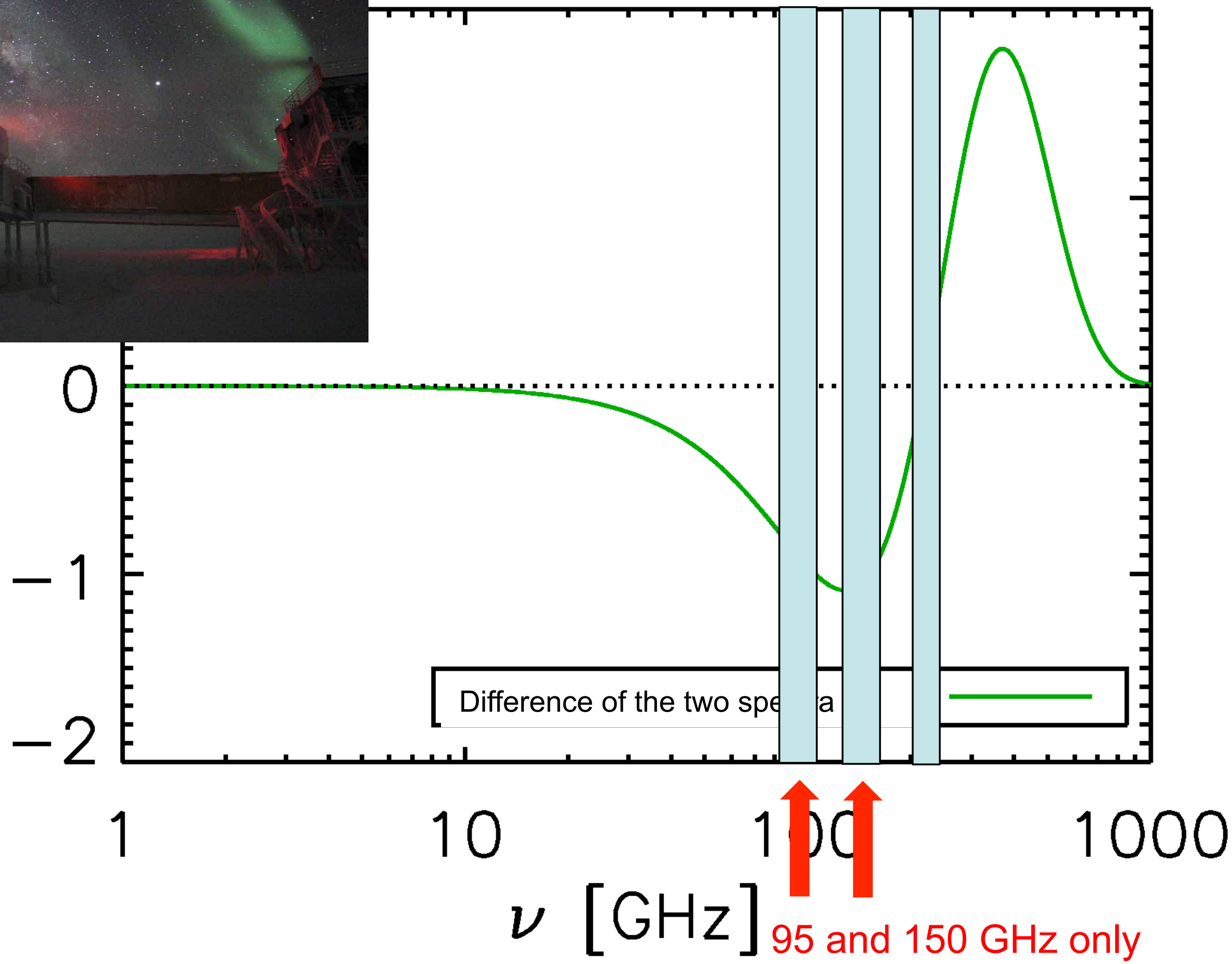


148 GHz only
for detection

Detecting the hot gas in halos with the SZ effect

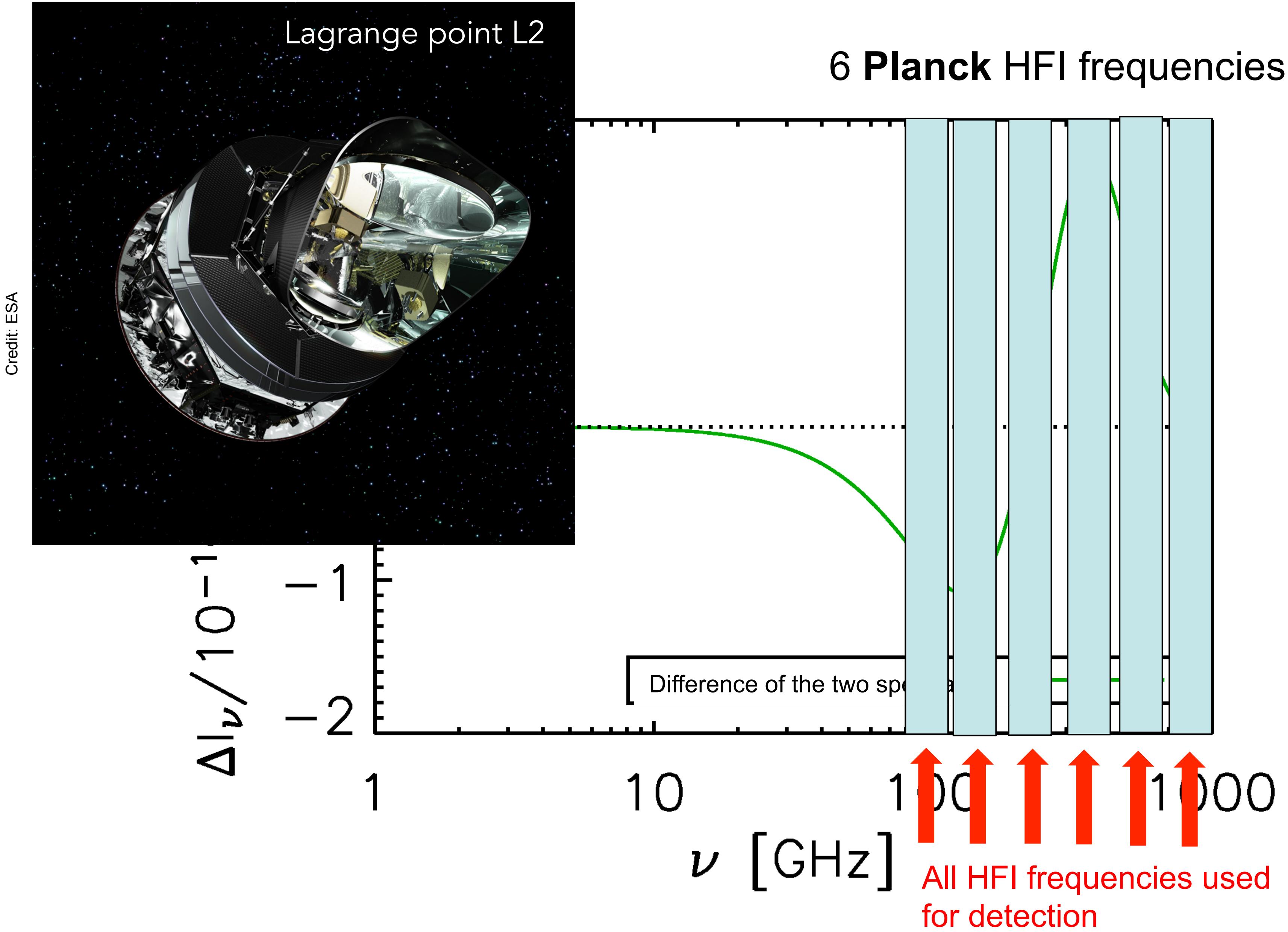
Credit: SPT, K. Vanderlinde

3 **SPT** frequencies

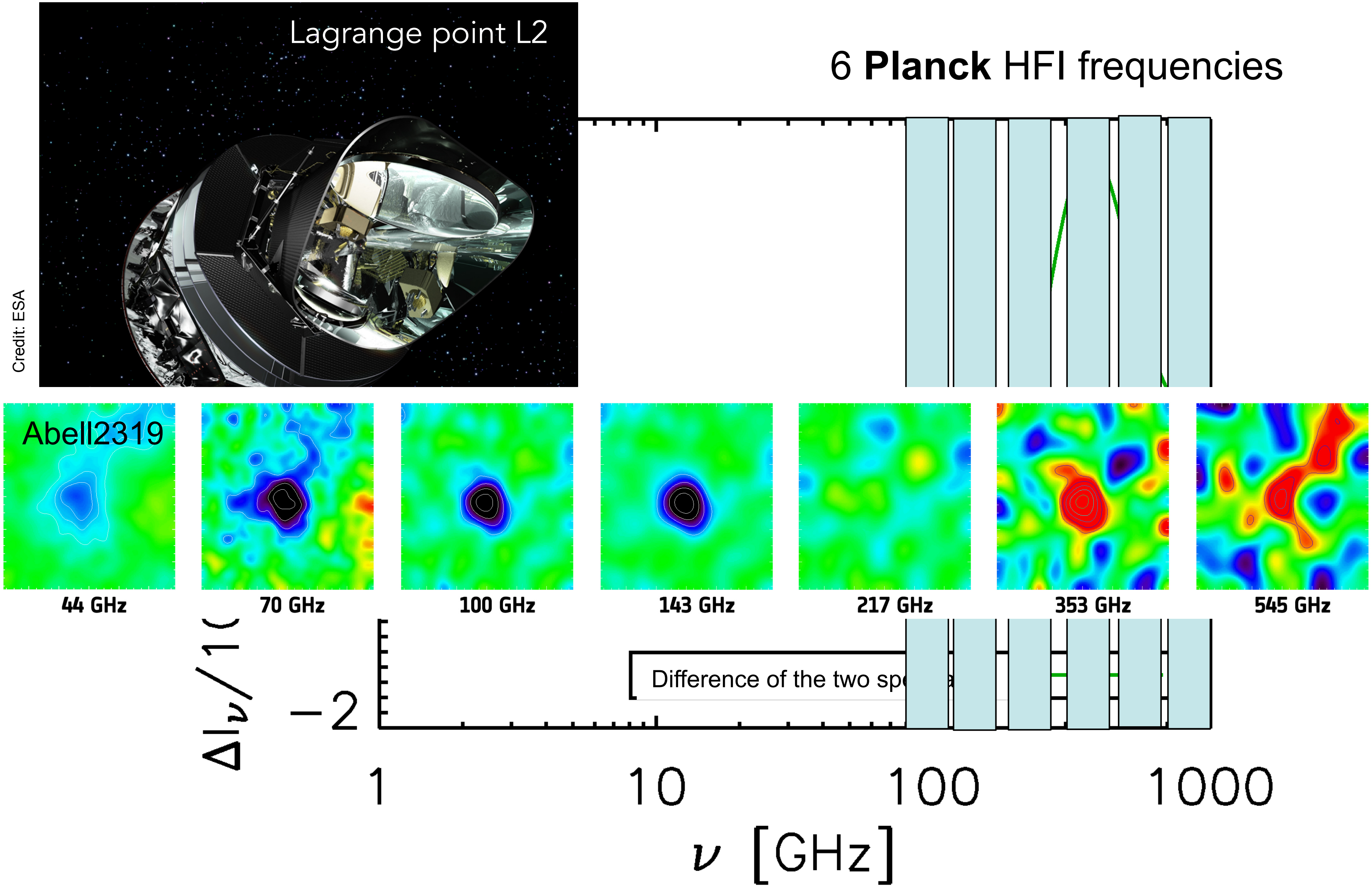


95 and 150 GHz only
for detection

Detecting the hot gas in halos with the SZ effect



Detecting the hot gas in halos with the SZ effect



Why using the SZ effect to detect clusters?

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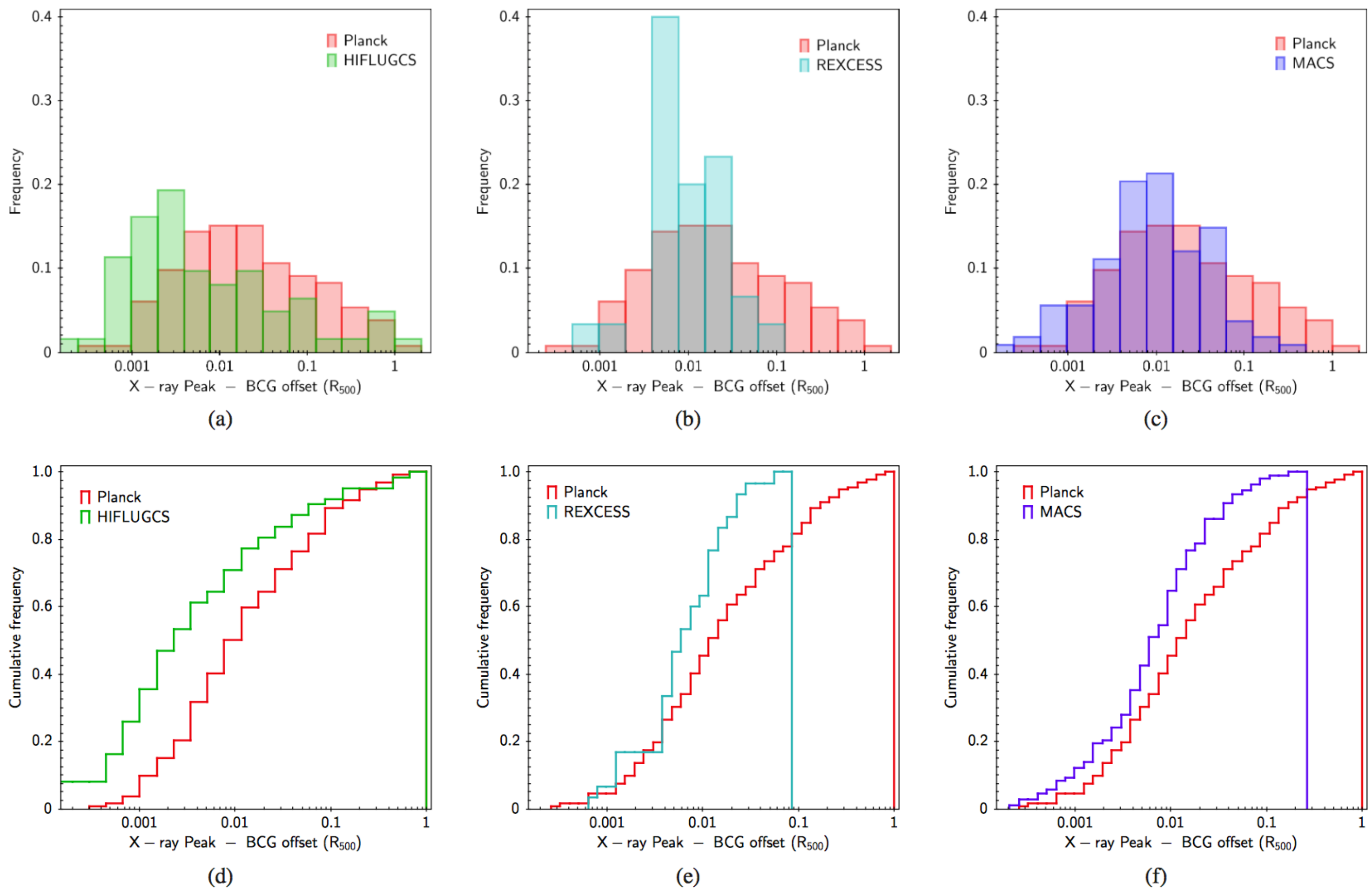
★ SZ flux ($\propto$ gas mass) closely related to total mass ➔clean detection

Why using the SZ effect to detect clusters?

★ SZ flux (∝ gas mass) closely related to total mass ➔clean detection

Rossetti et al. 2016



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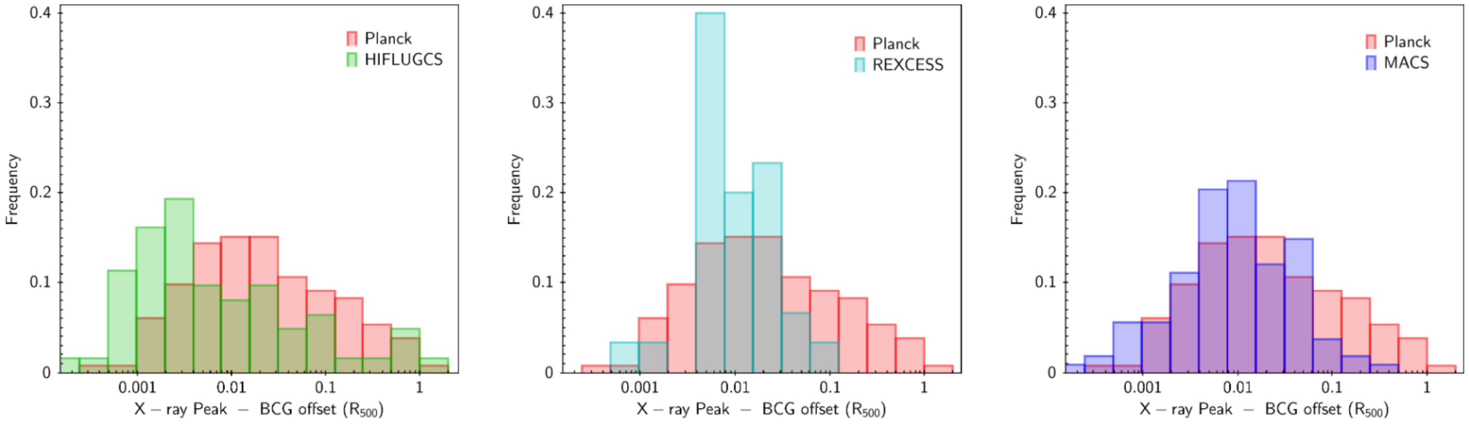


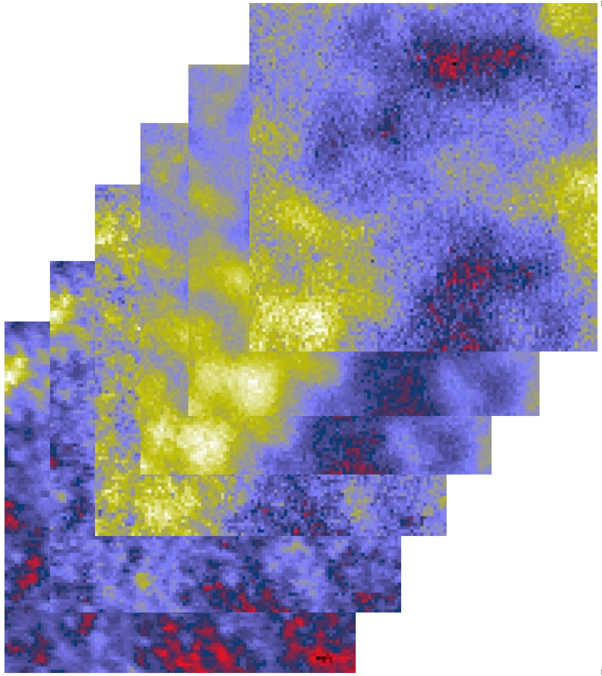
(a) (b) (c)

★ SZ effect independent of redshift ➔detection of high redshift clusters

Most massive clusters in the Universe in $0.5<z<1$ detected by Planck
Tens of massive clusters in $1<z<2$ detected by SPT

The SZ Matched Multi-Filter (MMF)

Planck maps



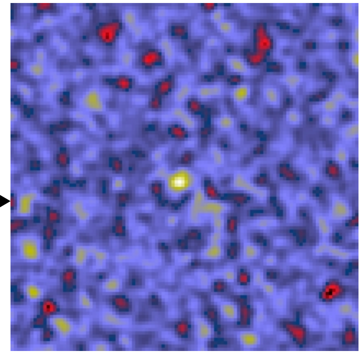
MMF

assumes

- SZ frequency spectrum
- cluster profile
- noise cross-power spectra

Herranz et al. 2002
Melin, Bartlett, Delabrouille 2006

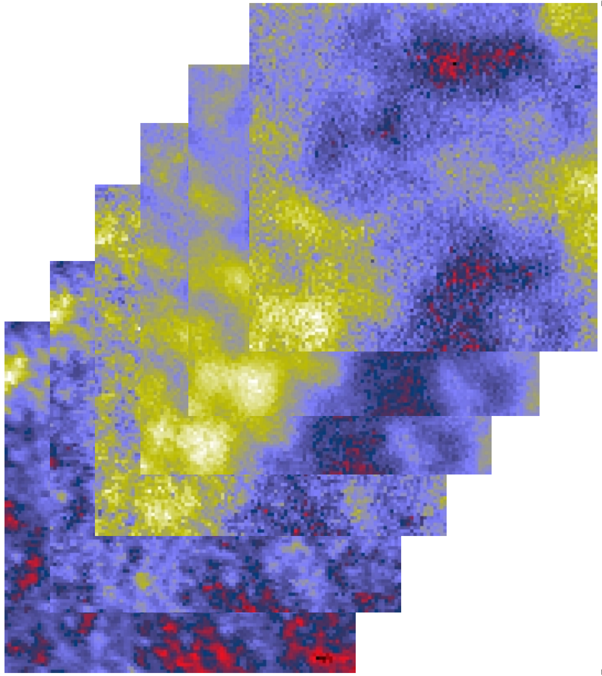
Filtered map



adopted by the three collaborations (Planck, SPT, ACT)

The SZ Matched Multi-Filter (MMF)

Planck maps



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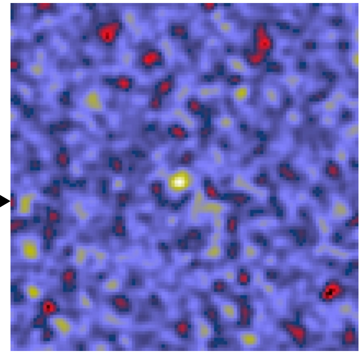
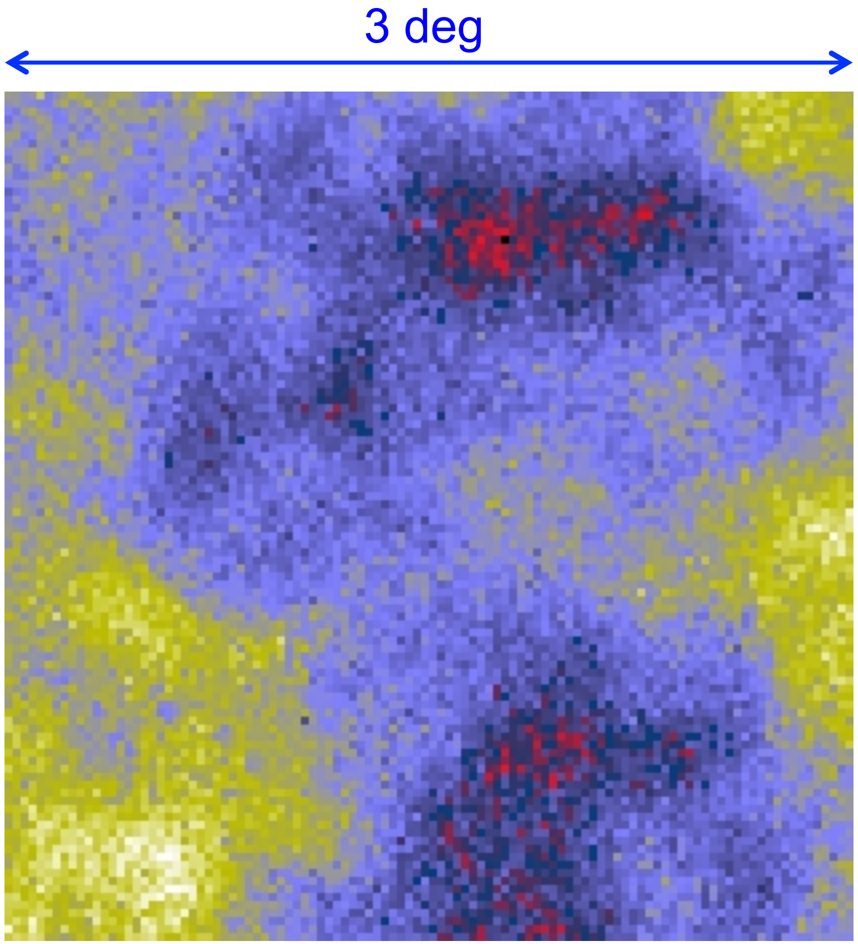


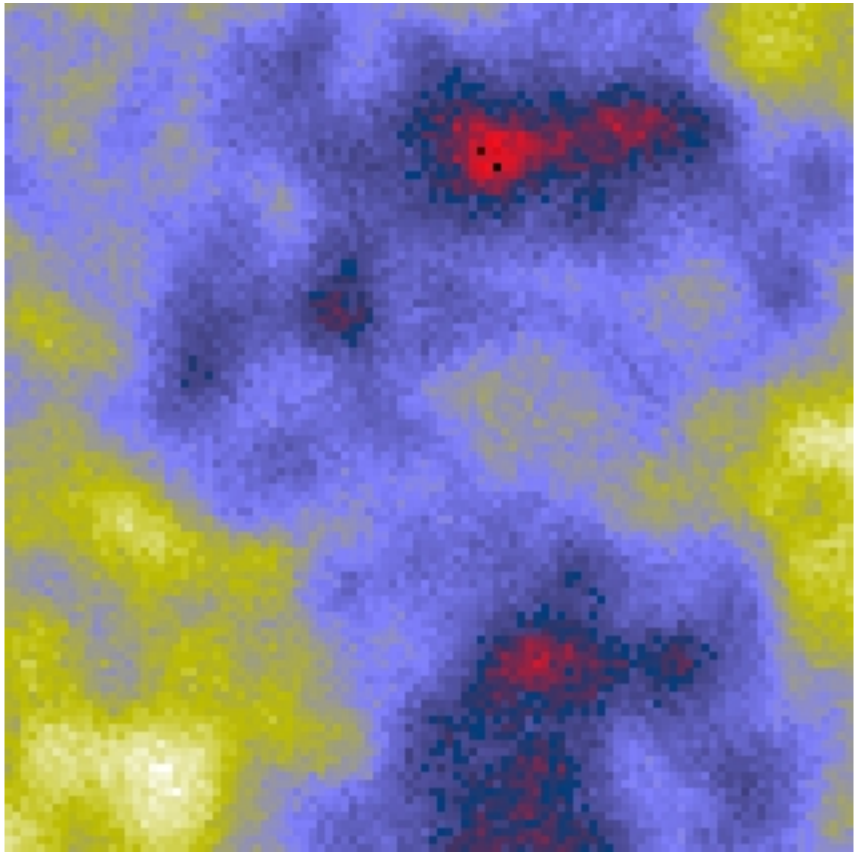
✧ Linear estimator
✧ Minimizes the variance of the noise
✧ Unbiased

PSZ2 G156.26+59.64 (z=0.59)



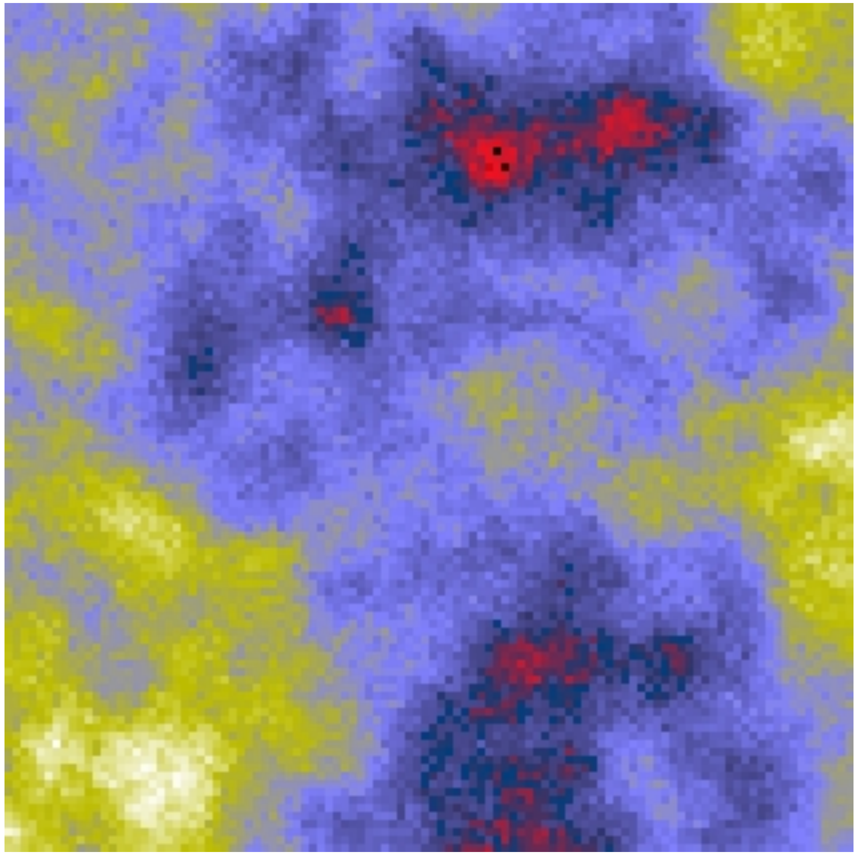
100 GHz

PSZ2 G156.26+59.64 (z=0.59)



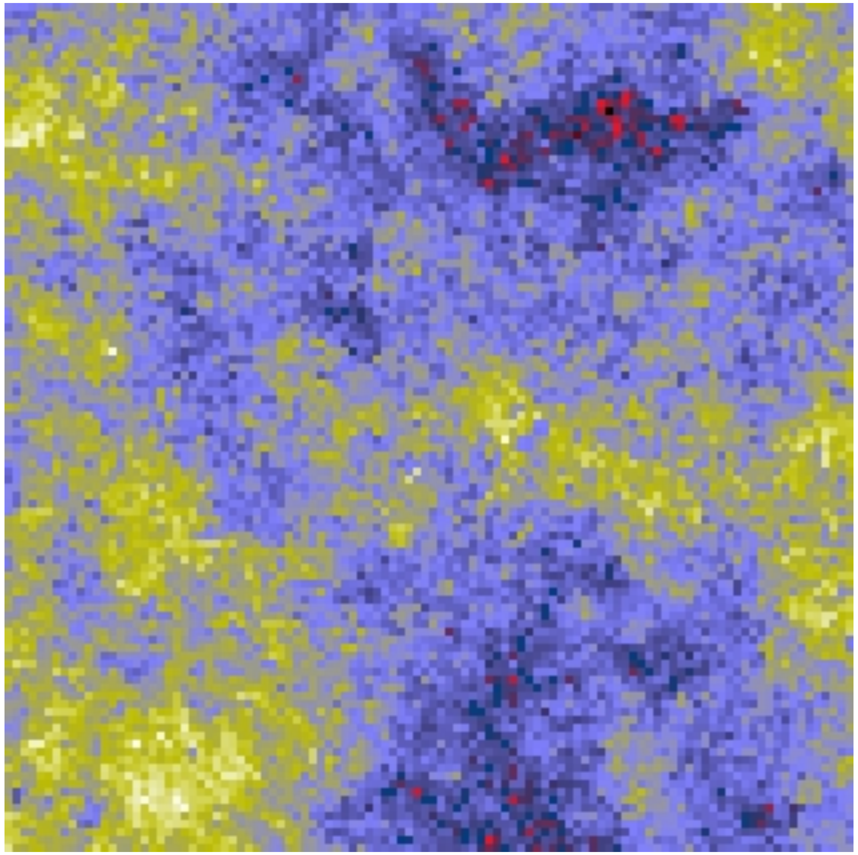
143 GHz

PSZ2 G156.26+59.64 (z=0.59)



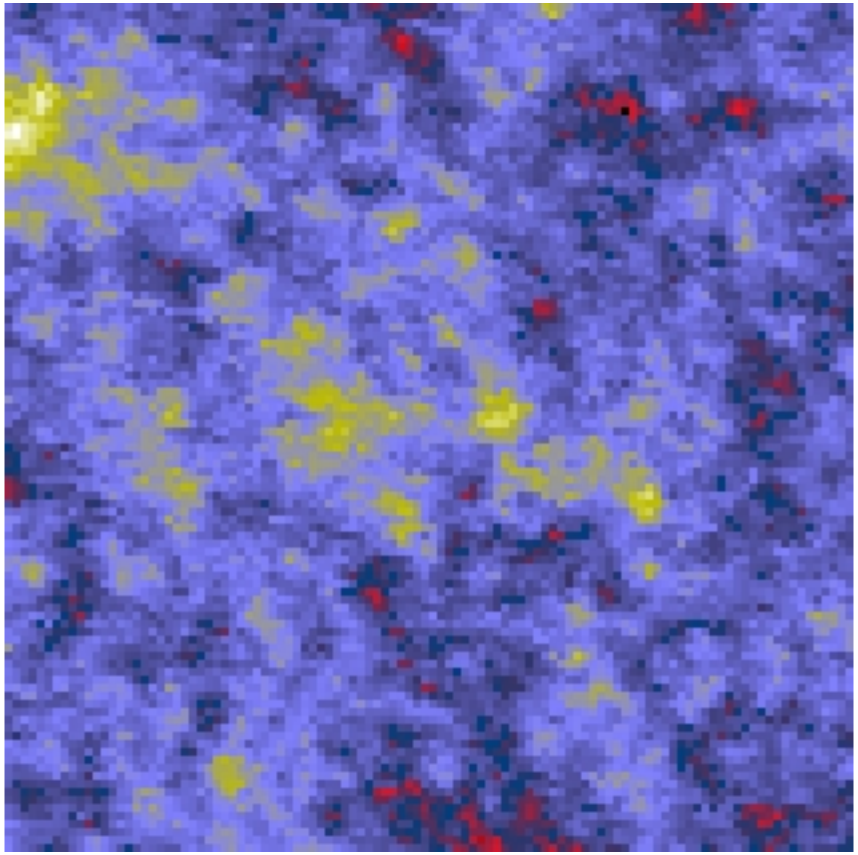
217 GHz

PSZ2 G156.26+59.64 (z=0.59)



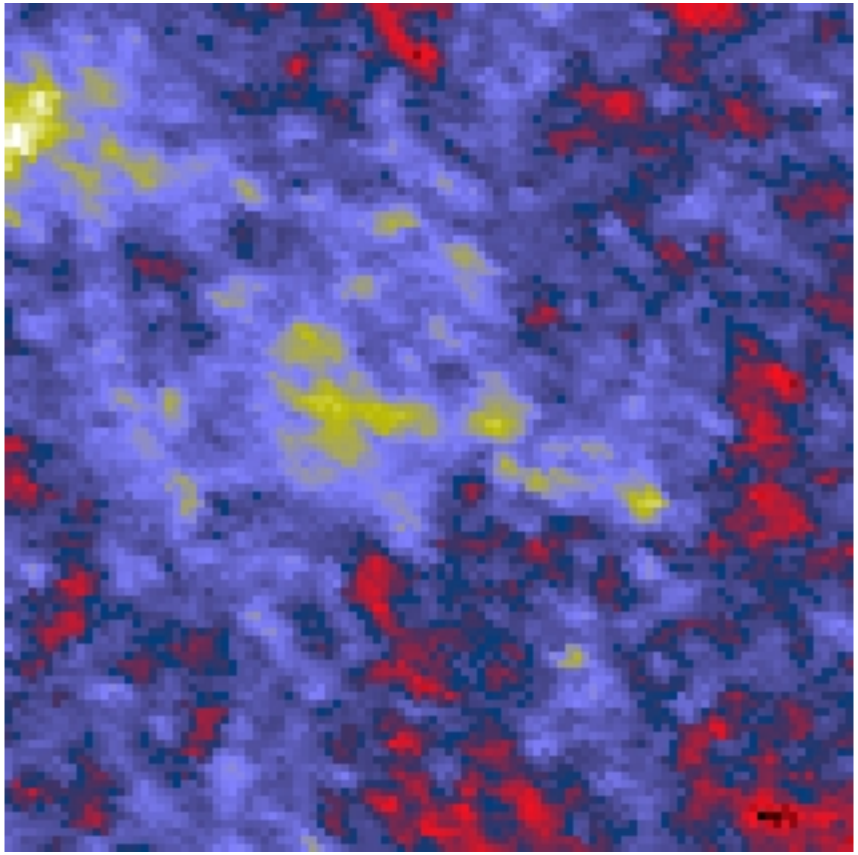
353 GHz

PSZ2 G156.26+59.64 (z=0.59)



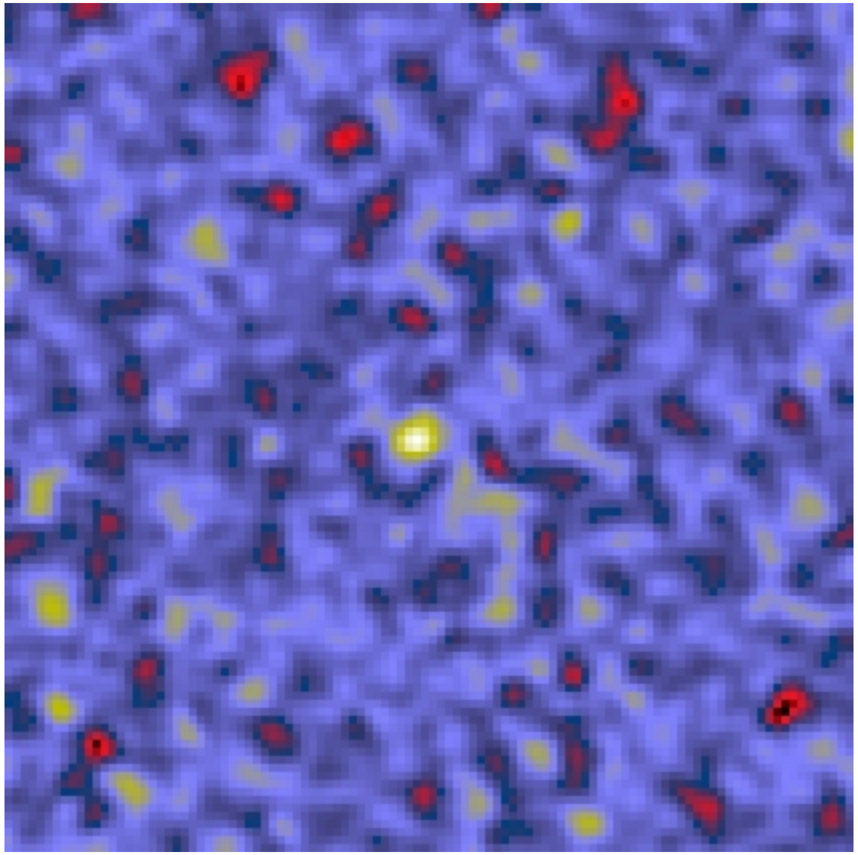
545 GHz

PSZ2 G156.26+59.64 (z=0.59)



857 GHz

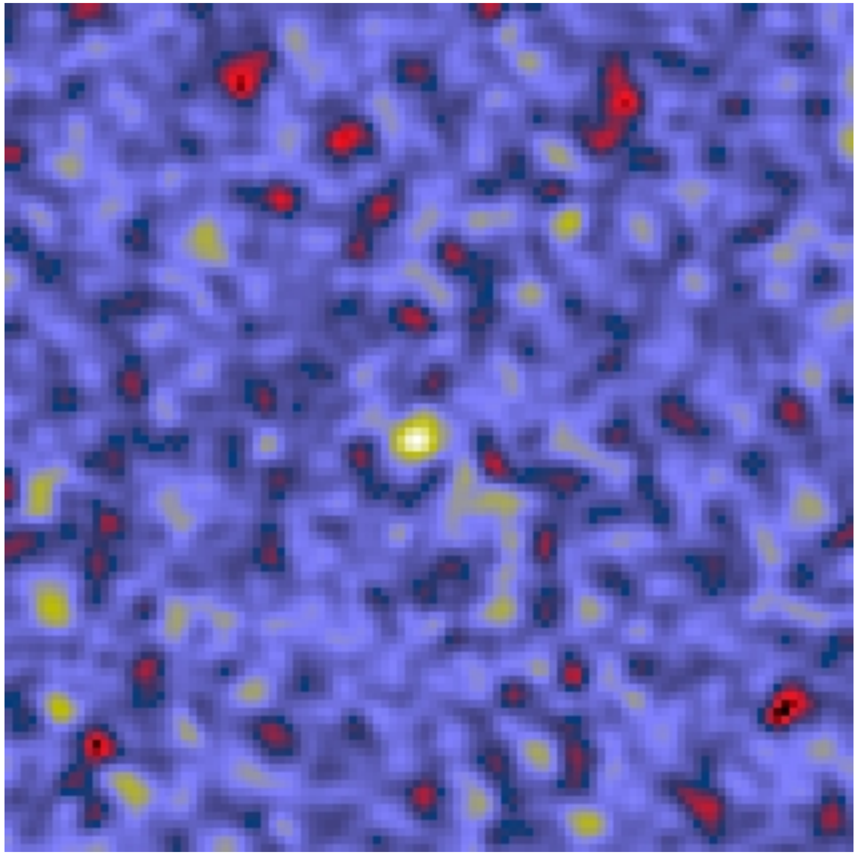
PSZ2 G156.26+59.64 (z=0.59)



S/N=5.9

Matched filtered SZ map

PSZ2 G156.26+59.64 (z=0.59)



Matched filtered SZ map

S/N=5.9

MMF used for
Planck Coll. 2011 VIII (ESZ)
Planck Coll. 2013 XXIX (PSZ1)
Planck Coll. 2015 XXVII (PSZ2)

Blind SZ catalogues

ACT

91 optically confirmed clusters (504 deg^2)
Hasselfield et al. 2013

182 SZ sources with S/N>4 (987.5 deg^2)
Hilton et al. 2017

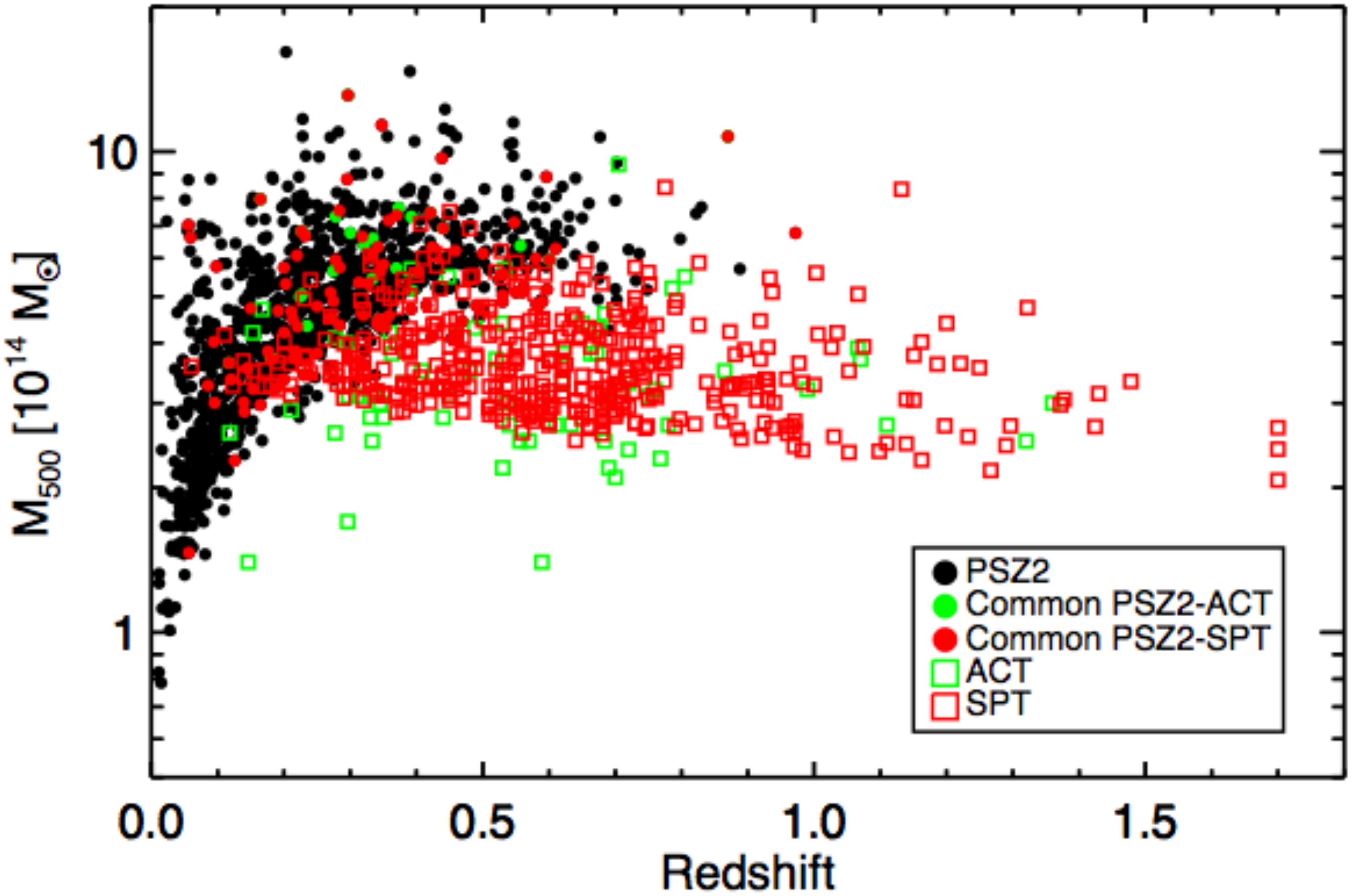
SPT

677 SZ sources with S/N>4.5 (2,500 deg^2)
Bleem et al. 2013

Planck

1653 SZ sources with S/N>4.5 (35,000 deg^2)
Planck Collaboration XXVII 2015

Main properties of the three catalogues



Warning: non-uniform redshift knowledge for Planck, PSZ2 should contain z>0.6 objects not visible here (optical follow-up still on-going)

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- Cosmology from SZ cluster counts

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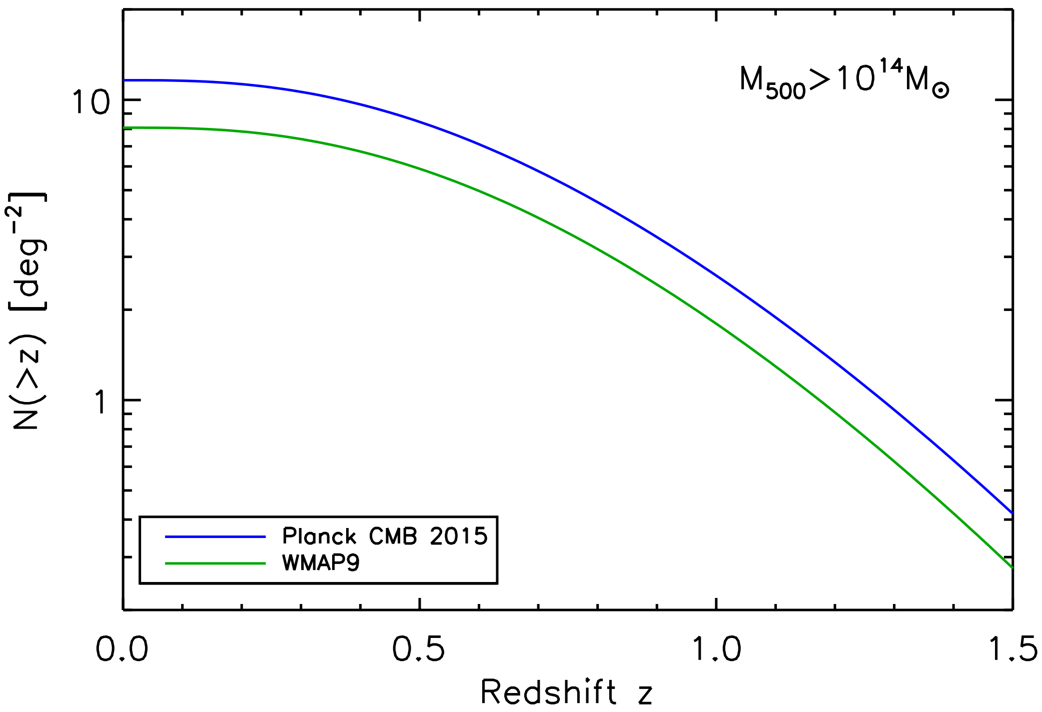
Cosmology from cluster counts



Cluster abundance and evolution are very sensitive to cosmological parameters σ_8 Ω_m

$\rightarrow$ independent from primary CMB, BAO, SNIa

The cosmological samples

Highly reliable candidate sub-samples
+
Selection function under control

ACT S/N>5.1 ➔ 15 clusters Hasselfield et al. 2013

SPT S/N>5 ➔ 100 clusters Bocquet et al. 2015
S/N>5 ➔ 377 clusters de Hann et al. 2016

Planck S/N>7 ➔ 189 clusters Planck Results XX 2015
S/N>6 (full dataset) ➔ 439 clusters
Planck Results XXIV 2015

The Planck SZ cosmological analysis

dN/dz (2013) and dN/dz/d(S/N) (2015)

Observations $\frac{dN}{dz}$ (need redshifts !)

TO BE COMPARED WITH

Predictions $$\frac{dN}{dz} = \int d\Omega \int dM_{500}\, \hat{\chi}(z, M_{500}, l, b)\, \frac{dN}{dz\, dM_{500}\, d\Omega}$$

completeness

mass function

Tinker et al. 2008
Watson et al. 2013

Completeness (z, M_{500})

from (θ_{500}, Y_{500}) to (z, M_{500})

$$\hat{\chi} = \int dY_{500} \int d\theta_{500} P(z, M_{500}|Y_{500}, \theta_{500})\, \chi(Y_{500}, \theta_{500}, l, b)$$

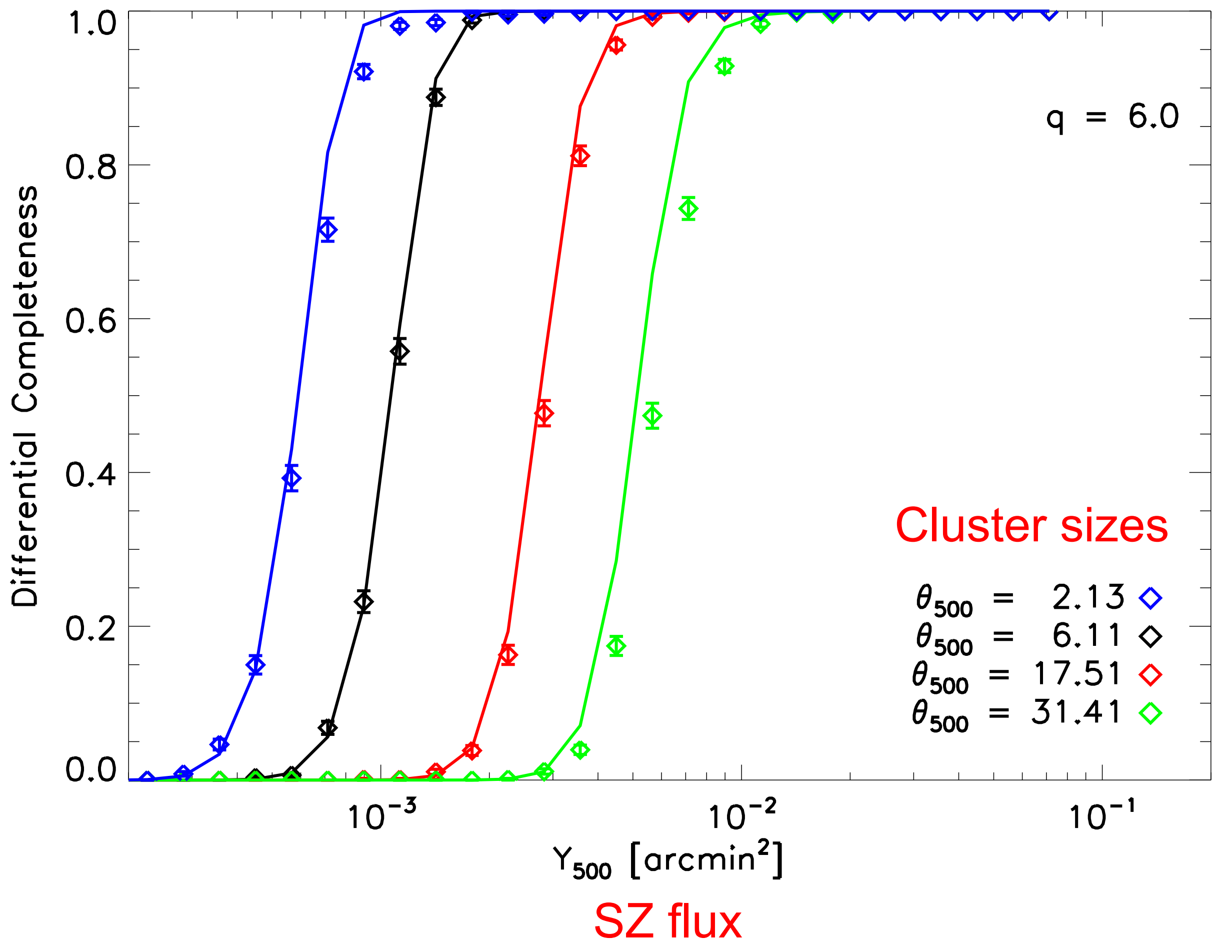
function of (z, M_{500})
depends on cosmology

need scaling laws
depends on cosmology

function of (θ_{500}, Y_{500})
independent of cosmology

Completeness (Y_{500},θ_{500})

$$\chi(Y_{500}, \theta_{500}, l, b)$$



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Scaling laws

from (θ_{500}, Y_{500}) to (z, M_{500})

Important slide !

$$\bar{\theta}_{500} = \theta_* \left[\frac{h}{0.7}\right]^{-2/3} \left[\frac{(1-b)\,M_{500}}{3\times10^{14}\mathrm{M_{sol}}}\right]^{1/3} E^{-2/3}(z) \left[\frac{D_\mathrm{A}(z)}{500\,\mathrm{Mpc}}\right]^{-1},$$

$$E^{-\beta}(z)\left[\frac{D_\mathrm{A}^2(z)\,\bar{Y}_{500}}{10^{-4}\,\mathrm{Mpc}^2}\right] = Y_* \left[\frac{h}{0.7}\right]^{-2+\alpha} \left[\frac{(1-b)\,M_{500}}{6\times10^{14}\,\mathrm{M_{sol}}}\right]^{\alpha}$$

Scaling laws

Important slide !

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α, Y* determined on X-ray data

Scaling laws

from (θ_{500}, Y_{500}) to (z, M_{500})

Important slide !

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1-b : bias between X-ray and true mass $M_{500,x}$=(1-b)M_{500}

Simulations indicate 1-b=0.8 (but high dispersion !)
We used 1-b=0.8 with a flat prior in [0.7,1] **in 2013**

Mass bias priors 2015

Von der linden et al. 2014

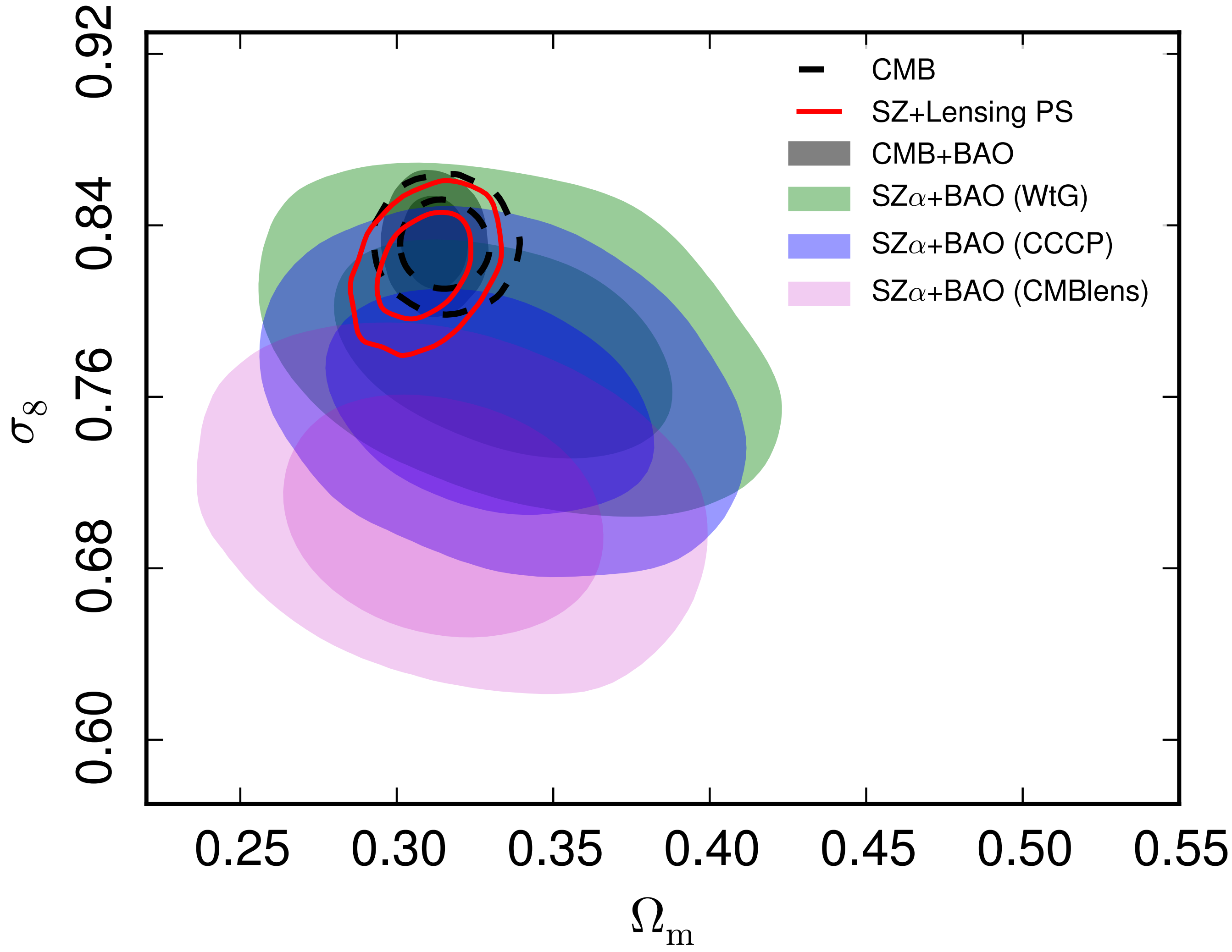
Hoekstra et al. 2015

Prior name	Quantity	Value & Gaussian errors
Weighing the Giants (WtG)	$1 - b$	0.688 ± 0.072
Canadian Cluster Comparison Project (CCCP)	$1 - b$	0.780 ± 0.092
CMB lensing (LENS)	$1/(1 - b)$	$0.99 \quad \pm 0.19$
Baseline 2013	$1 - b$	$0.8\,[-0.1, +0.2]$

Notes. CMB lensing directly measures $1/(1 - b)$, which we implement in our analysis; purely for reference, that constraint translates approximately to $1 - b = 1.01^{+0.24}_{-0.16}$. The last line shows the 2013 baseline — a reference model defined by $1 - b = 0.8$ with a flat prior in the [0.7, 1] range.

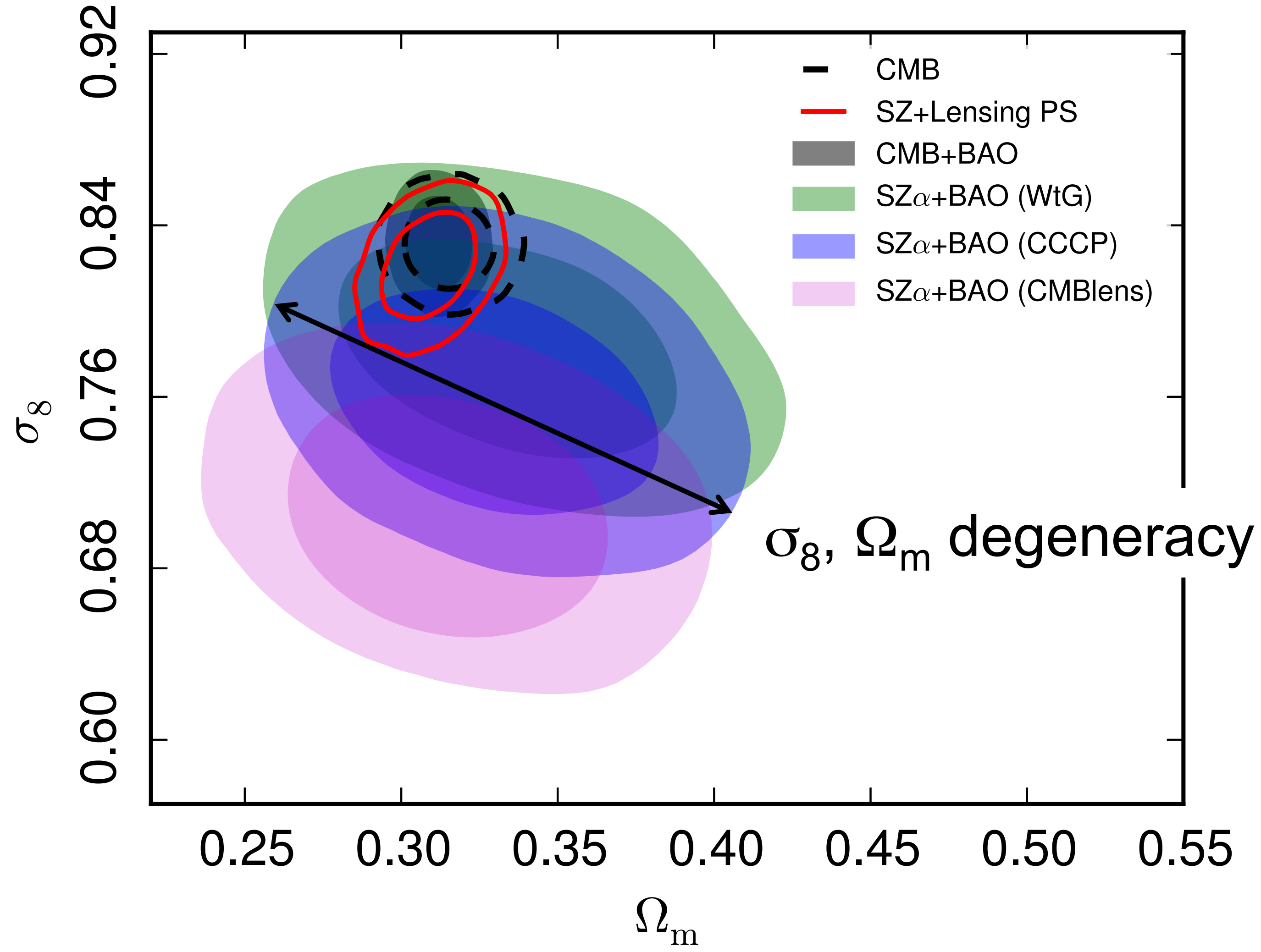
NEW (CMB halo lensing) !!!

Planck cluster cosmology 2015



Planck Results XXIV 2015

Planck cluster cosmology 2015



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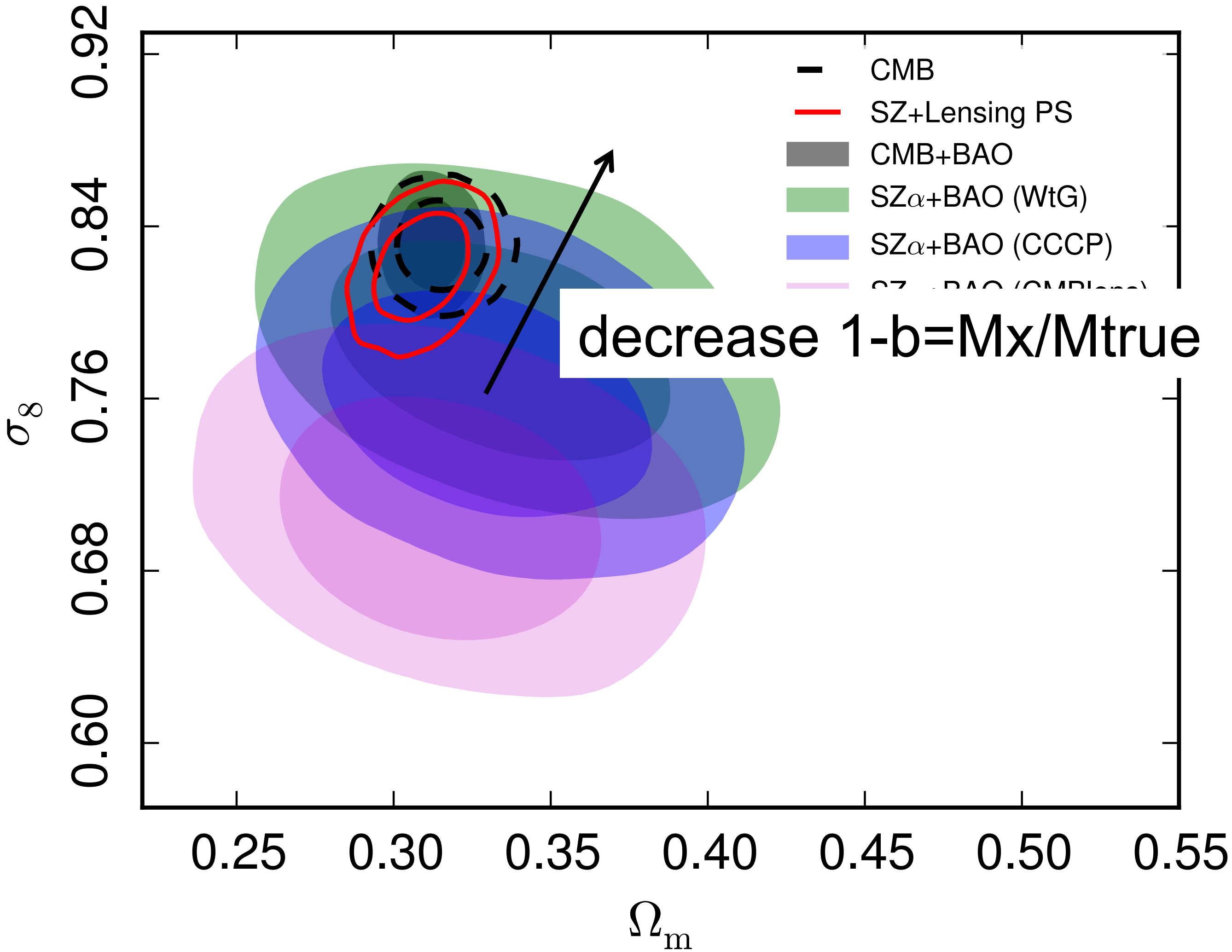

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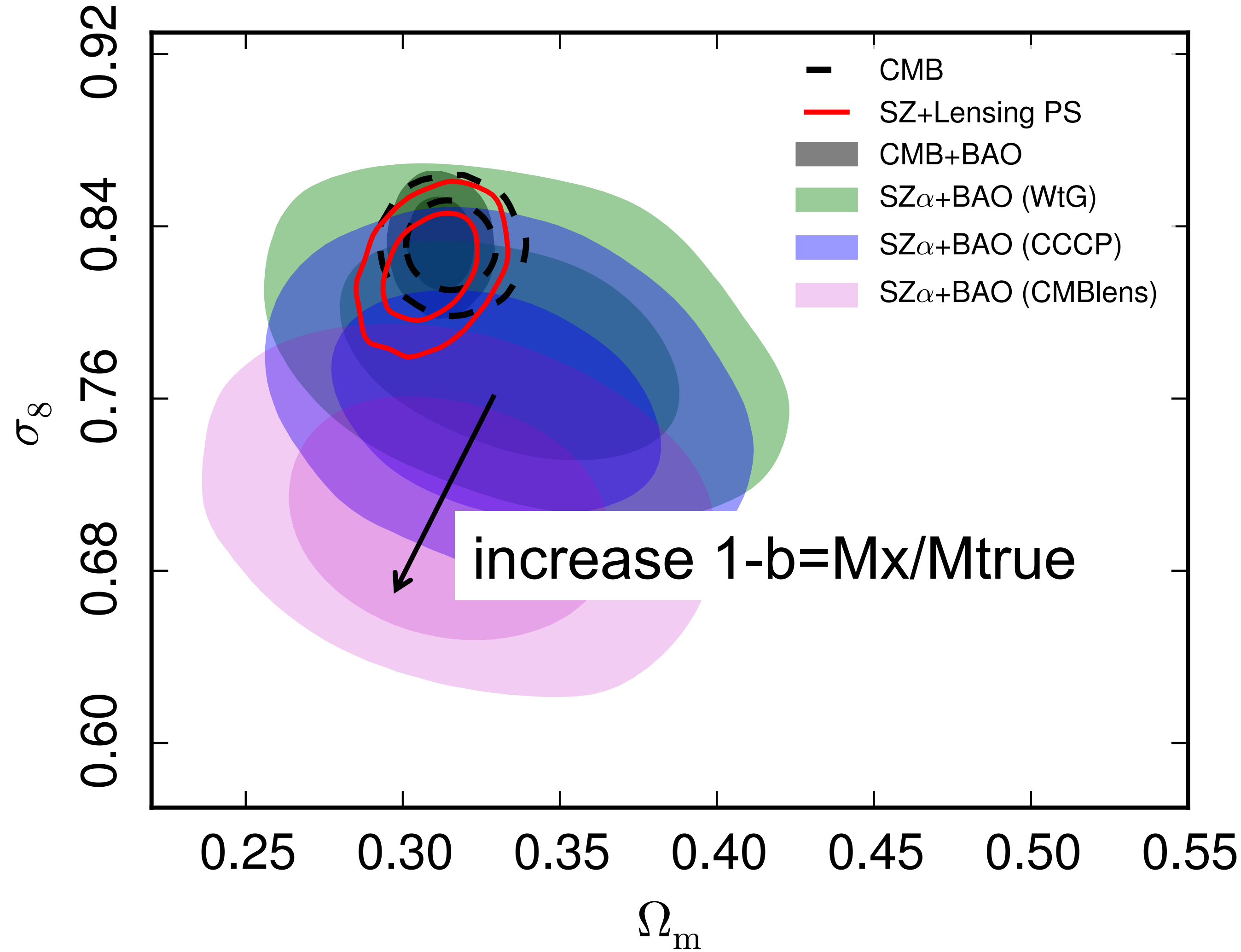
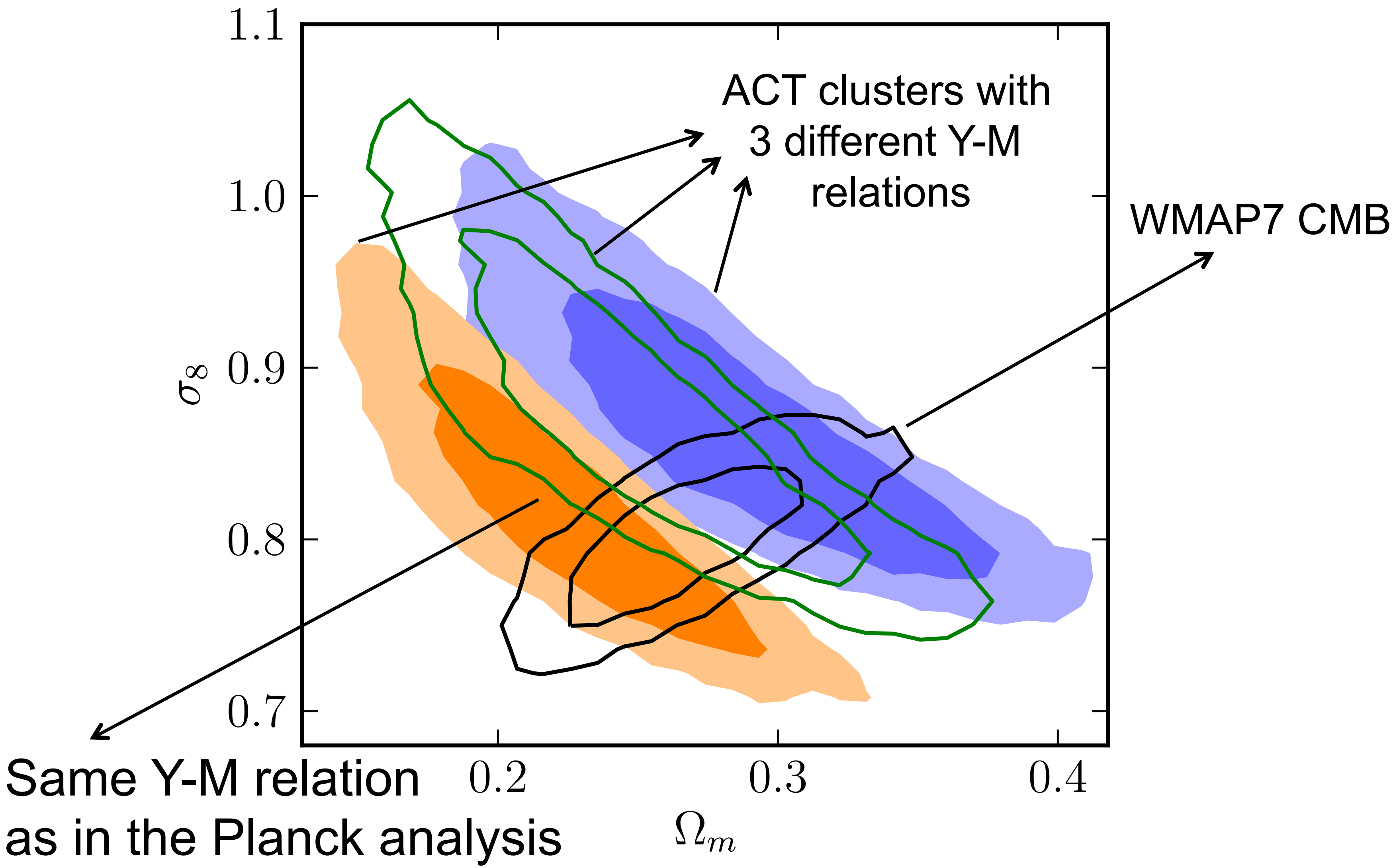


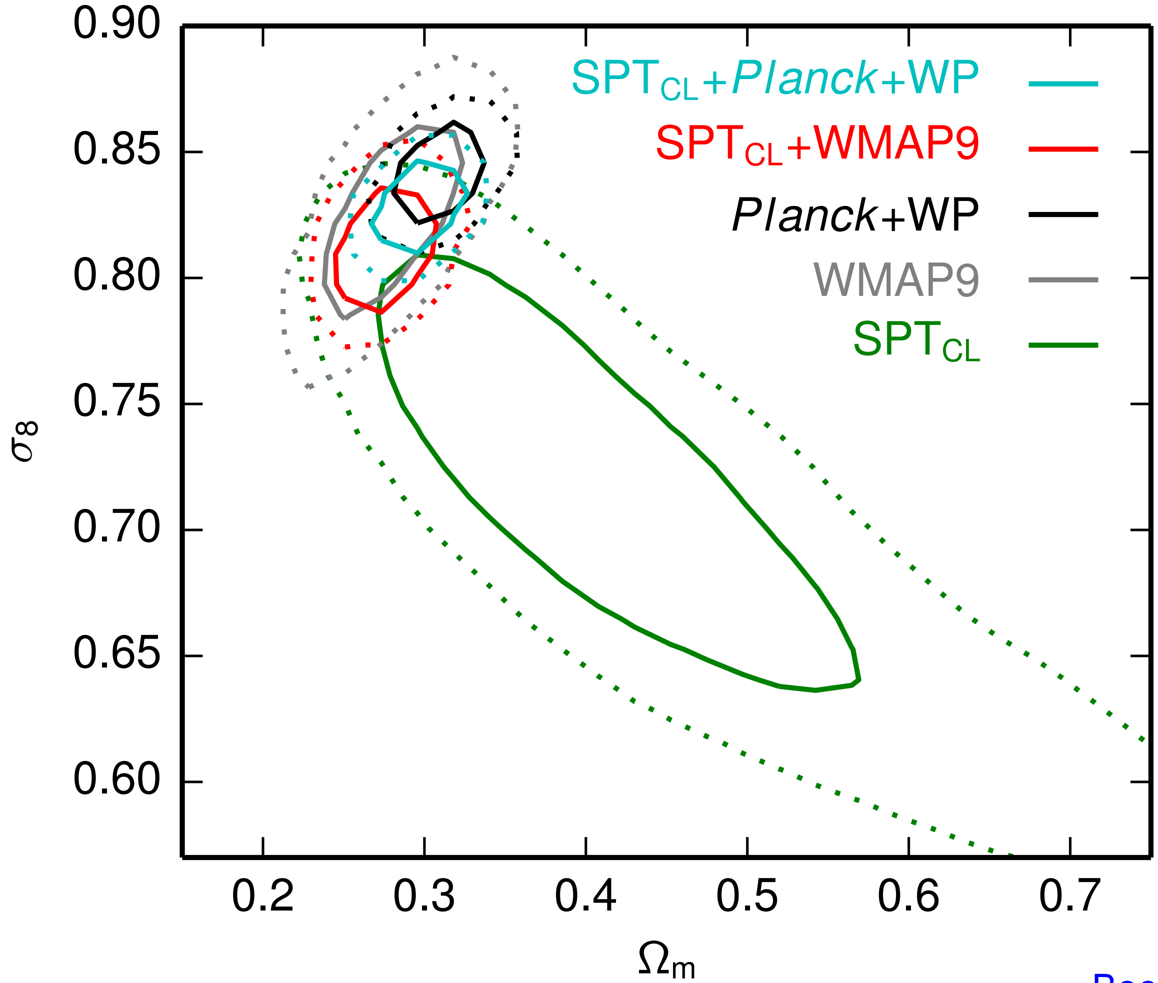
Planck Results XXIV 2015

ACT cluster cosmology 2013



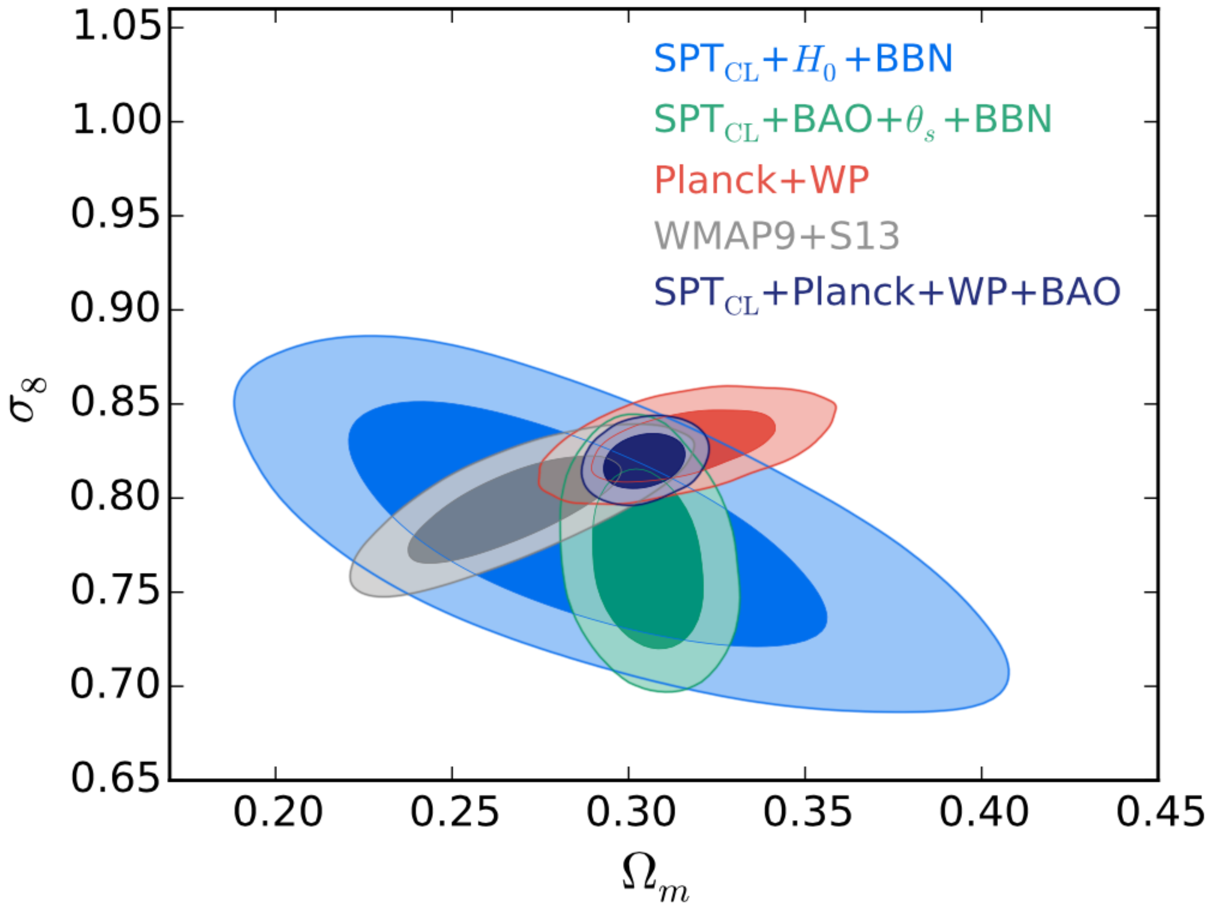
Hasselfield et al. 2013

SPT cluster cosmology 2015



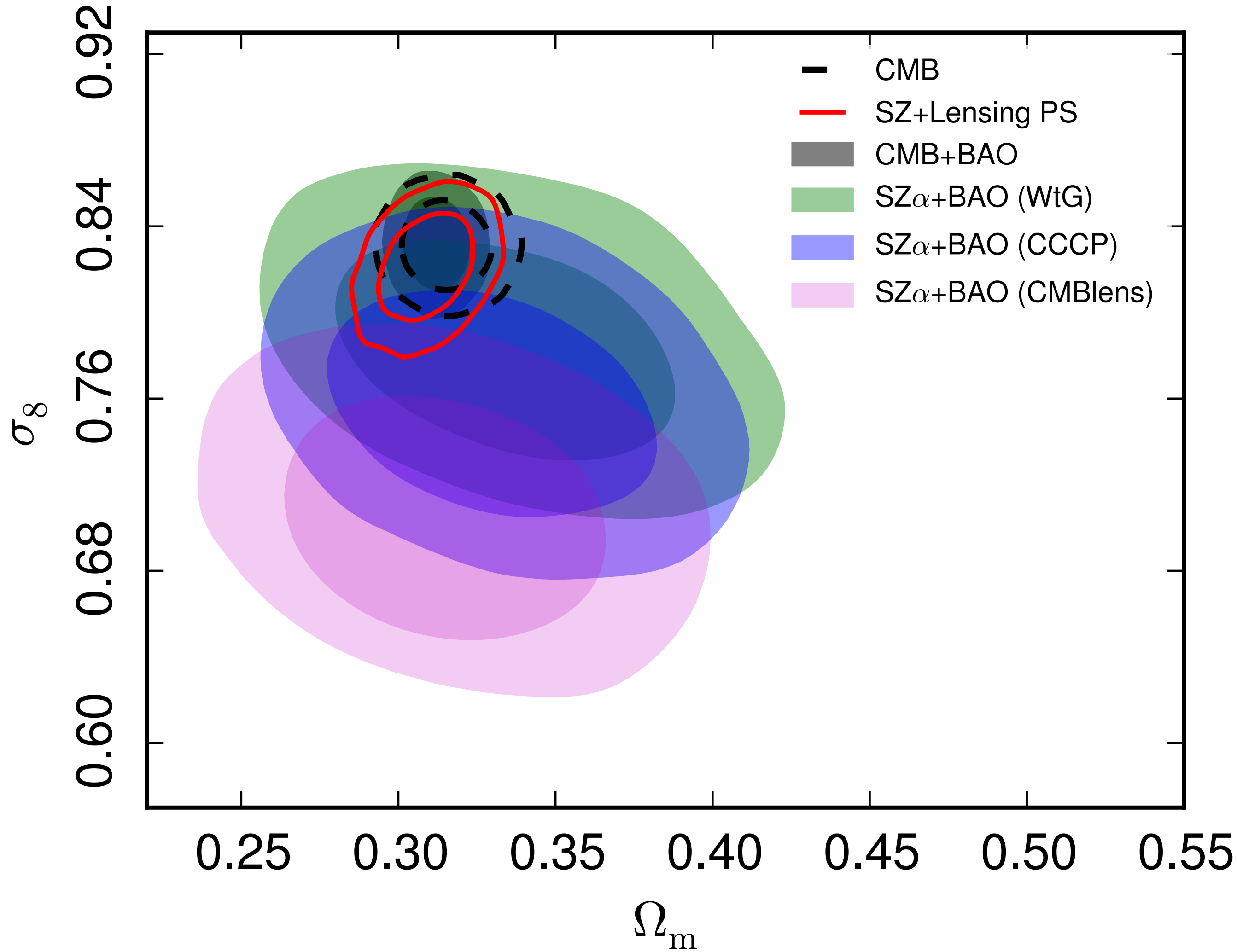
Bocquet et al. 2015

SPT cluster cosmology 2016



De Hann et al. 2016

Planck cluster cosmology 2015



Planck Results XXIV 2015

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How to reconcile Planck CMB and SZ counts?

- Mass calibration? $P(z, M_{500}|Y_{500}, \theta_{500})$
- New physics? Neutrino mass?
- Baryonic effects in the mass function? $\frac{dN}{dz\, dM_{500}\, d\Omega}$
- Selection function of SZ surveys? $\chi(Y_{500}, \theta_{500}, l, b)$
- Primary CMB?

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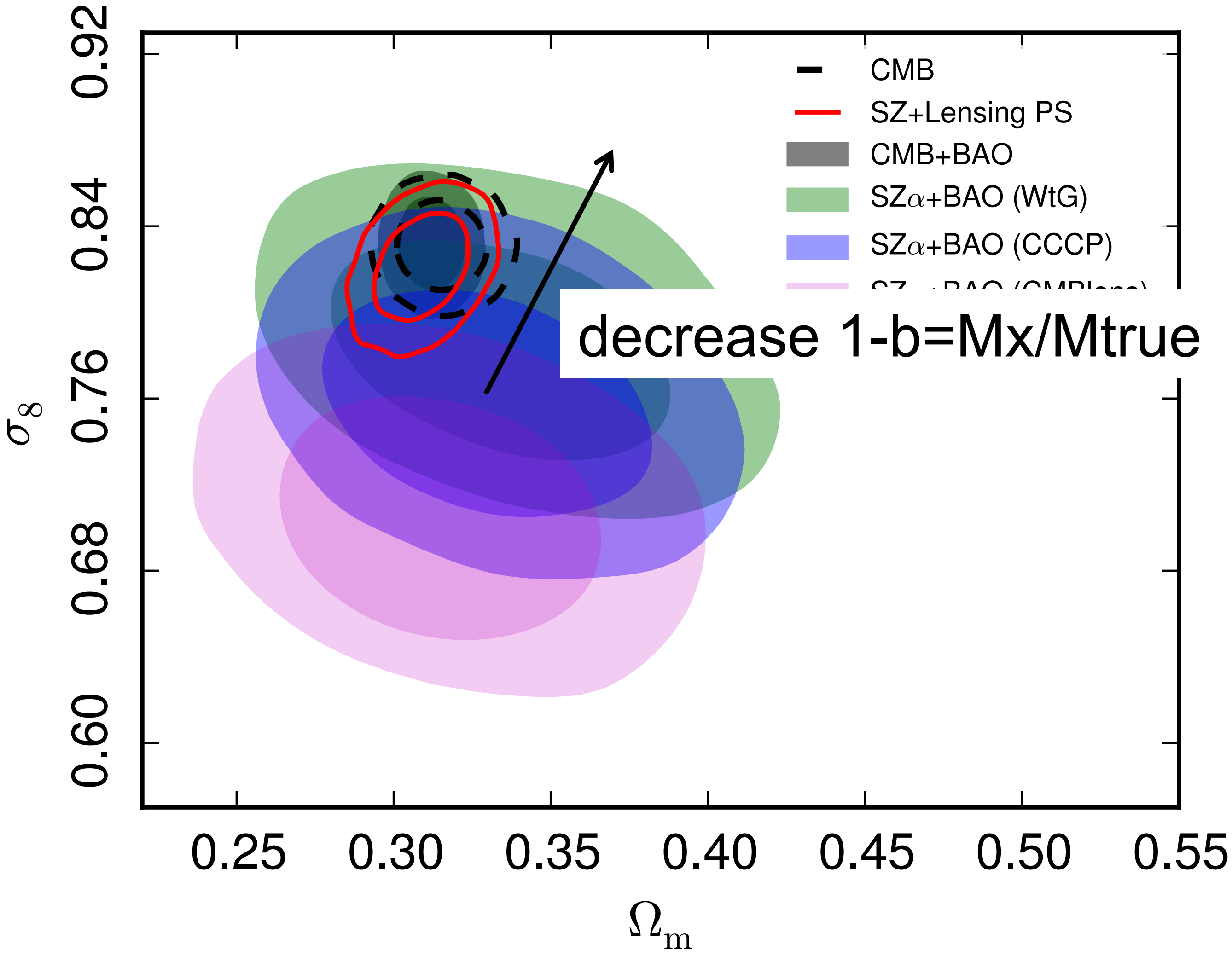
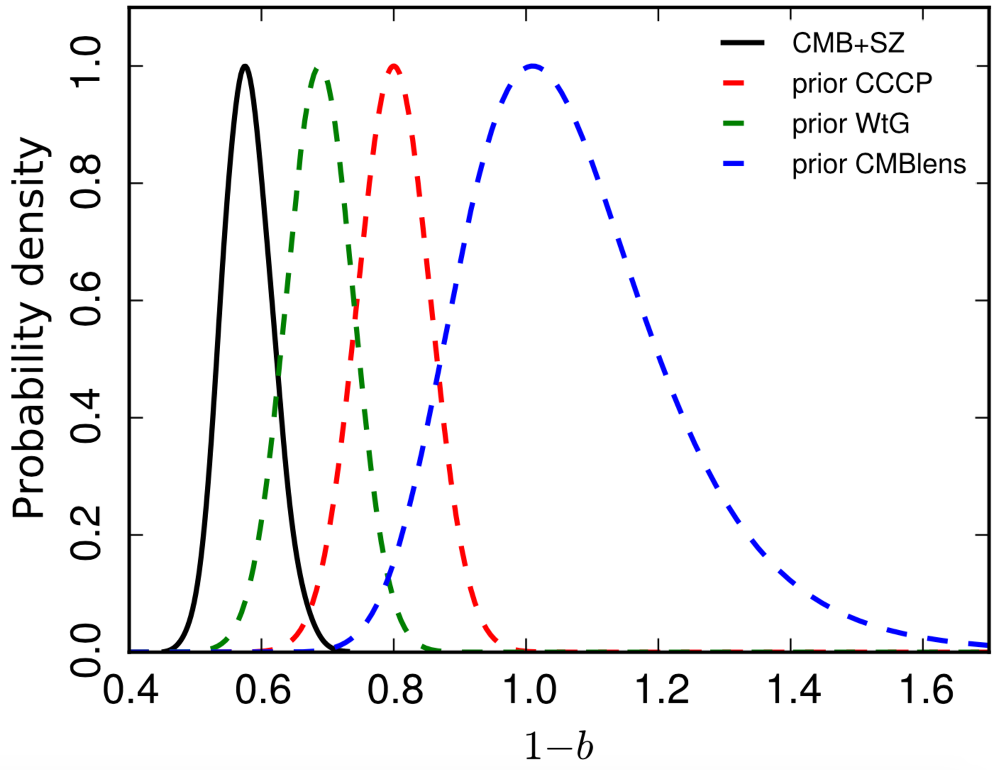


Planck Results XXIV 2015

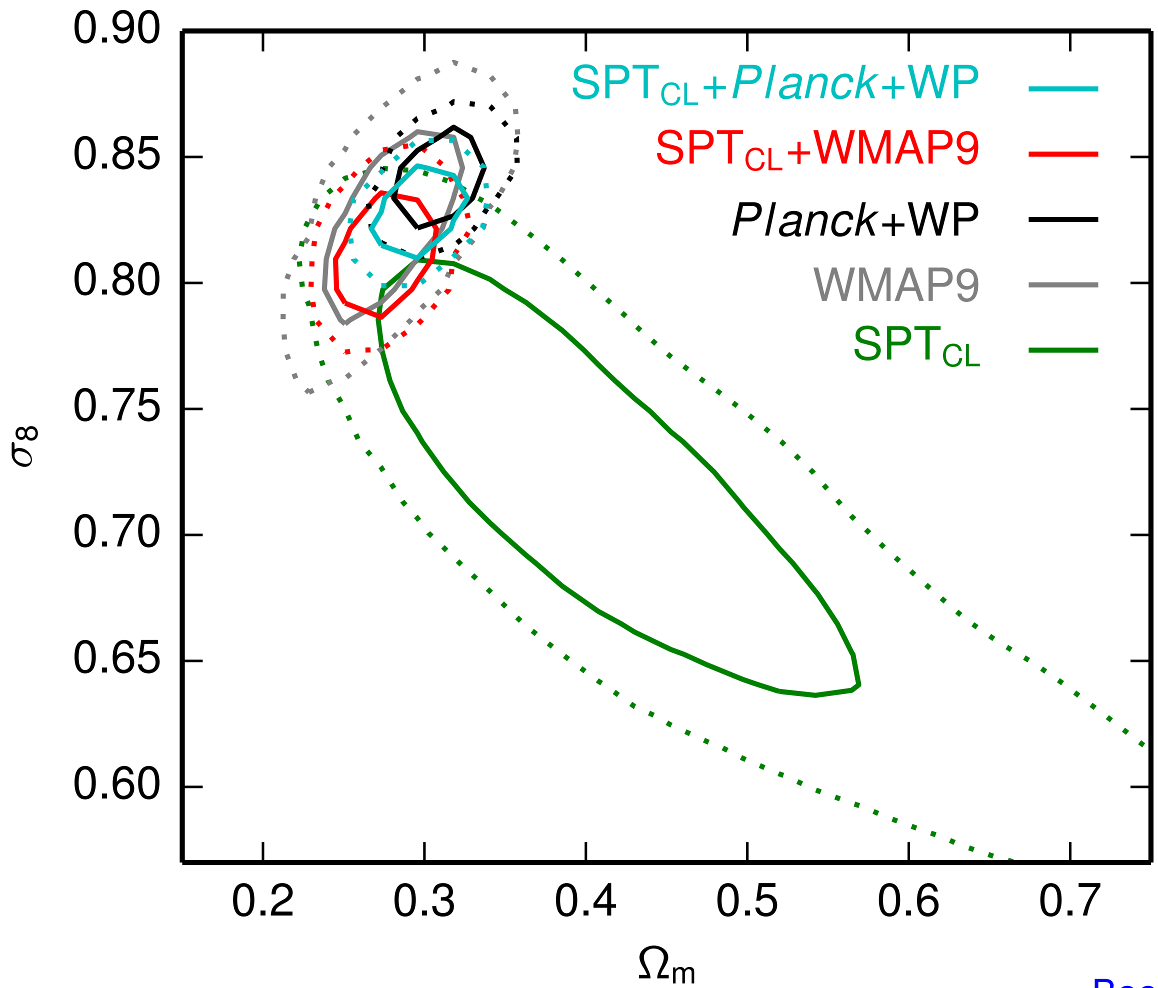
Planck cluster cosmology 2015

Tension can disappear
if primary CMB is used with clusters to constrain
the Y-M normalisation and cosmo parameters jointly



➔1-b=0.58 ± 0.04

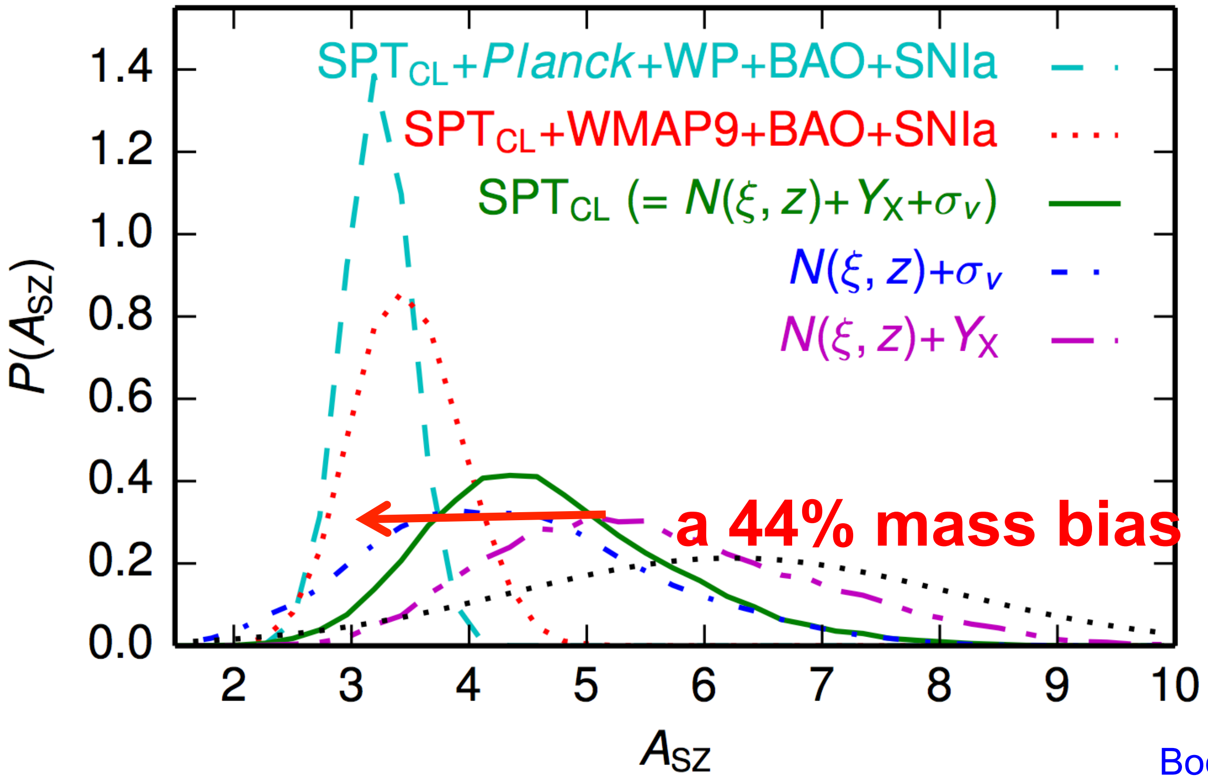
SPT cluster cosmology 2015



Bocquet et al. 2015

SPT cluster cosmology 2015

$$\zeta = A_{SZ}\left(\frac{M_{500,c}}{3\times10^{14}M_\odot h^{-1}}\right)^{\overset{\approx 1.5}{B_{SZ}}}\left(\frac{E(z)}{E(0.6)}\right)^{C_{SZ}}$$

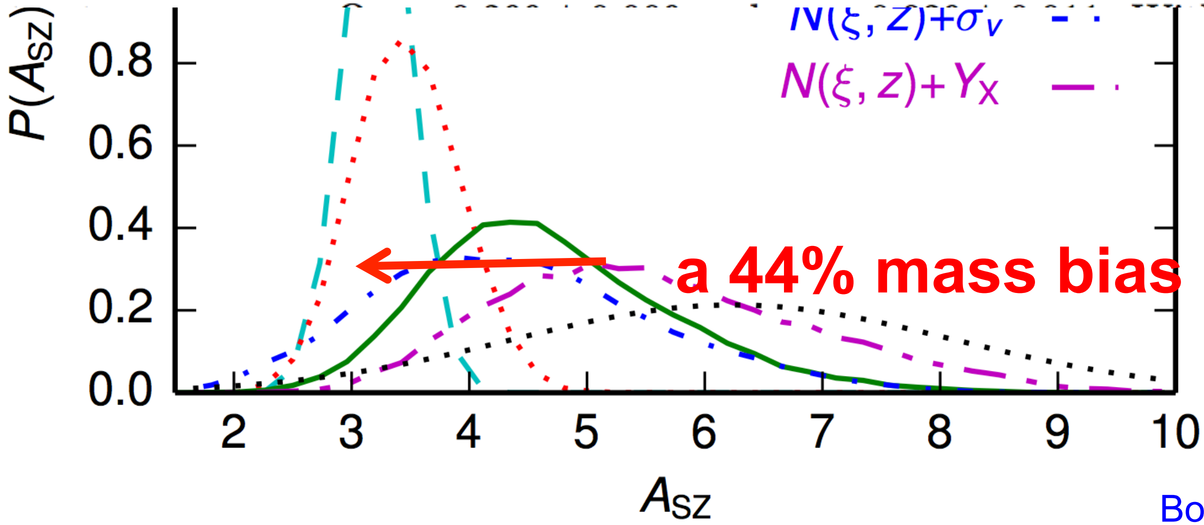


Bocquet et al. 2015

SPT cluster cosmology 2015

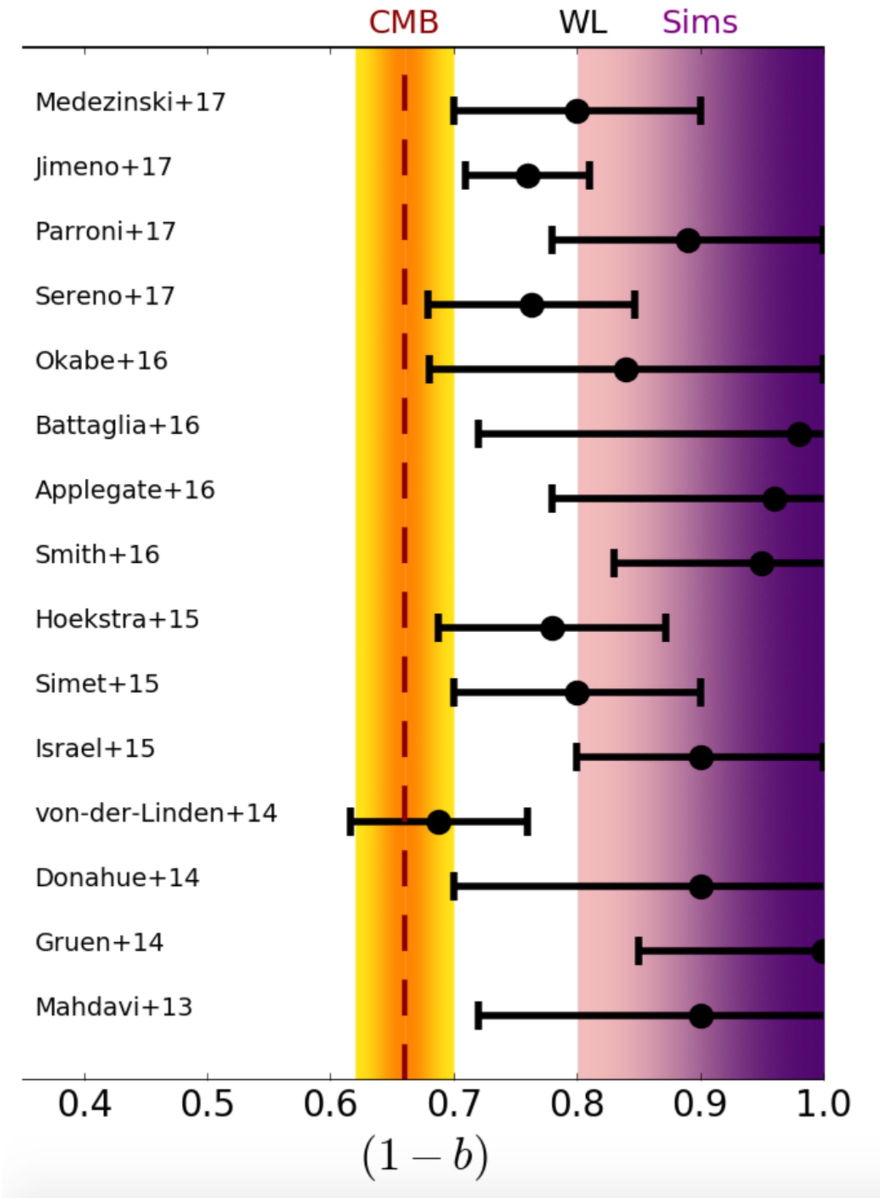
$$\zeta = A_{\rm SZ}\left(\frac{M_{500,c}}{3\times 10^{14} M_{\odot} h^{-1}}\right)^{\overset{\approx 1.5}{B_{\rm SZ}}}\left(\frac{E(z)}{E(0.6)}\right)^{C_{\rm SZ}}$$

larger $\sum m_\nu$ further reconciles the results. When we combine the $\mathrm{SPT_{CL}}$ and *Planck*+WP datasets with information from baryon acoustic oscillations and supernovae Ia, the preferred cluster masses are 1.9σ higher than the $Y_{\rm X}$ calibration and 0.8σ higher than the σ_v calibration. Given the scale of these shifts ($\sim$44% and $\sim$23% in mass, respectively), we execute a goodness of fit test; it reveals no tension, indicating that the best-fit model provides an adequate description of the data. Using the



Bocquet et al. 2015

Direct constraints on 1-b

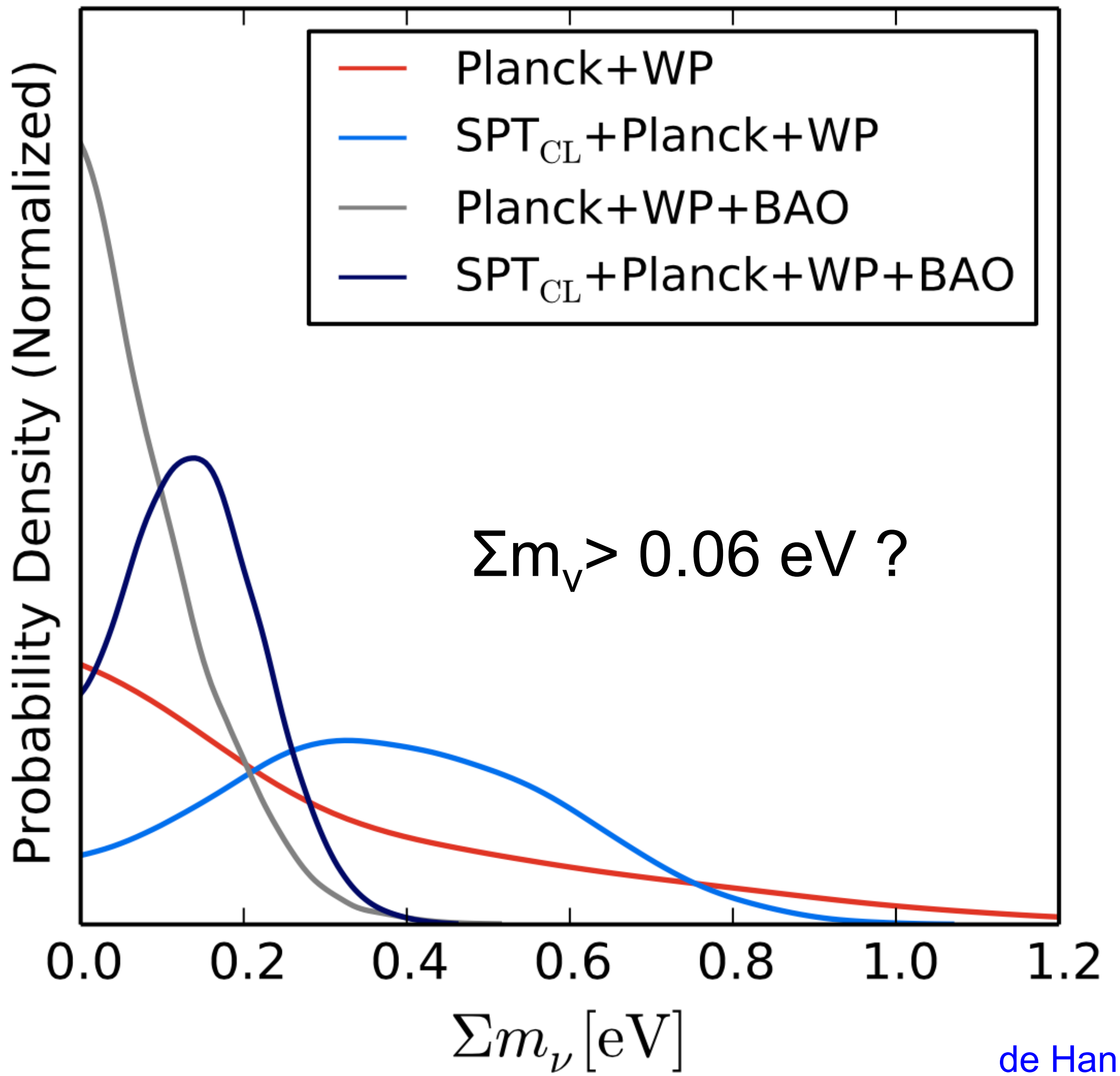


Salvati et al. 2017

How to reconcile Planck CMB and SZ counts?

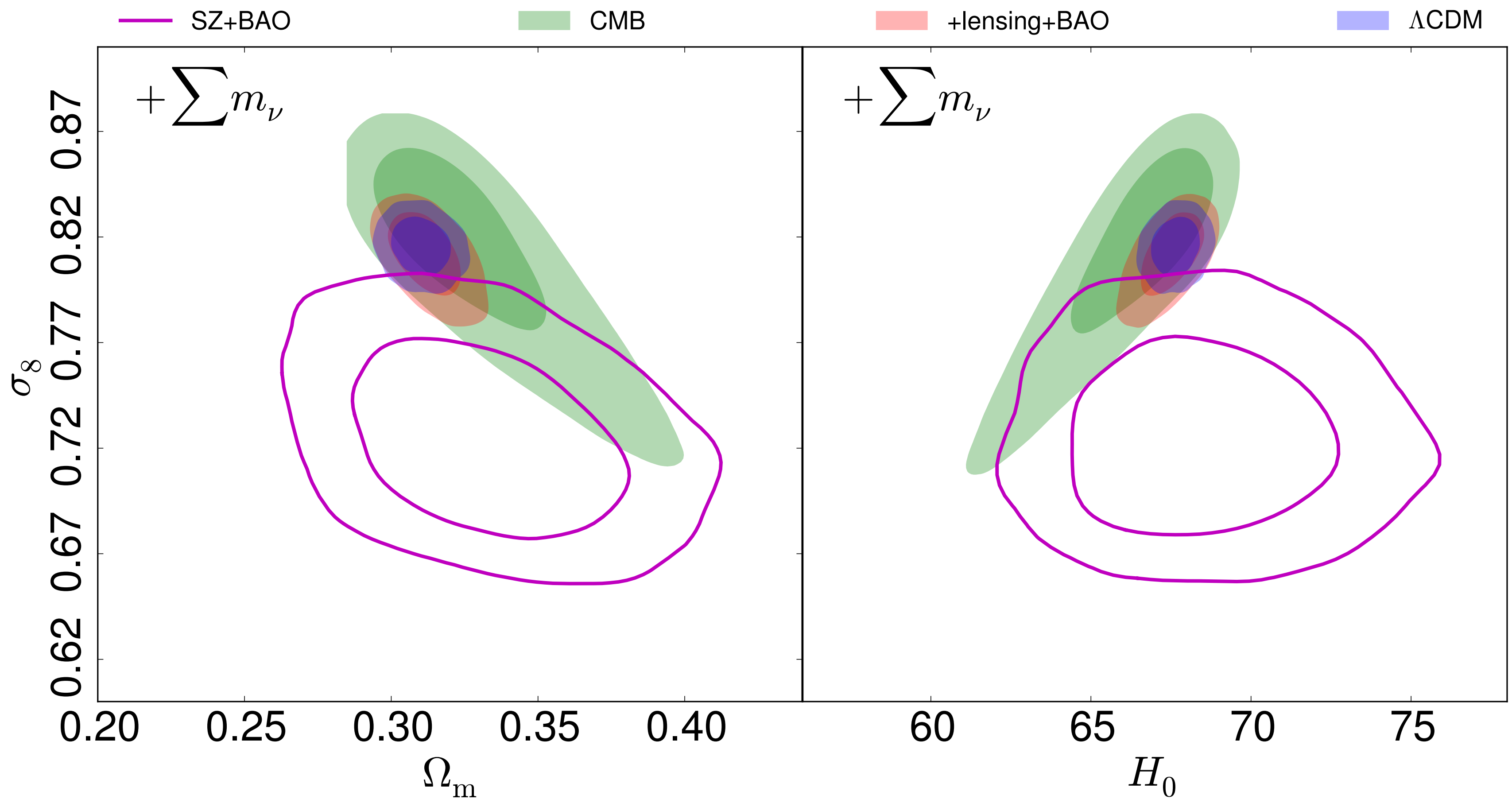
- Mass calibration? $P(z, M_{500} | Y_{500}, \theta_{500})$
- New physics? Neutrino mass?
- Baryonic effects in the mass function? $\frac{dN}{dz\, dM_{500}\, d\Omega}$
- Selection function of SZ surveys? $\chi(Y_{500}, \theta_{500}, l, b)$
- Primary CMB?

Planck CMB+SZ and the neutrino masses



de Hann et al. 2016

Planck SZ: a non-zero neutrino mass helps but…



Planck Results XXIV 2015

How to reconcile Planck CMB and SZ counts?

- Mass calibration? $P(z, M_{500}|Y_{500}, \theta_{500})$

- New physics? Neutrino mass?

- Baryonic effects in the mass function? $\frac{dN}{dz\, dM_{500}\, d\Omega}$

- Selection function of SZ surveys? $\chi(Y_{500}, \theta_{500}, l, b)$

- Primary CMB?

Baryonic effects in the mass function

- Cui et al. 2012 → increase in cluster counts
- Velliscig et al. 2014 →20% decrease in cluster counts
- Martizzi et al. 2014 →5-10% decrease in cluster counts
- Cusworth et al. 2014 →15% decrease in cluster counts
- Bocquet et al. 2015 →no effect on cluster counts

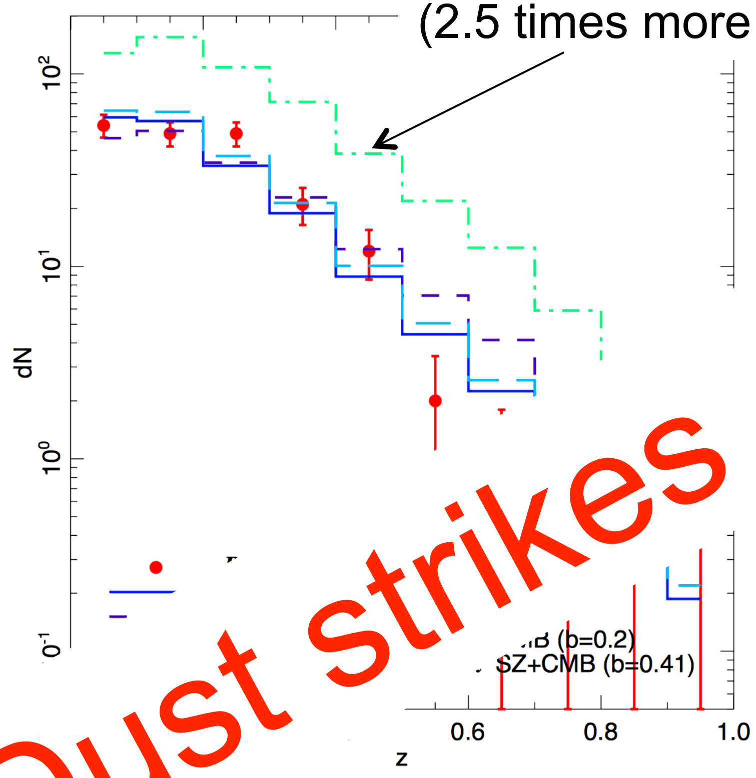
→ Not sufficient (would need a 60% decrease)

How to reconcile Planck CMB and SZ counts?

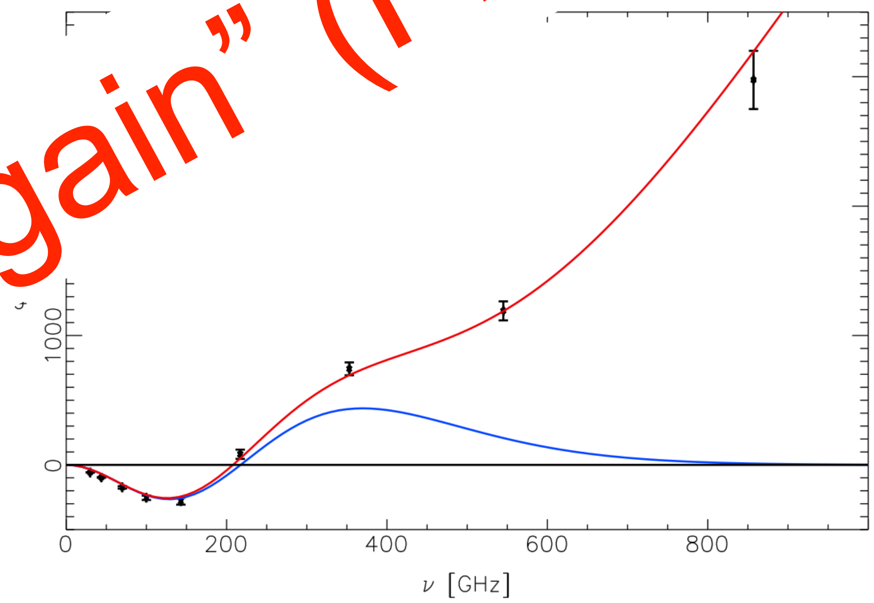
- Mass calibration? $P(z, M_{500}|Y_{500}, \theta_{500})$
- New physics? Neutrino mass?
- Baryonic effects in the mass function? $\frac{dN}{dz\, dM_{500}\, d\Omega}$
- Selection function of SZ surveys? $\chi(Y_{500}, \theta_{500}, l, b)$
- Primary CMB?

Selection function of SZ surveys?

CMB prediction
(2.5 times more clusters than observed



Planck Results XX 2013

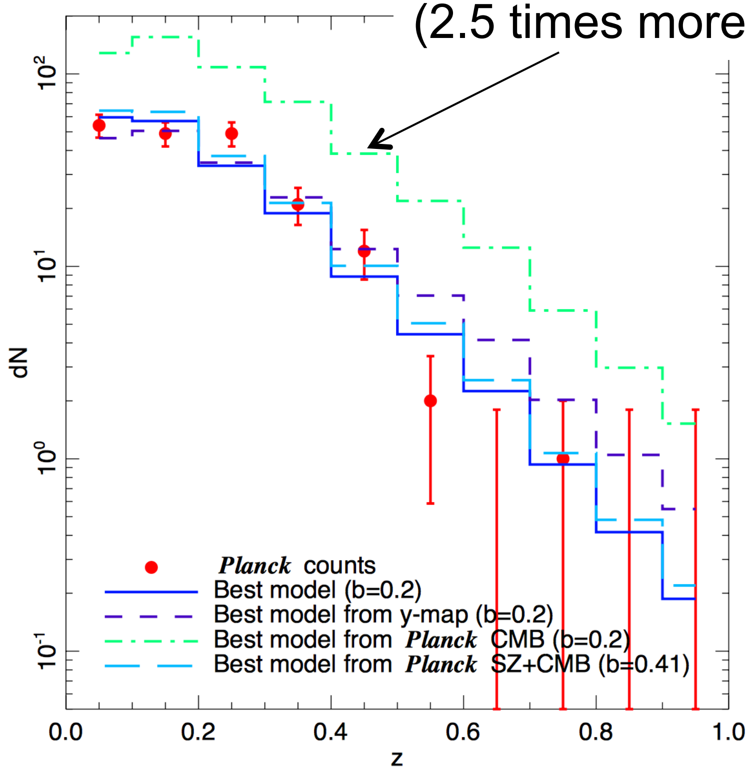


Planck Results XXIII 2015

"Dust strikes again" (FRB) ?

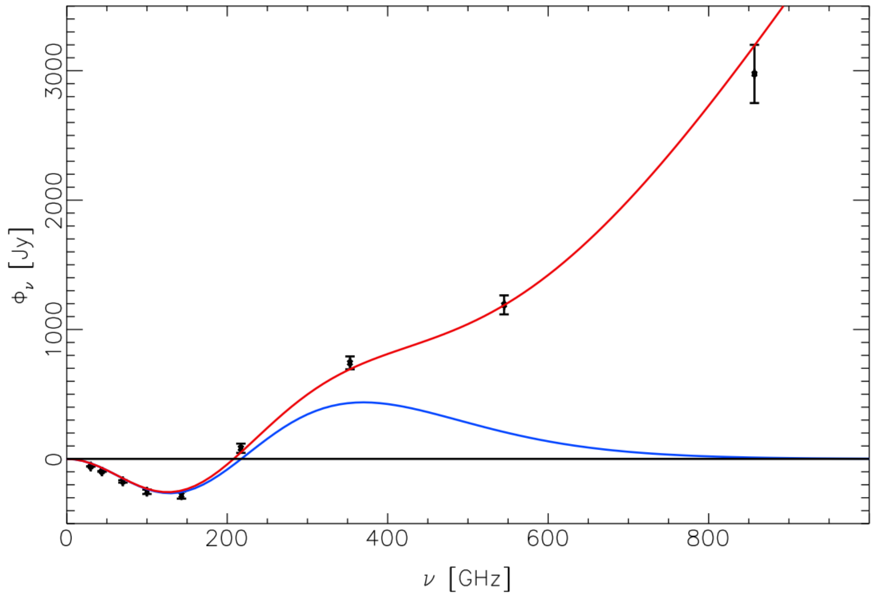
Selection function of SZ surveys?

CMB prediction
(2.5 times more clusters than observed)



Planck Results XX 2013

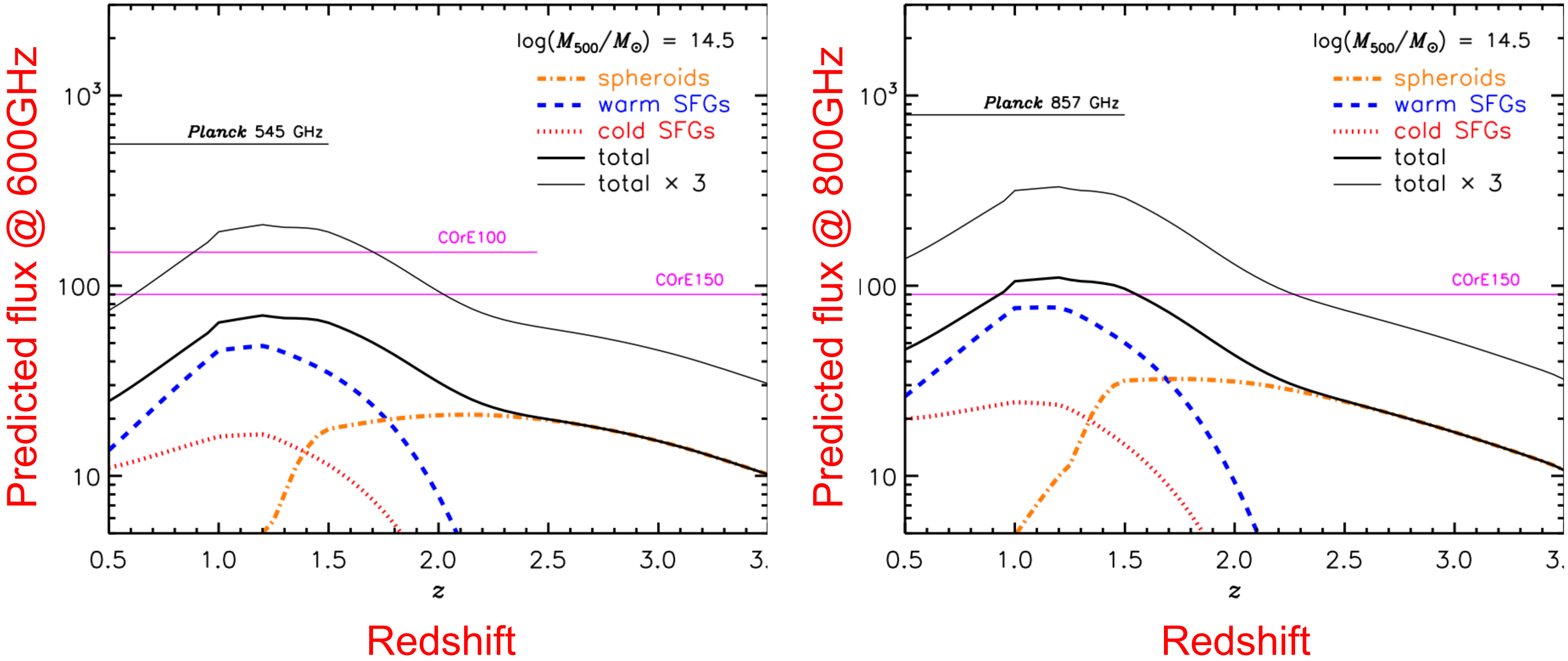
Impact of dust in clusters?



Planck Results XXIII 2015

The Cai & De Zotti dust model

De Zotti et al. 2016
arXiv:1609.07263

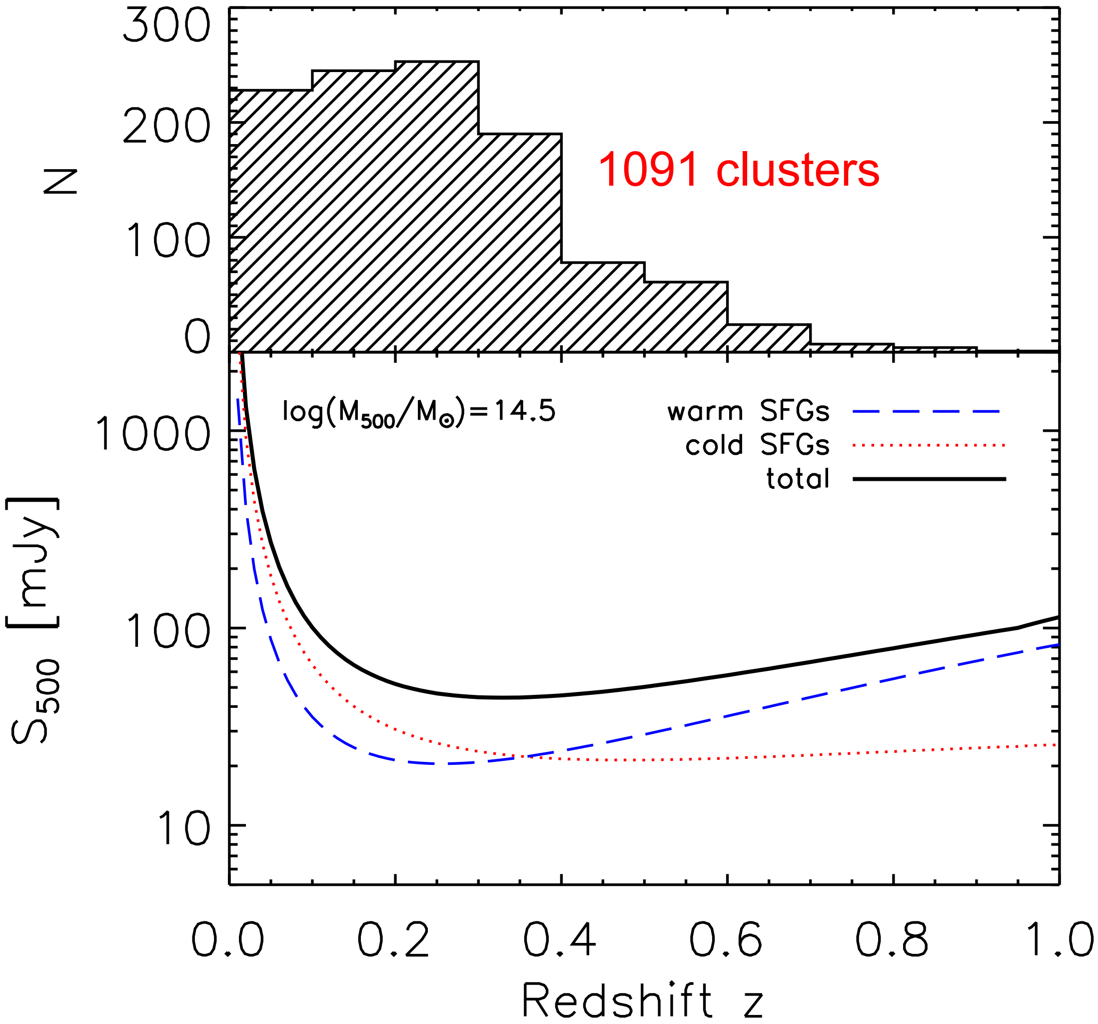


Model based on Herschel data of field and cluster galaxies (Alberts et al. 2014, 2016) and on luminosity functions and spectral energy distributions from Cai. et al. 2013

➡ No cross-check with Planck 857GHz & no information on spatial distribution

PSZ2 distribution and Cai & De Zotti model (0<z<1)

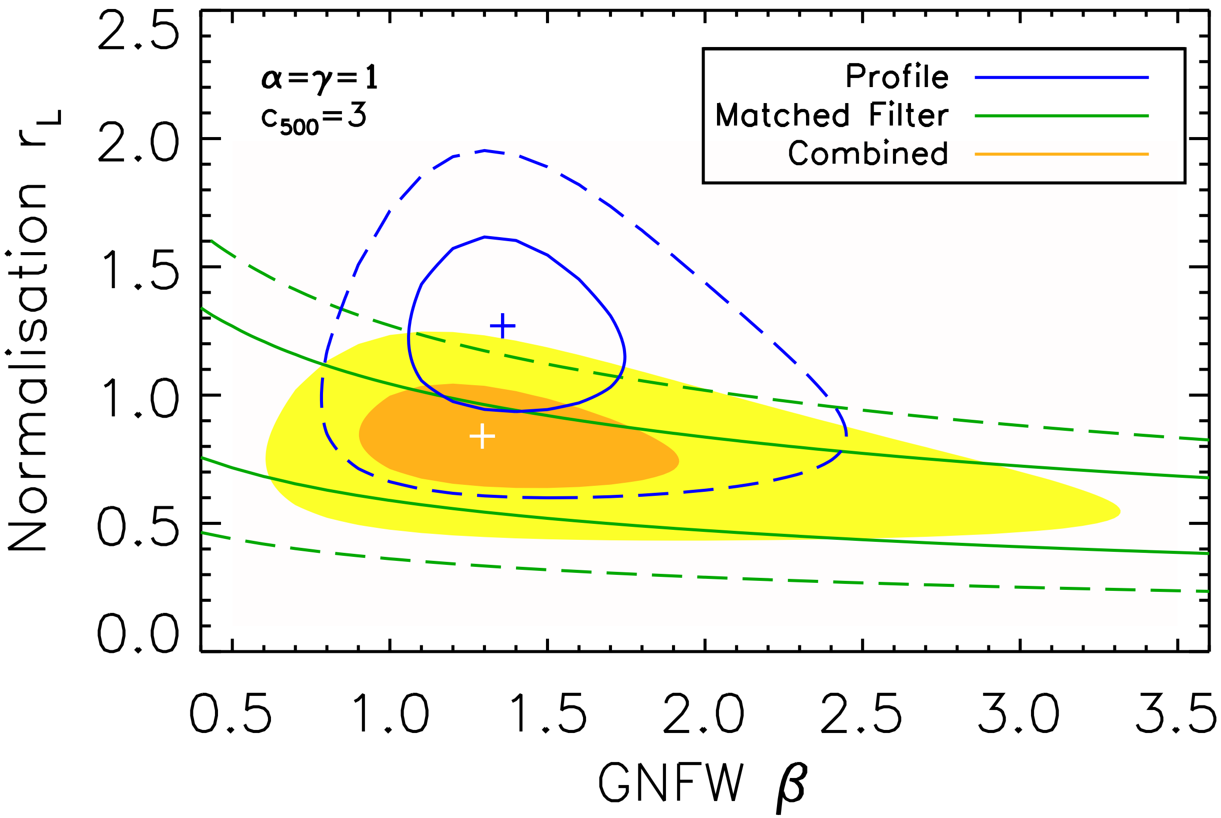
Melin et al. submitted to A&A



Dust in clusters: best fits

Melin et al. submitted to A&A

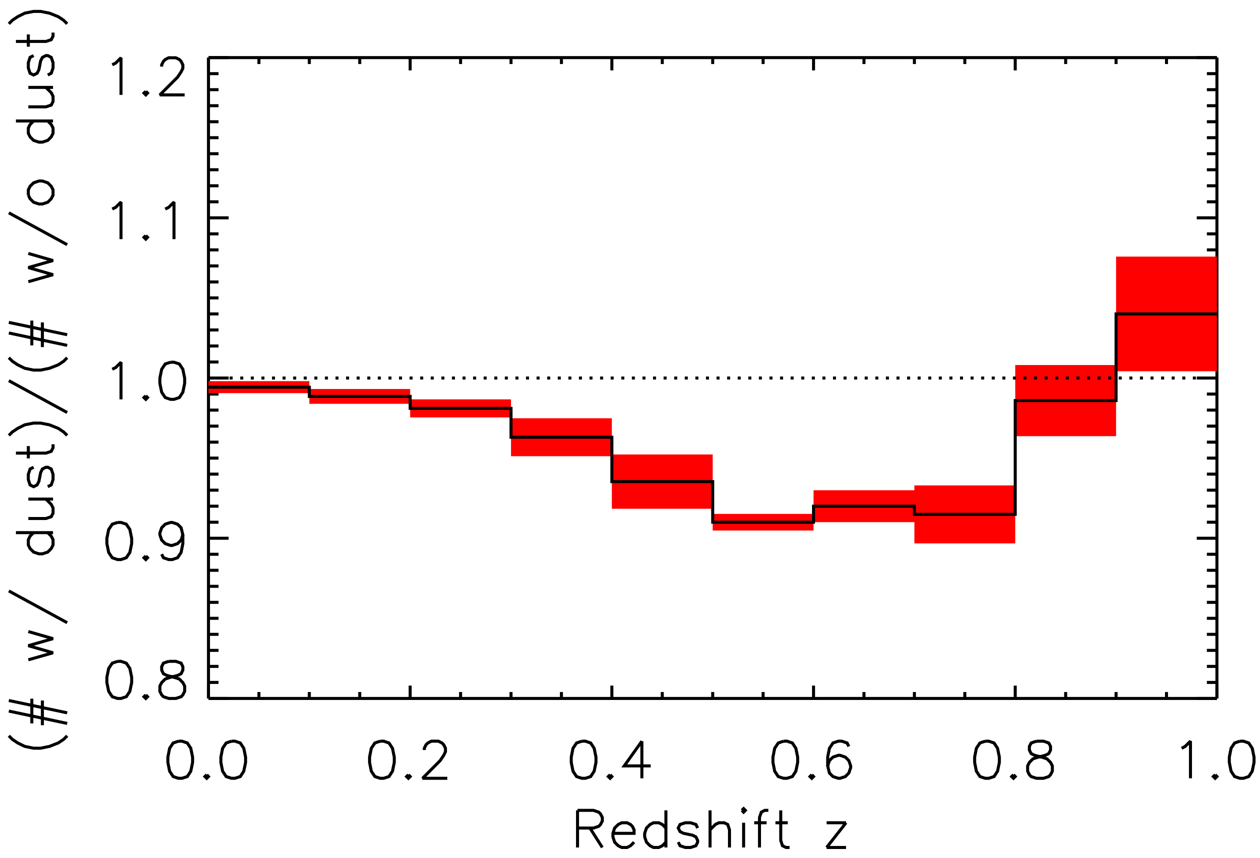
Normalisation of the L_{IR}-M relation relative to the Cai & De Zotti dust model



External slope of the fitted GNFW profile

Dust in clusters: impact on survey completeness

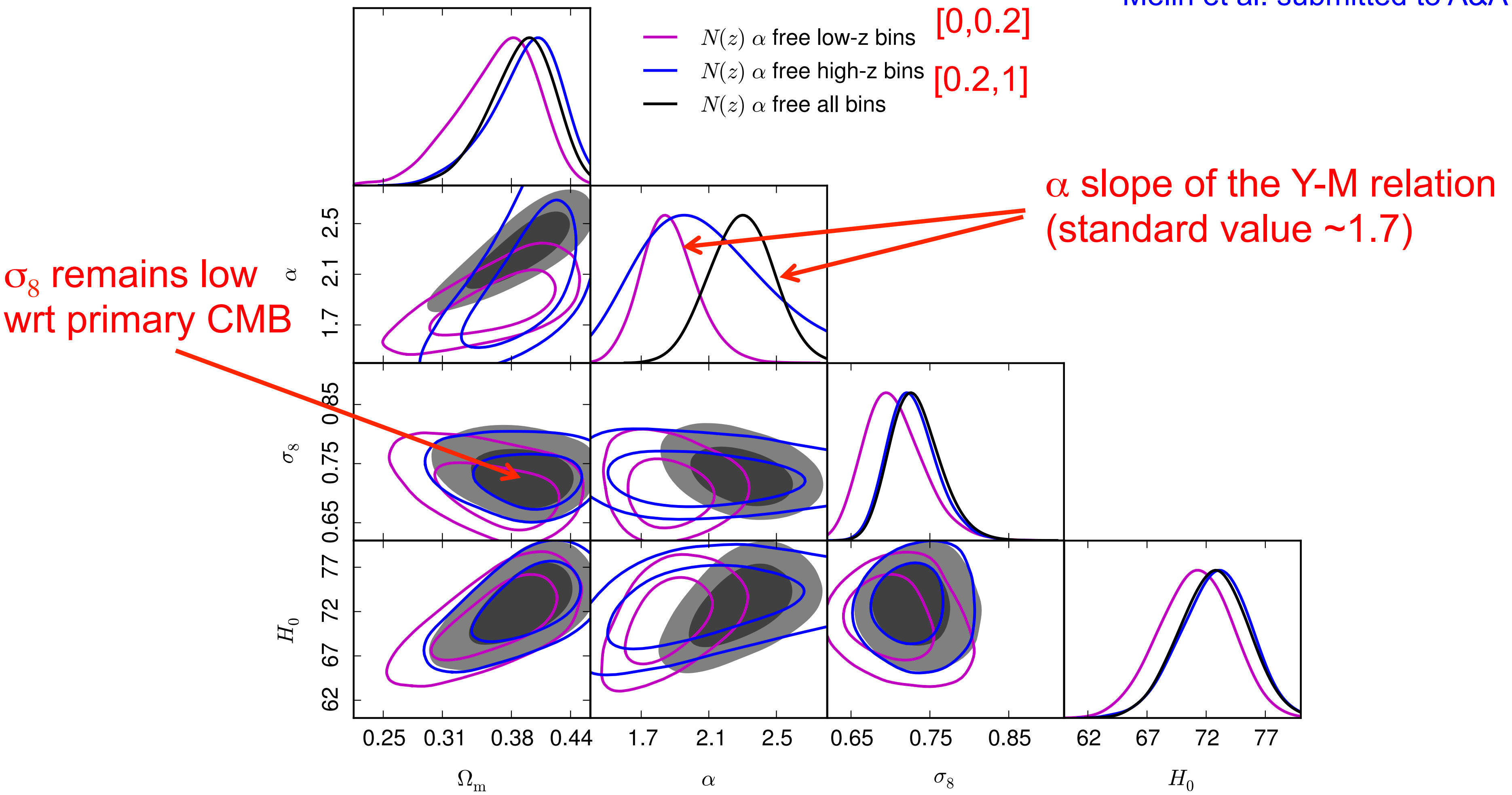
Melin et al. submitted to A&A



Maximum: ~<9% loss in [0.5,0.8]

Planck cluster cosmology 2015

Melin et al. submitted to A&A



Negligible shifts in cosmological parameters
Does not help to reconcile low-z and high-z counts

How to reconcile Planck CMB and SZ counts?

- Mass calibration? $P(z, M_{500}|Y_{500}, \theta_{500})$
- New physics? Neutrino mass?
- Baryonic effects in the mass function? $\frac{dN}{dz\, dM_{500}\, d\Omega}$
- Selection function of SZ surveys? $\chi(Y_{500}, \theta_{500}, l, b)$
- Primary CMB?

Primary CMB?

Primary CMB anisotropies actually constrain $\mathbf{A_s e^{-2\tau}}$

(see E. Komatsu's lecture)

	Planck		*Planck*+lensing		*Planck*+WP	
Parameter	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± 0.012

Planck
Results XVI **2013**

Primary CMB?

Planck Results XIII **2015**

Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits	TT,TE,EE+lowP 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016
$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1184 ± 0.0012	0.1198 ± 0.0015
$100\theta_{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046	1.04106 ± 0.00041	1.04077 ± 0.00032
τ	0.078 ± 0.019	0.066 ± 0.016	0.067 ± 0.013	0.079 ± 0.017
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.062 ± 0.029	3.064 ± 0.024	3.094 ± 0.034
n_s	0.9655 ± 0.0062	0.9677 ± 0.0060	0.9681 ± 0.0044	0.9645 ± 0.0049
H_0	67.31 ± 0.96	67.81 ± 0.92	67.90 ± 0.55	67.27 ± 0.66
Ω_Λ	0.685 ± 0.013	0.692 ± 0.012	0.6935 ± 0.0072	0.6844 ± 0.0091
Ω_m	0.315 ± 0.013	0.308 ± 0.012	0.3065 ± 0.0072	0.3156 ± 0.0091
$\Omega_m h^2$	0.1426 ± 0.0020	0.1415 ± 0.0019	0.1413 ± 0.0011	0.1427 ± 0.0014
$\Omega_m h^3$	0.09597 ± 0.00045	0.09591 ± 0.00045	0.09593 ± 0.00045	0.09601 ± 0.00029
σ_8	0.829 ± 0.014	0.8149 ± 0.0093	0.8154 ± 0.0090	0.831 ± 0.013
$\sigma_8 \Omega_m^{0.5}$	0.466 ± 0.013	0.4521 ± 0.0088	0.4514 ± 0.0066	0.4668 ± 0.0098
$\sigma_8 \Omega_m^{0.25}$	0.621 ± 0.013	0.6069 ± 0.0076	0.6066 ± 0.0070	0.623 ± 0.011

Planck+WP 68% limits
0.02205 ± 0.00028
0.1199 ± 0.0027
1.04131 ± 0.00063
$0.089^{+0.012}_{-0.014}$
0.9603 ± 0.0073
$3.089^{+0.024}_{-0.027}$
$0.685^{+0.018}_{-0.016}$
$0.315^{+0.016}_{-0.018}$
0.829 ± 0.012

Planck Results XVI **2013**

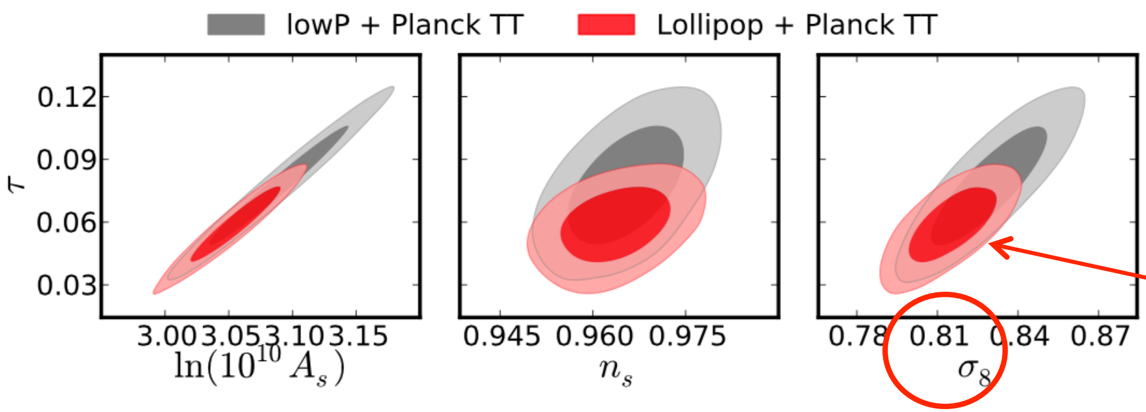
Primary CMB?

Planck Results XIII **2015**

TT,TE,EE+lowP 68 % limits
0.02225 ± 0.00016
0.1198 ± 0.0015
1.04077 ± 0.00032
0.079 ± 0.017
3.094 ± 0.034
0.9645 ± 0.0049
67.27 ± 0.66
0.6844 ± 0.0091
0.3156 ± 0.0091
0.1427 ± 0.0014
0.09601 ± 0.00029
0.831 ± 0.013
0.4668 ± 0.0098
0.623 ± 0.011

Planck Intermediate Results XLVII **2016**

$$\tau = 0.058^{+0.012}_{-0.012}\,, \qquad \texttt{lollipop+PlanckTT}\,; \qquad (5)$$



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$0.315^{+0.016}_{-0.018}$
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Planck Results XVI **2013**

Primary CMB?

Planck Results XIII **2015**

TT,TE,EE+lowP 68 % limits
0.02225 ± 0.00016
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0.1427 ± 0.0014
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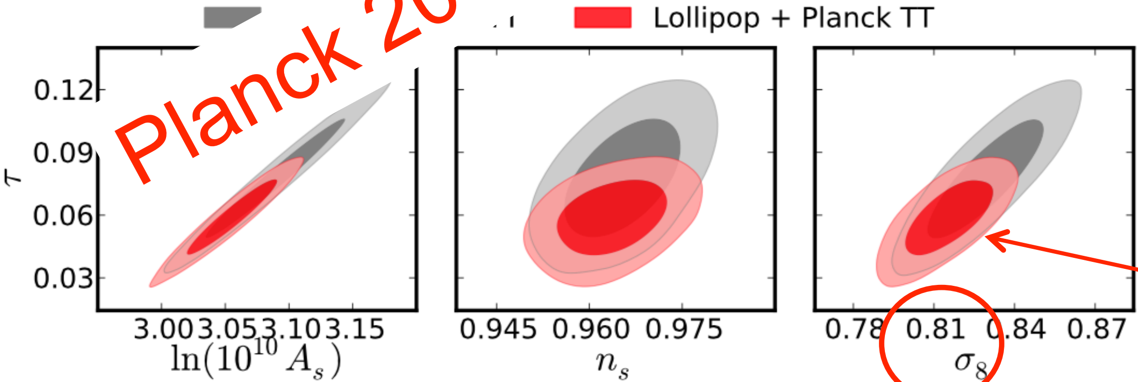
0.4668 ± 0.0098
0.623 ± 0.011

Planck Intermediate Results XLVII 2016

$$\tau = 0.058^{+0.012}_{-0.012}\,; \quad \text{+PlanckTT}\,; \qquad (5)$$

Planck 2018 release ?



Planck+WP 68% limits
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0.1199 ± 0.0027
1.04131 ± 0.00063
$0.089^{+0.012}_{-0.014}$
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$3.089^{+0.024}_{-0.027}$
$0.685^{+0.018}_{-0.016}$
$0.315^{+0.016}_{-0.018}$
0.829 ± 0.012

Planck Results XVI **2013**

First conclusions

- **ACT, SPT and Planck cluster constraints are in good agreement**
  The size/depth of the samples are different and the analyses made independently

- **SZ constraints** are **limited by uncertainties on scaling relations** (Y-M)

- **Mass scale (1-b) is the key** now.
  ➔Simulation studies, Shear measurements, CMB halo lensing

- **Future experiments** (eROSITA 2016, Euclid 2020) will provide additional data which will allow a 1% mass scale calibration

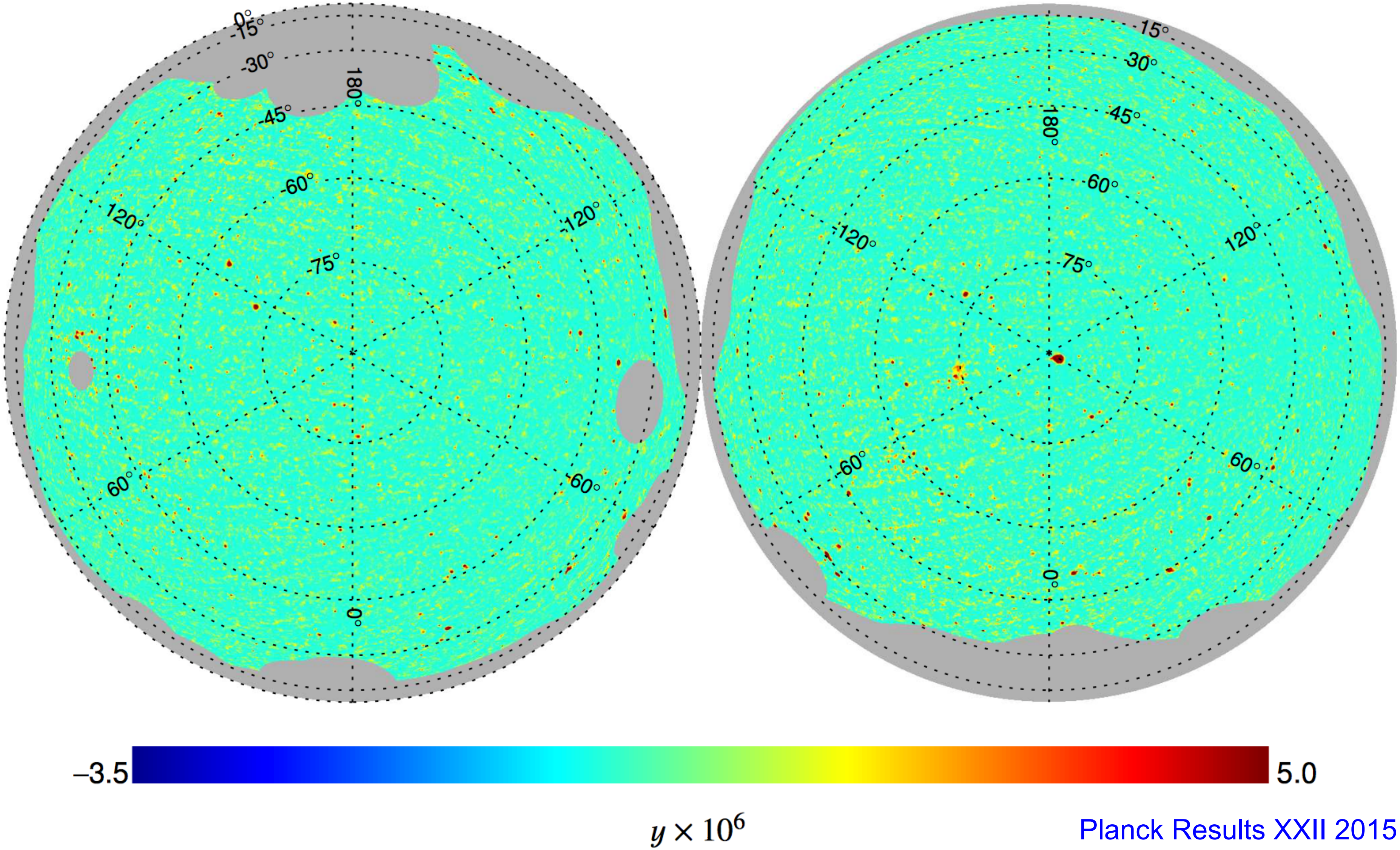
SZ cosmology from cluster counts

SZ power spectrum, kinetic SZ,
CMB data as a probe of the LSS

Outline

- SZ power spectrum
- Kinetic SZ
- CMB halo lensing
- Dust

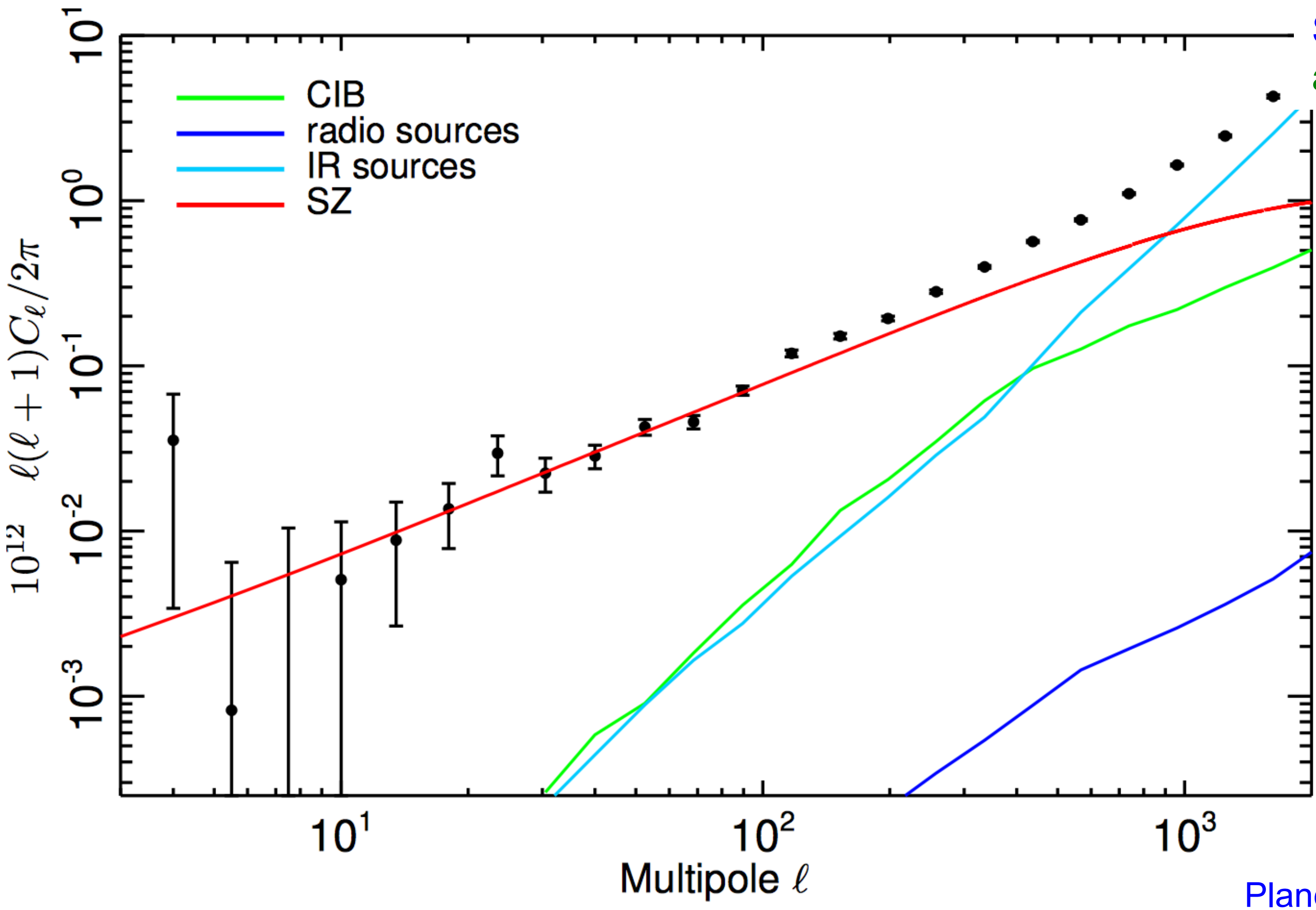
SZ maps & power spectrum



Planck Results XXII 2015

SZ maps & power spectrum

(see also Salvati et al. 2017 and B. Bolliet's talk)

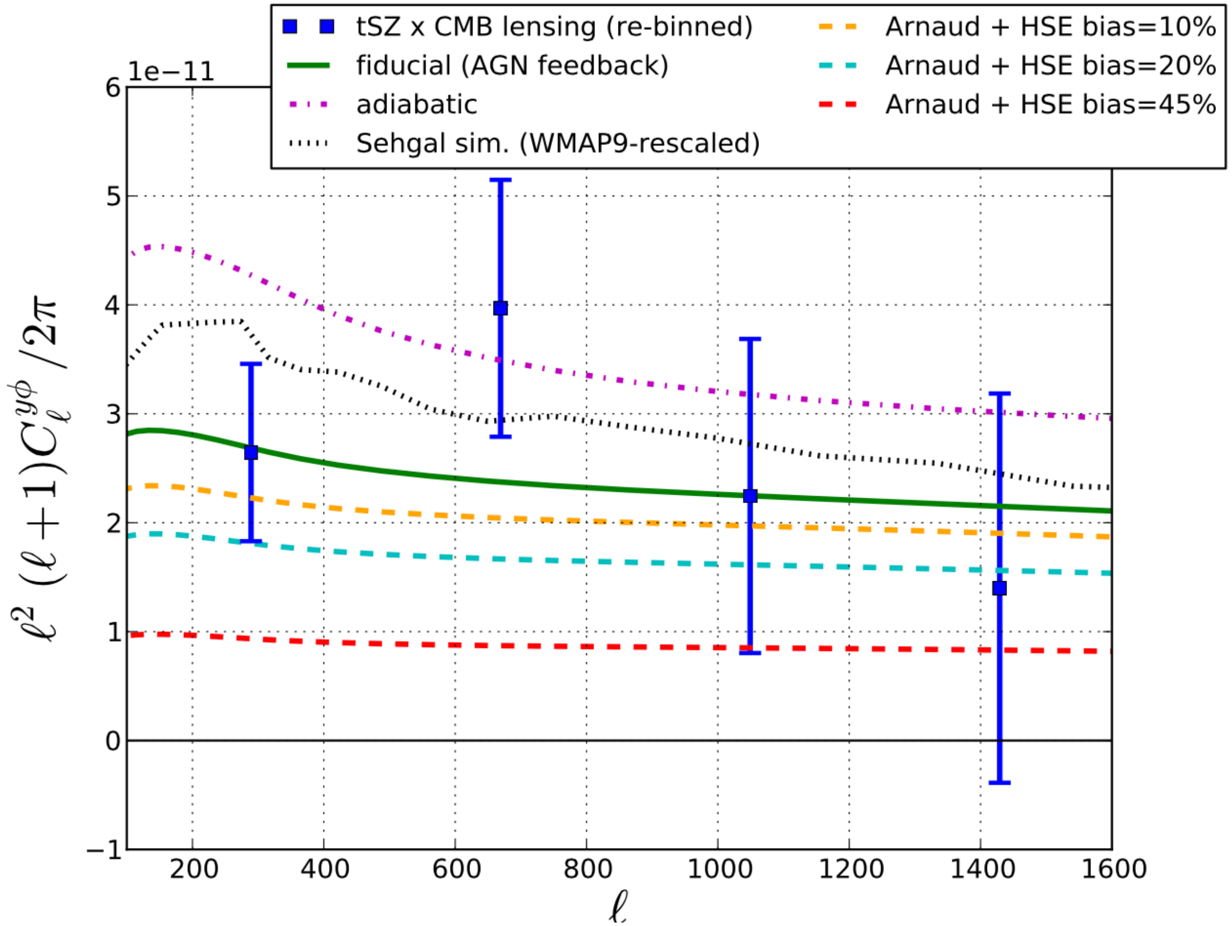


Planck Results XXII 2015

➡ Cosmological constraints consistent with SZ cluster counts

Cross Correlation Studies:
tSZ x CMB lensing

(see also
K. Osato's talk)



➔Constraints on the normalization of the Y-M relation
(crucial for cosmology with clusters)

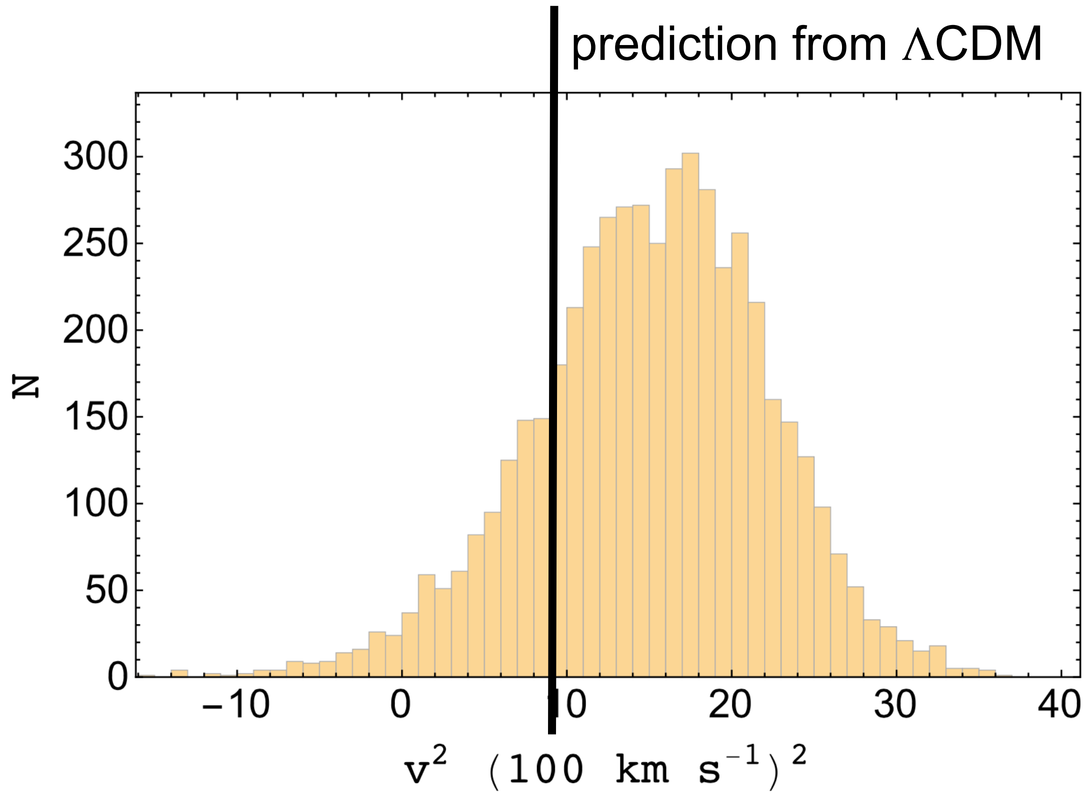
Hill & Spergel (2014)

Outline

- SZ power spectrum
- Kinetic SZ
- CMB halo lensing
- Dust

kSZ cosmological constraints

Looking for the variance of cluster velocities

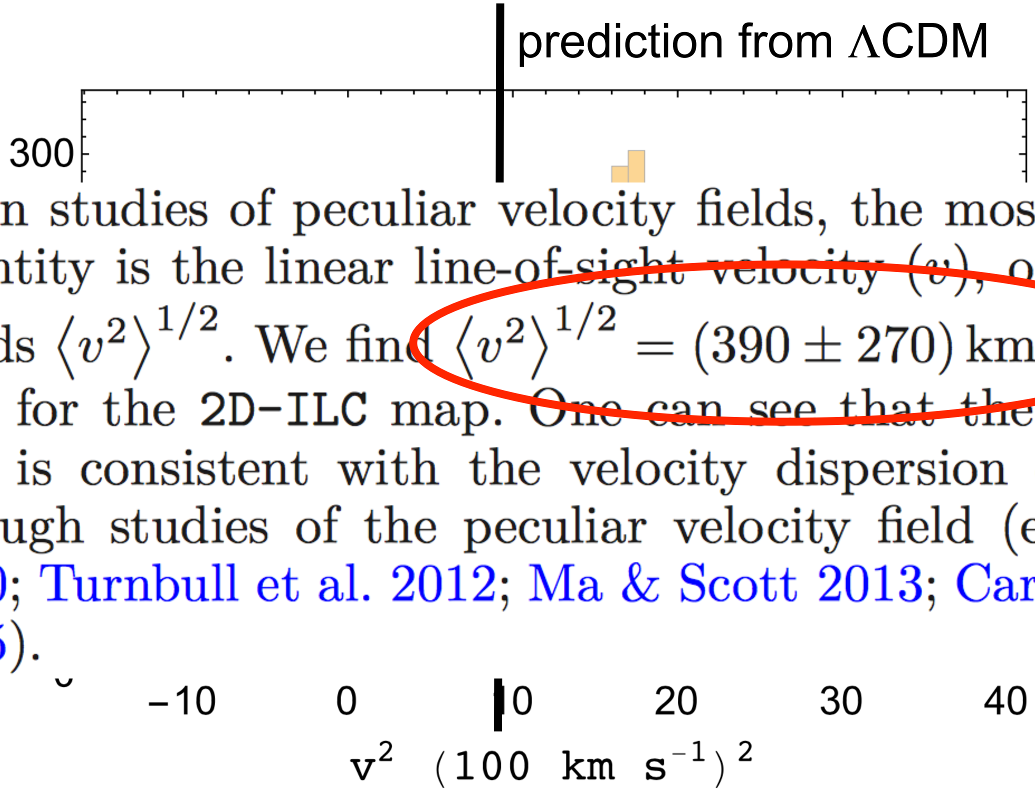


Planck Intermediate Results LIII 2017

Lacking both resolution and sensitivity…

kSZ cosmological constraints

Looking for the variance of cluster velocities

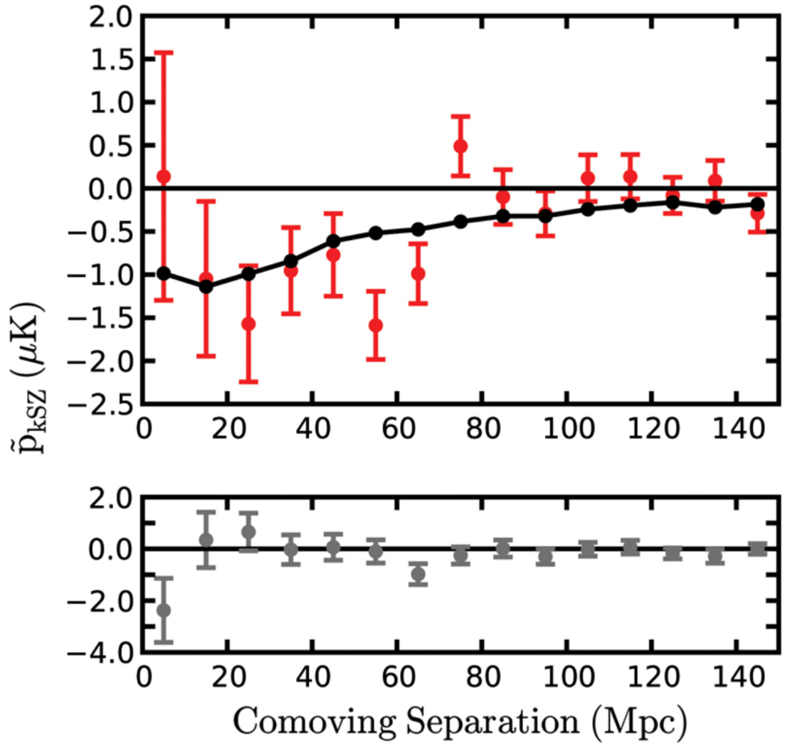


In studies of peculiar velocity fields, the most relevant quantity is the linear line-of-sight velocity $\langle v \rangle$, or in other words $\langle v^2 \rangle^{1/2}$. We find $\langle v^2 \rangle^{1/2} = (390 \pm 270)\,\mathrm{km\,s^{-1}}$ (68% CL) for the 2D-ILC map. One can see that the value we find is consistent with the velocity dispersion estimated through studies of the peculiar velocity field (e.g., Riess 2000; Turnbull et al. 2012; Ma & Scott 2013; Carrick et al. 2015).

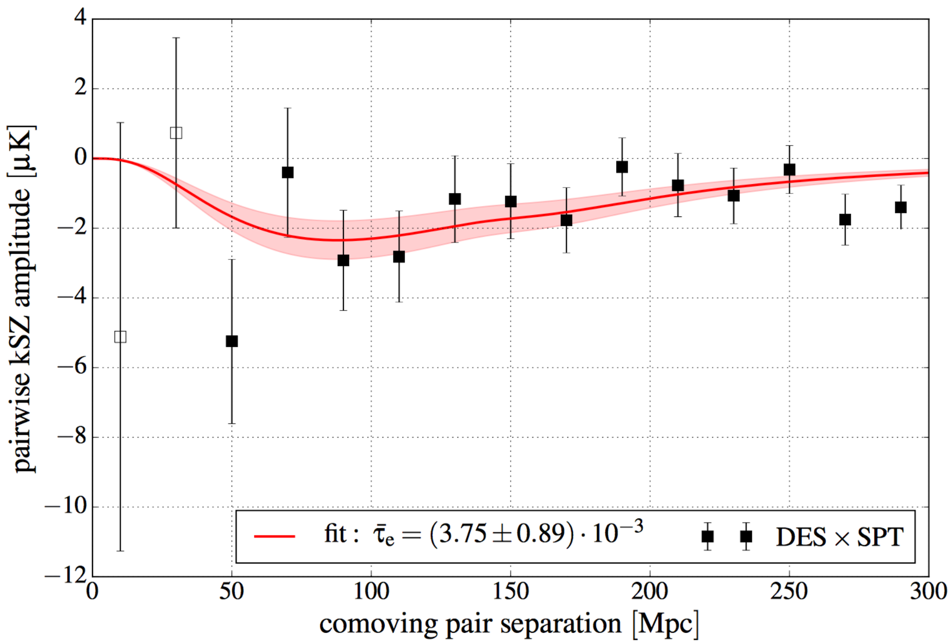
Planck Intermediate Results LIII 2017

Lacking both resolution and sensitivity…

kSZ cosmological constraints: pairwise momentum



SDSS and ACT - Hand et al. 2012
(see also De Bernardis et al. 2017)



DES and SPT - Soergel et al. 2016

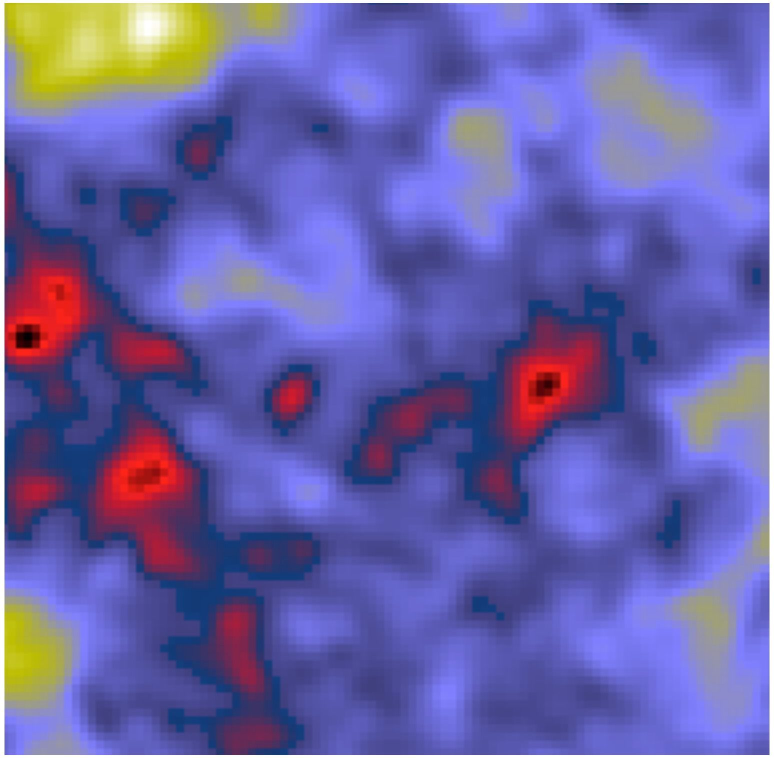
Very promising…

Outline

- SZ power spectrum
- Kinetic SZ
- CMB halo lensing
- Dust

Cluster CMB lensing…, what can we do now?

A2163 simulation



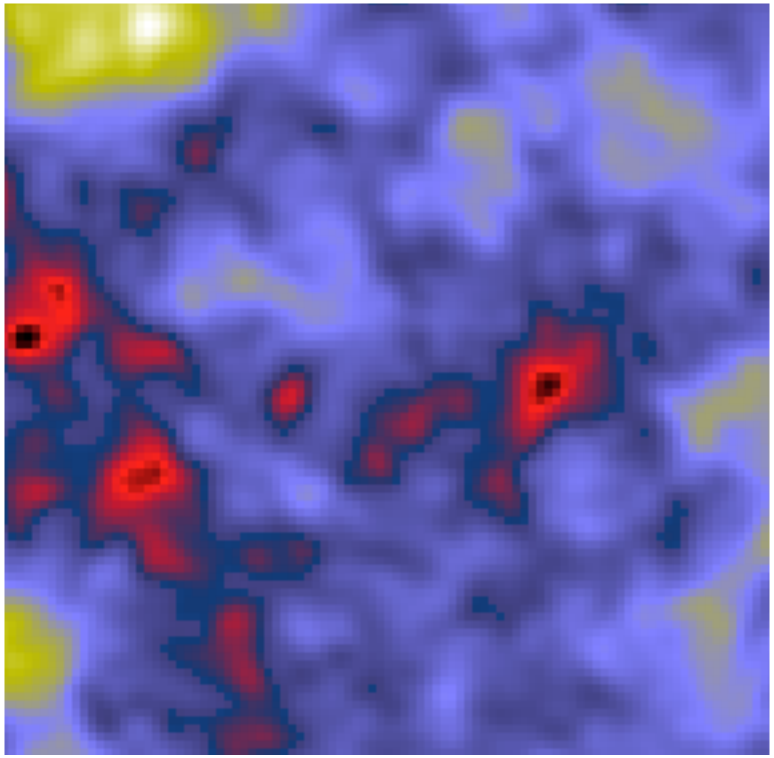
2.5 deg

(see also
A. Lewis' lecture
and
S. Patil's talk)

Unlensed CMB

Cluster CMB lensing…, what can we do now?

A2163 simulation



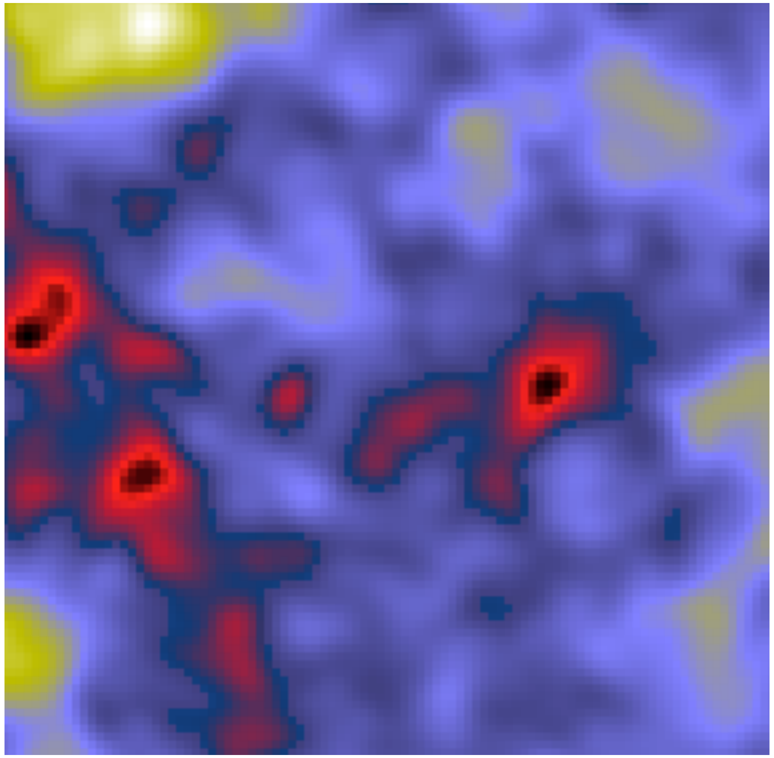
2.5 deg

(see also
A. Lewis' lecture
and
S. Patil's talk)

Lensed CMB

Cluster CMB lensing…, what can we do now?

A2163 simulation

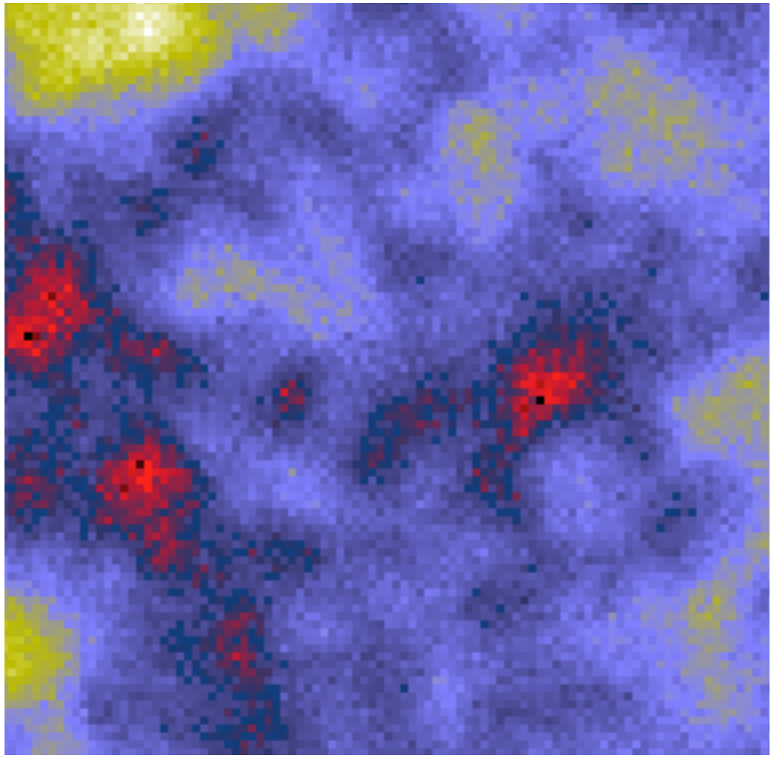


2.5 deg

Lensed CMB
+5arcmin beam

Cluster CMB lensing…, what can we do now?

A2163 simulation

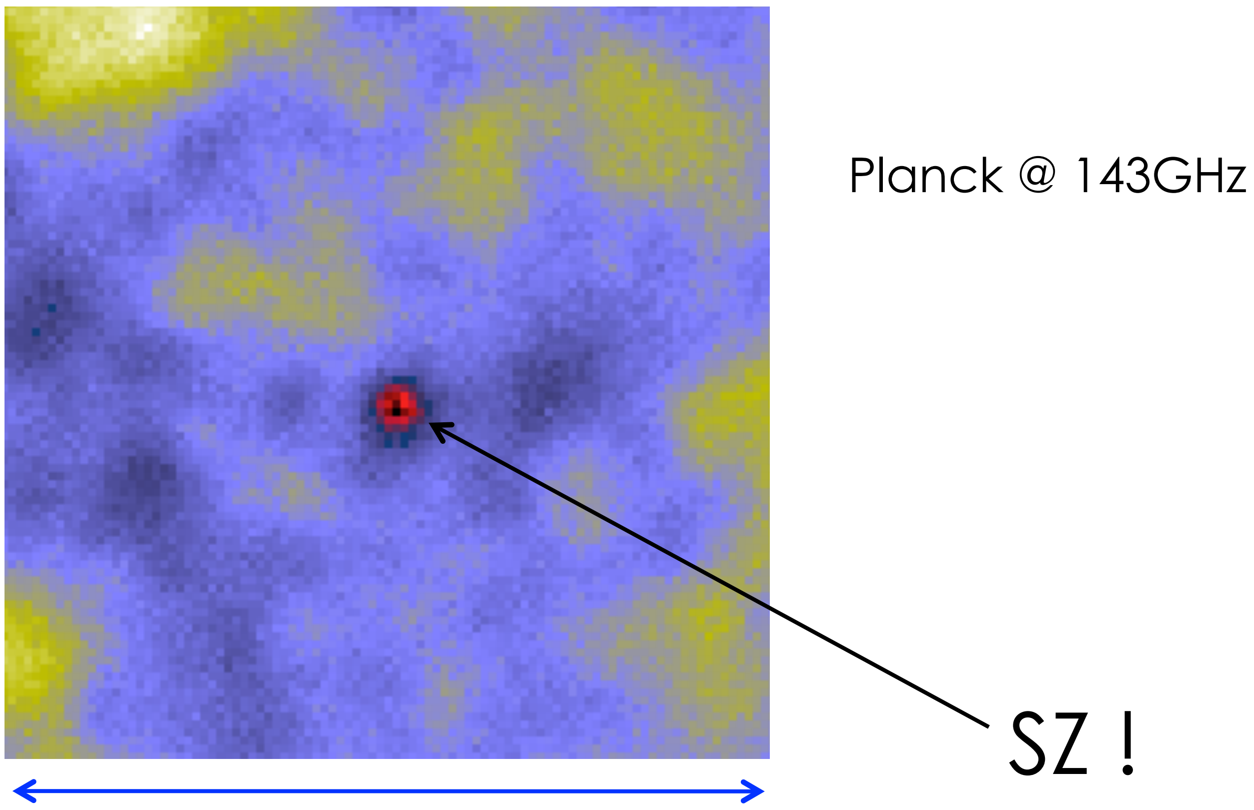


2.5 deg

Lensed CMB
+5arcmin beam
+instrumental noise

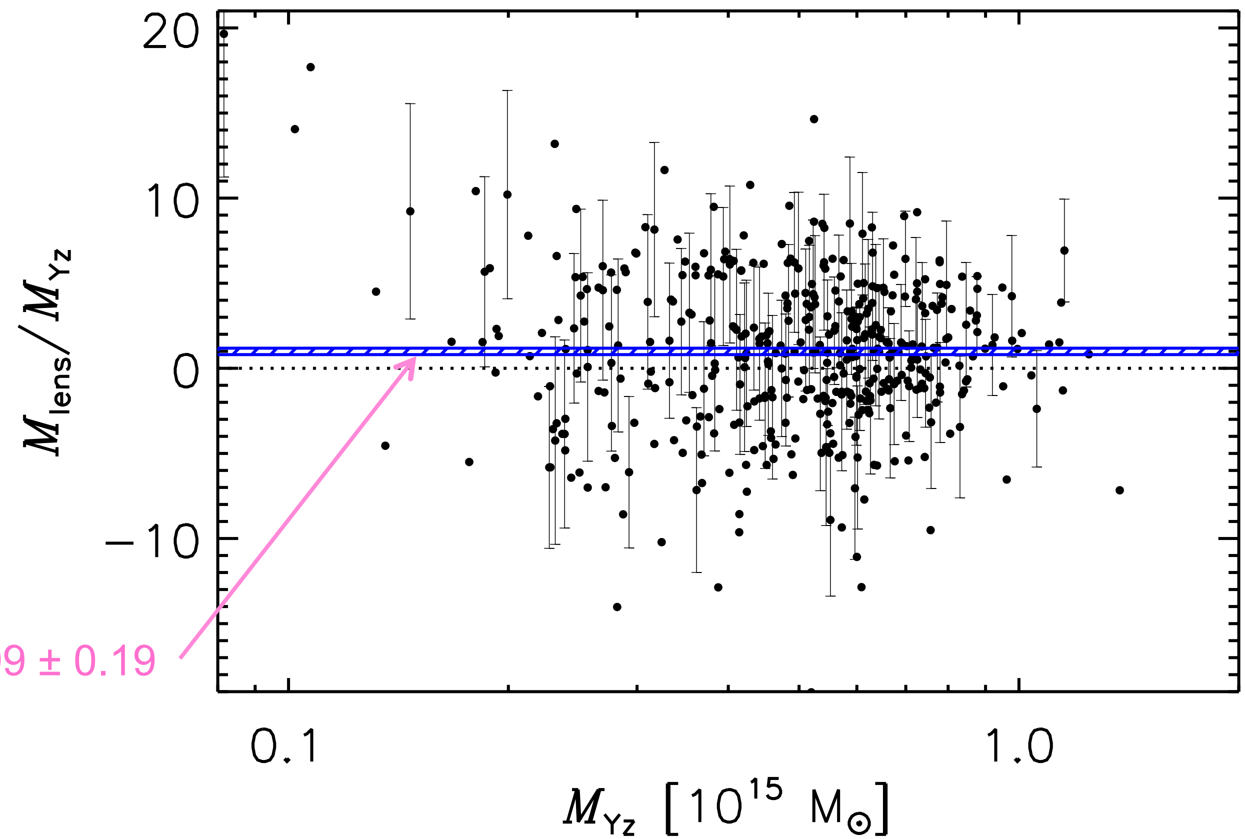
Cluster CMB lensing…, what can we do now?

A2163 simulation



Cluster CMB lensing: application to Planck data

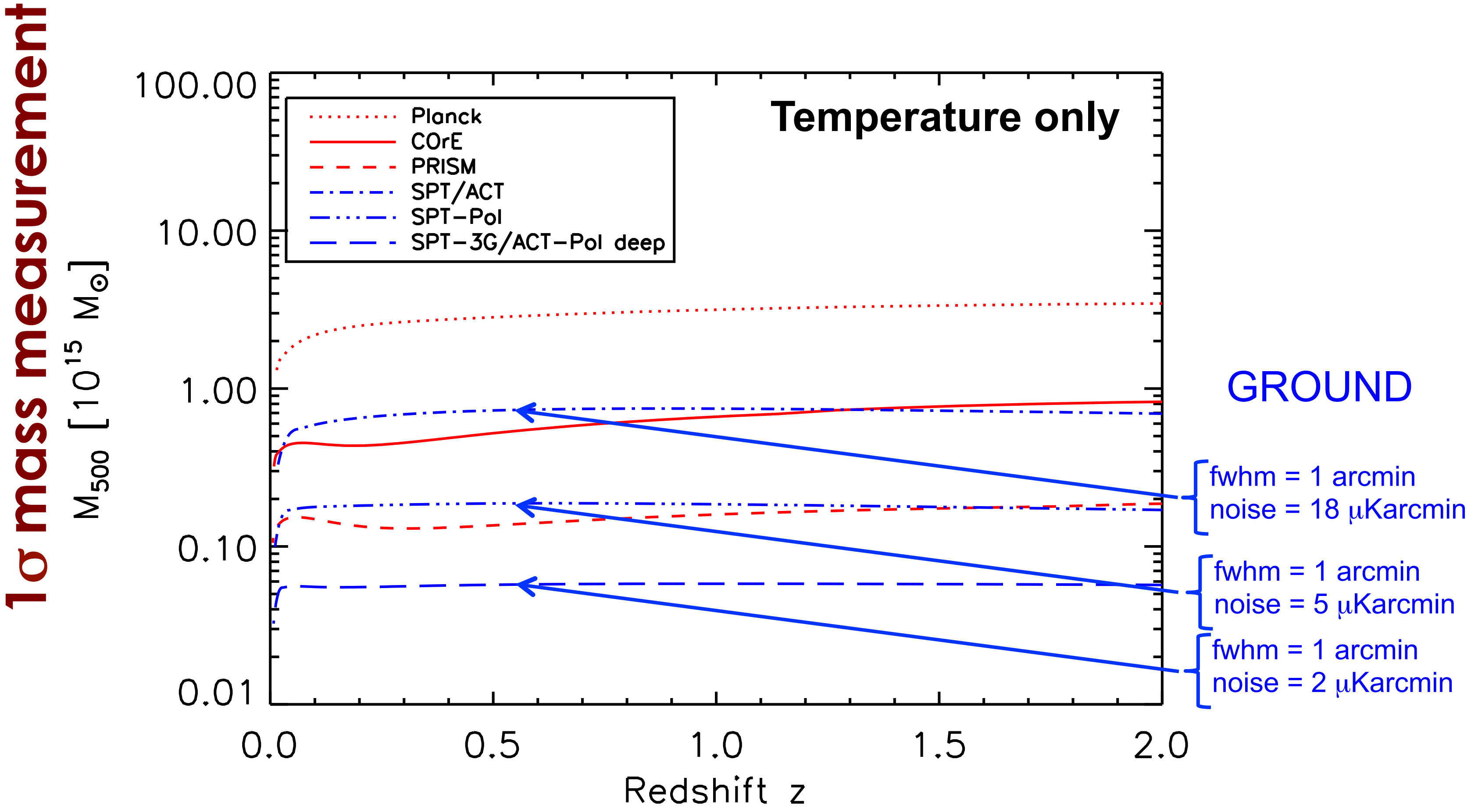
Planck Coll. 2015 XXIV



$M_{\rm lens}/M_{\rm Yz}$=0.99 ± 0.19

Cluster CMB lensing: future surveys

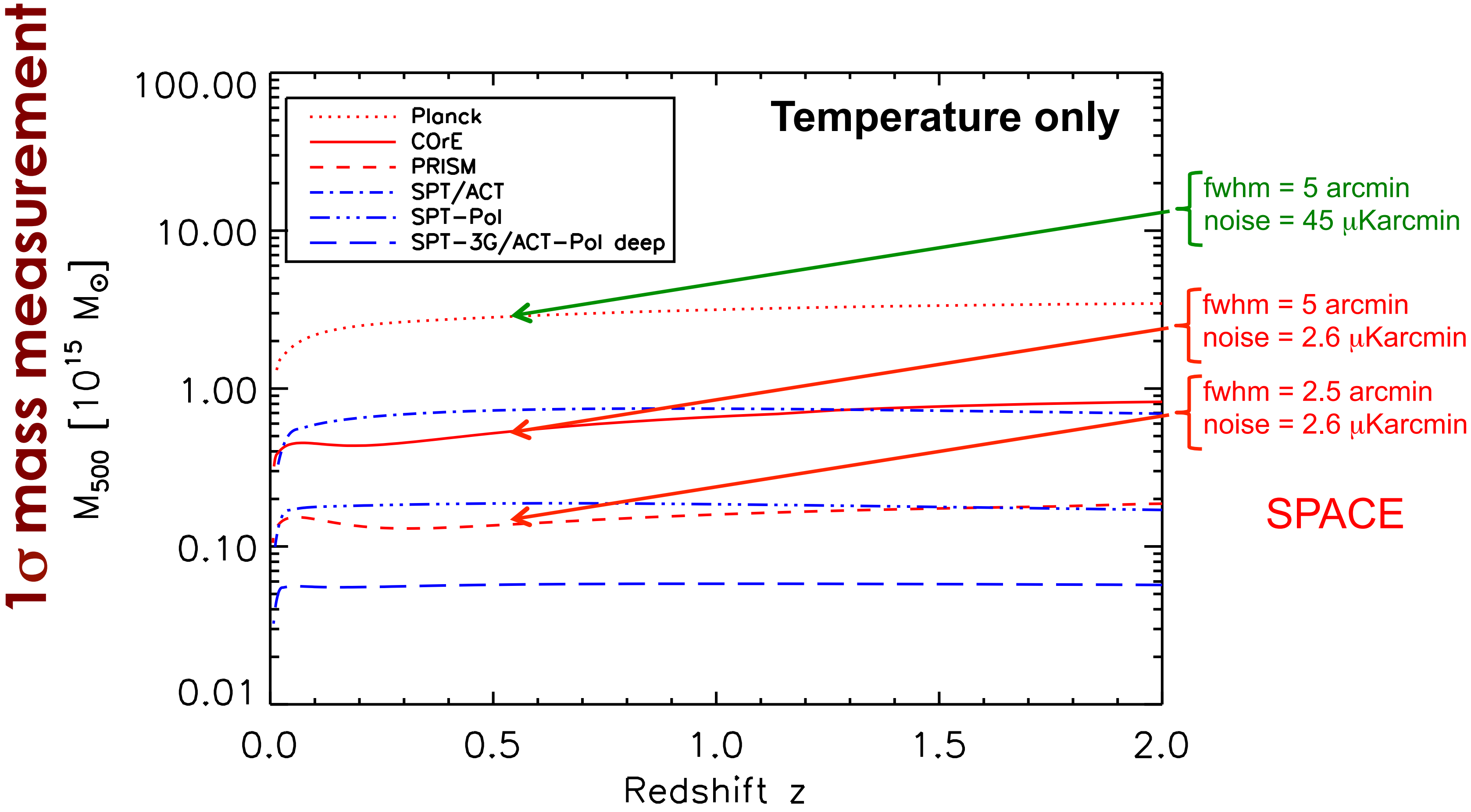
Melin & Bartlett 2015
arXiv:1408.5633



does not take into account ability to eliminate contaminating signals

Cluster CMB lensing: future surveys

Melin & Bartlett 2015
arXiv:1408.5633

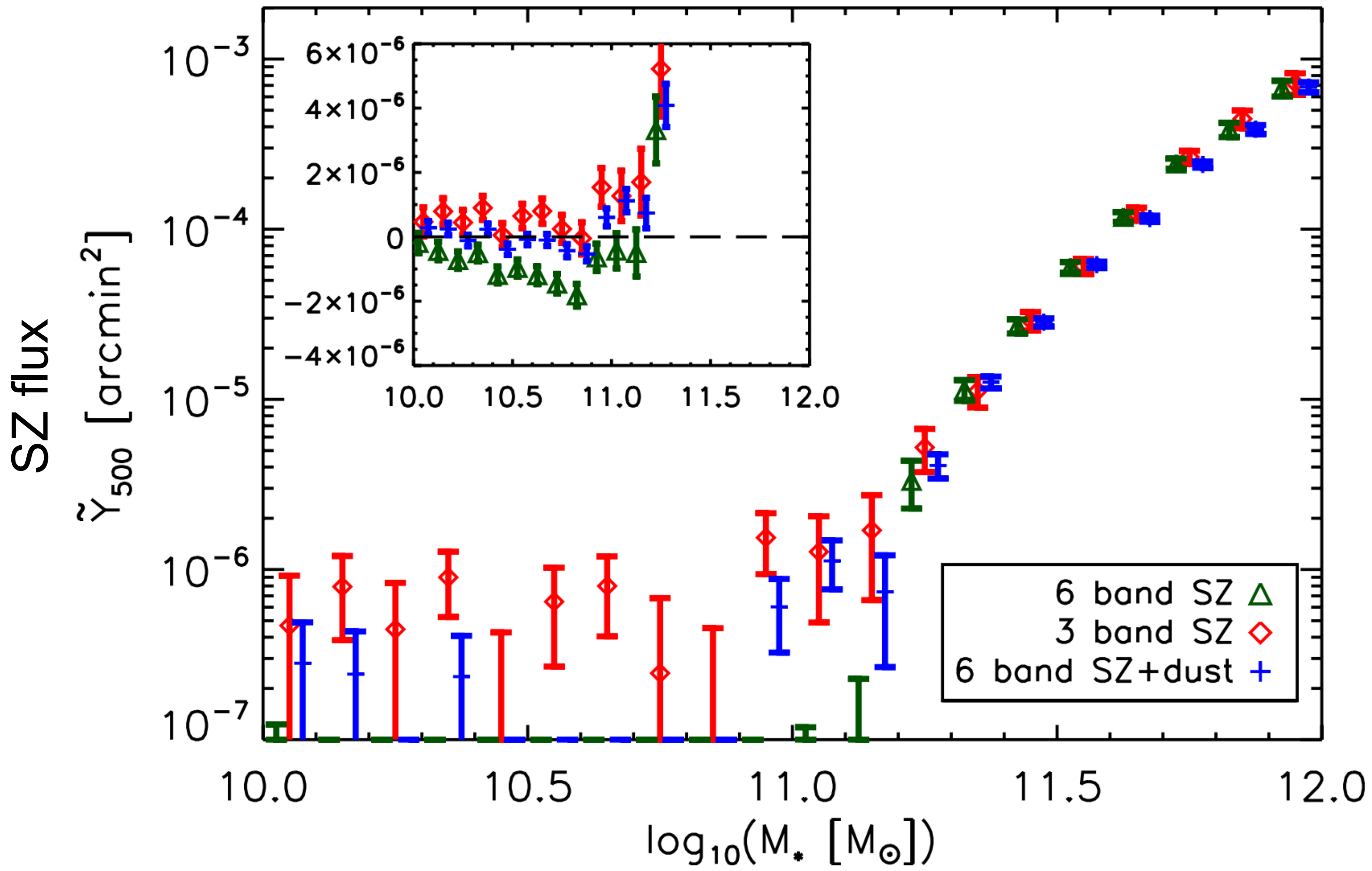


does not take into account ability to eliminate contaminating signals

Outline

- SZ power spectrum
- Kinetic SZ
- CMB halo lensing
- Dust

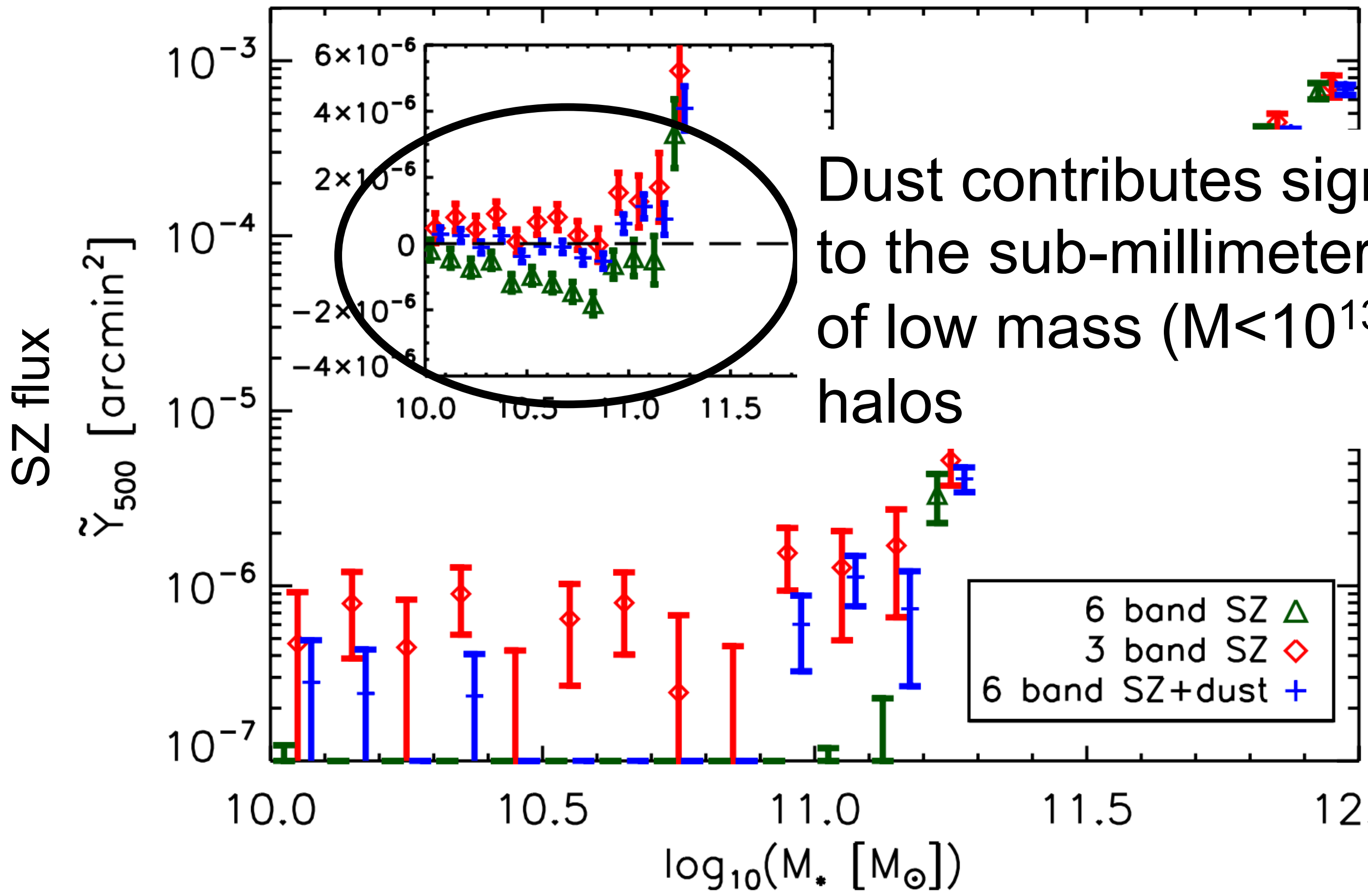
Population Studies



Locally brightest galaxies
(LBG)

Planck Collaboration XI (2013)

Population Studies



Dust contributes significantly to the sub-millimeter flux of low mass ($M<10^{13}\ M_\odot$) halos

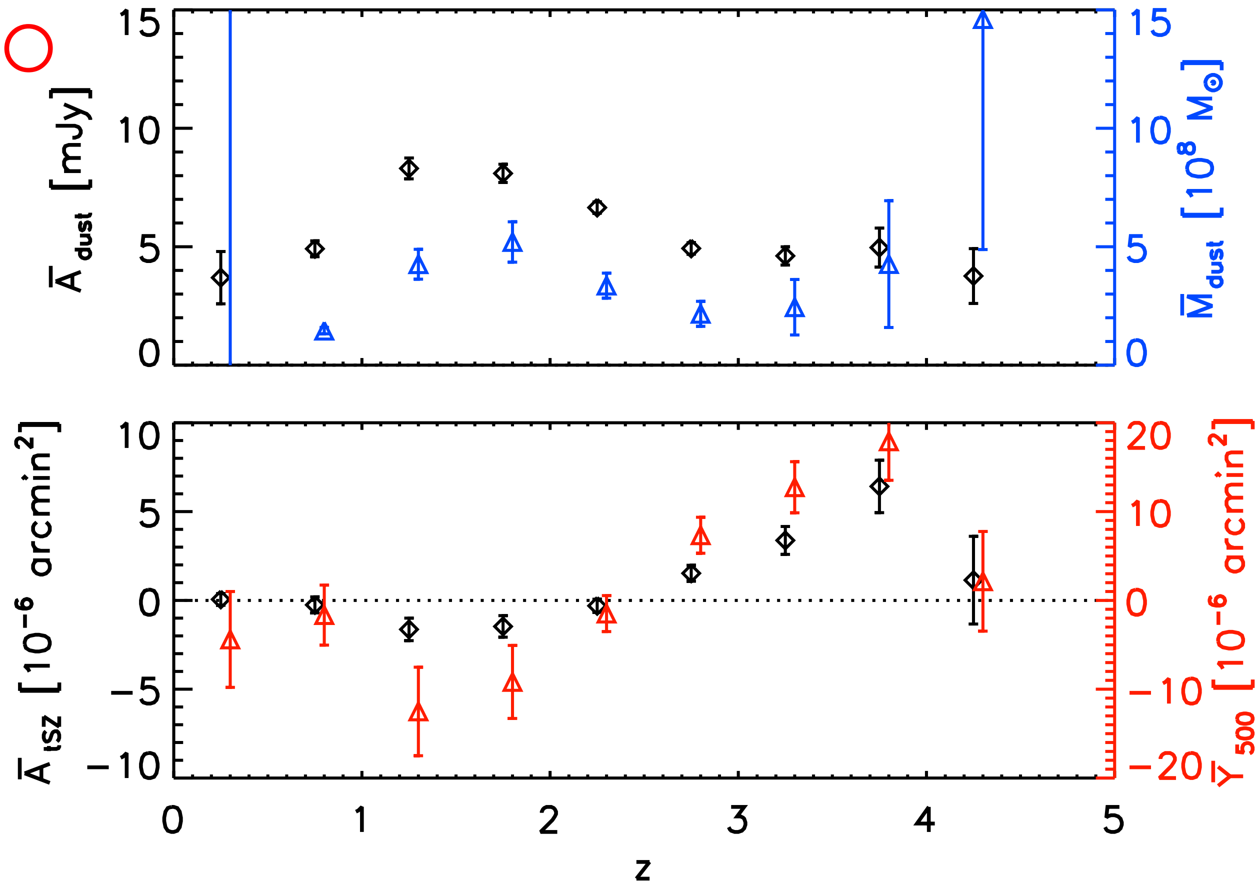
Locally brightest galaxies (LBG)

Planck Collaboration XI (2013)

Large-Scale Structure: QSO

Verdier et al. 2016

(BOSS) QSO



Dust traces Star formation

tSZ @ z>3 !

Radio-quiet subsample (no FIRST counterpart)

LSS science & millimetre surveys

Cosmic Web

Baryons ⇄ Dark Matter

- Spatial distribution? → nodes, filaments → **tSZ (large cluster catalogue)**, **tSZ (all-sky y map)**, **CMB lensing (cluster mass)**
- Velocities? → **kSZ & pSZ**
- Baryon physics? → hot gas, stars → **Far-IR (dust)**, **tSZ & tSZrel**

LSS science & millimetre surveys

Cosmic Web

Baryons ⇄ Dark Matter

Require
sensitivity,
resolution (at least Planck resolution),
large frequency coverage (>350 GHz)