SZ cosmology
Status & future directions

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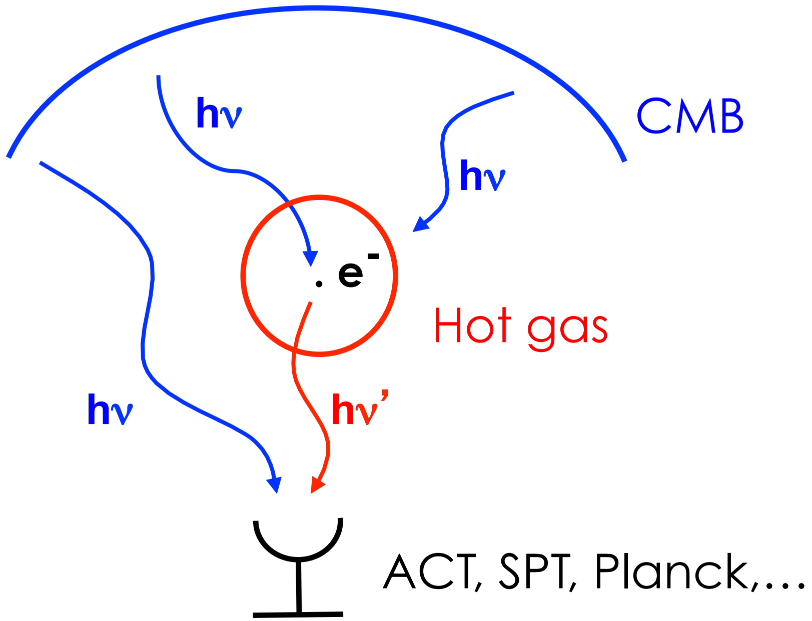
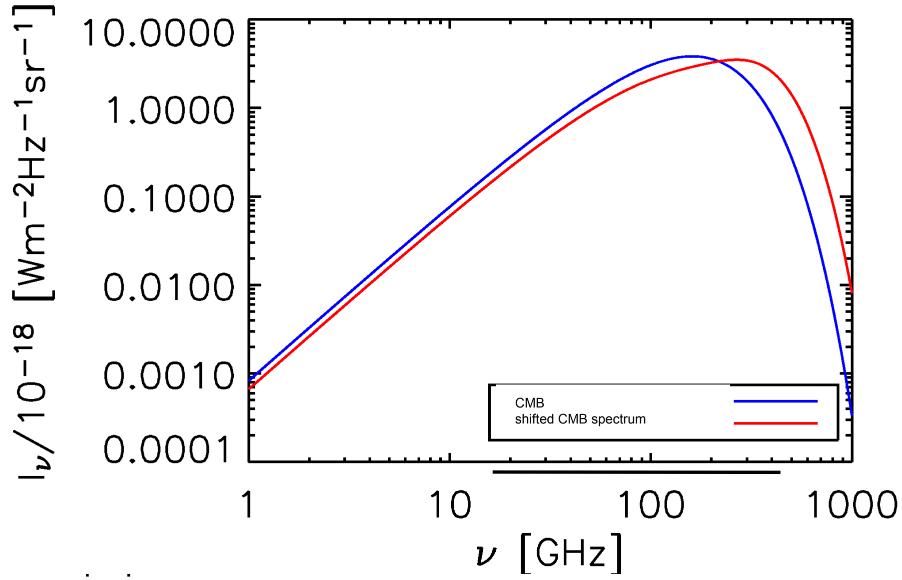
Outline

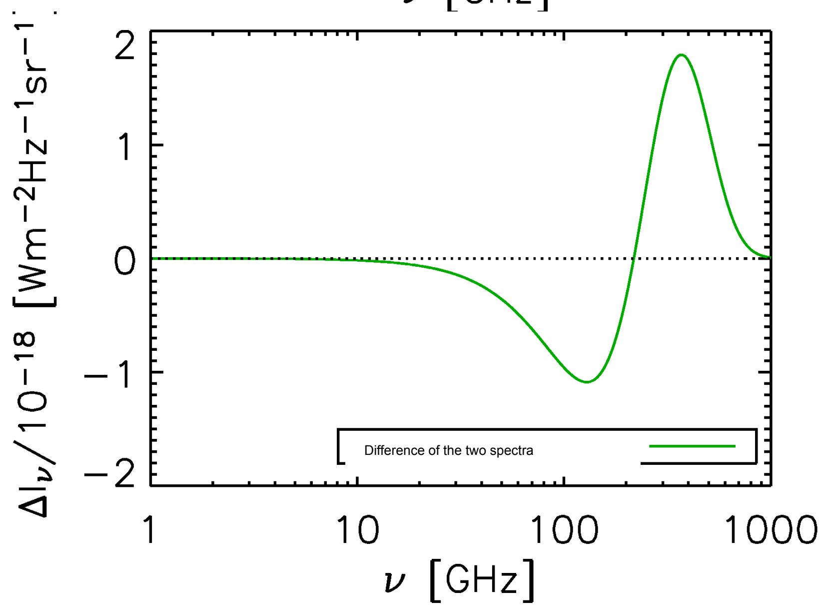
- Sunyaev-Zeldovich (SZ) catalogues
- Cosmology from SZ cluster counts
  ➔ tension & possible solutions
- Future directions

Detecting the hot gas in halos with the SZ effect

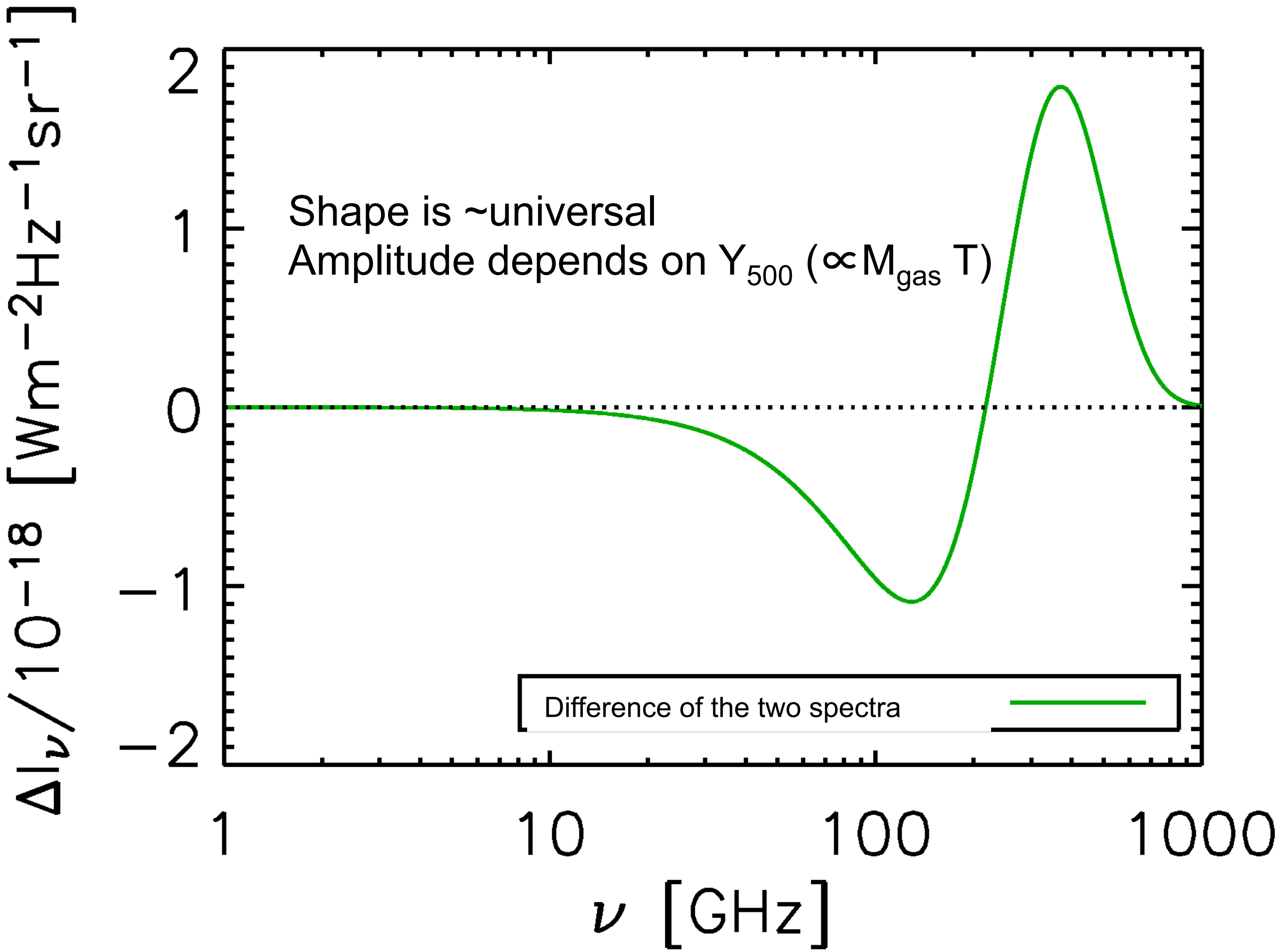
Sunyaev and Zeldovich 1970,1972



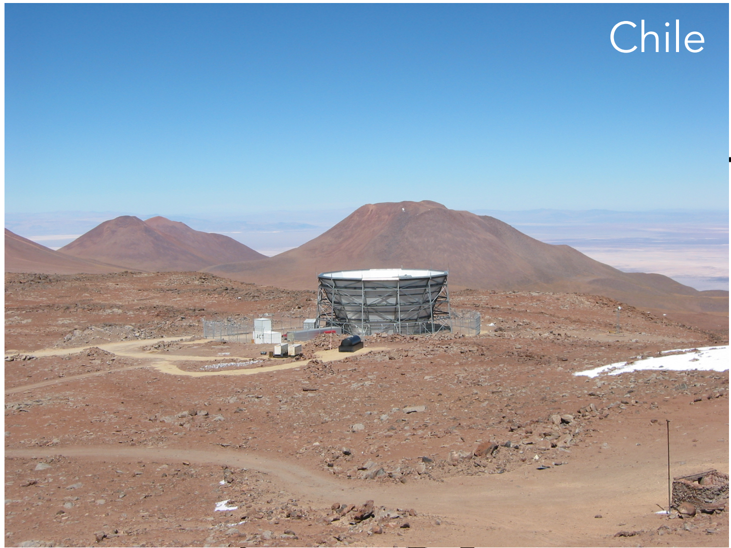




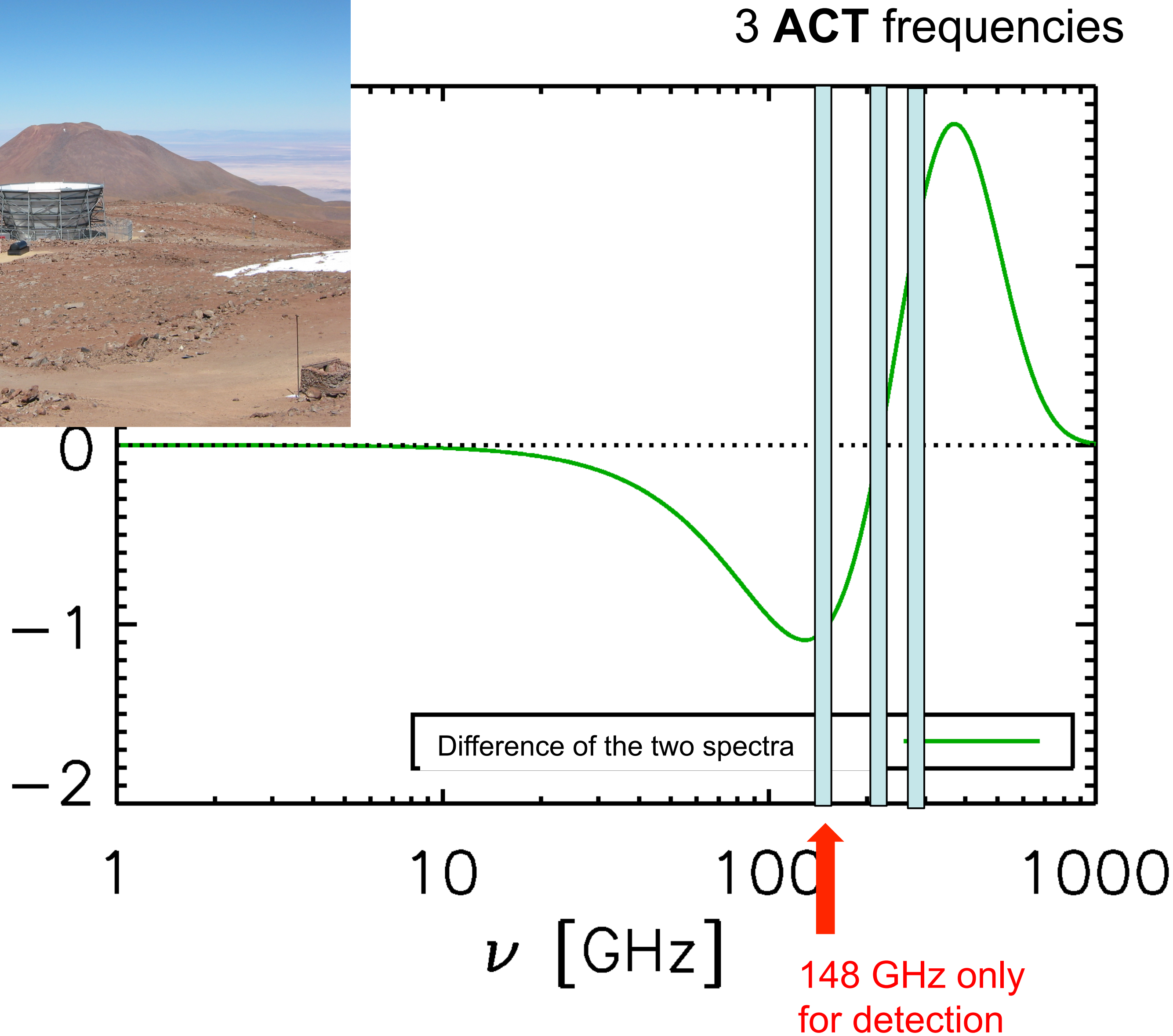
Detecting the hot gas in halos with the SZ effect



Detecting the hot gas in halos with the SZ effect

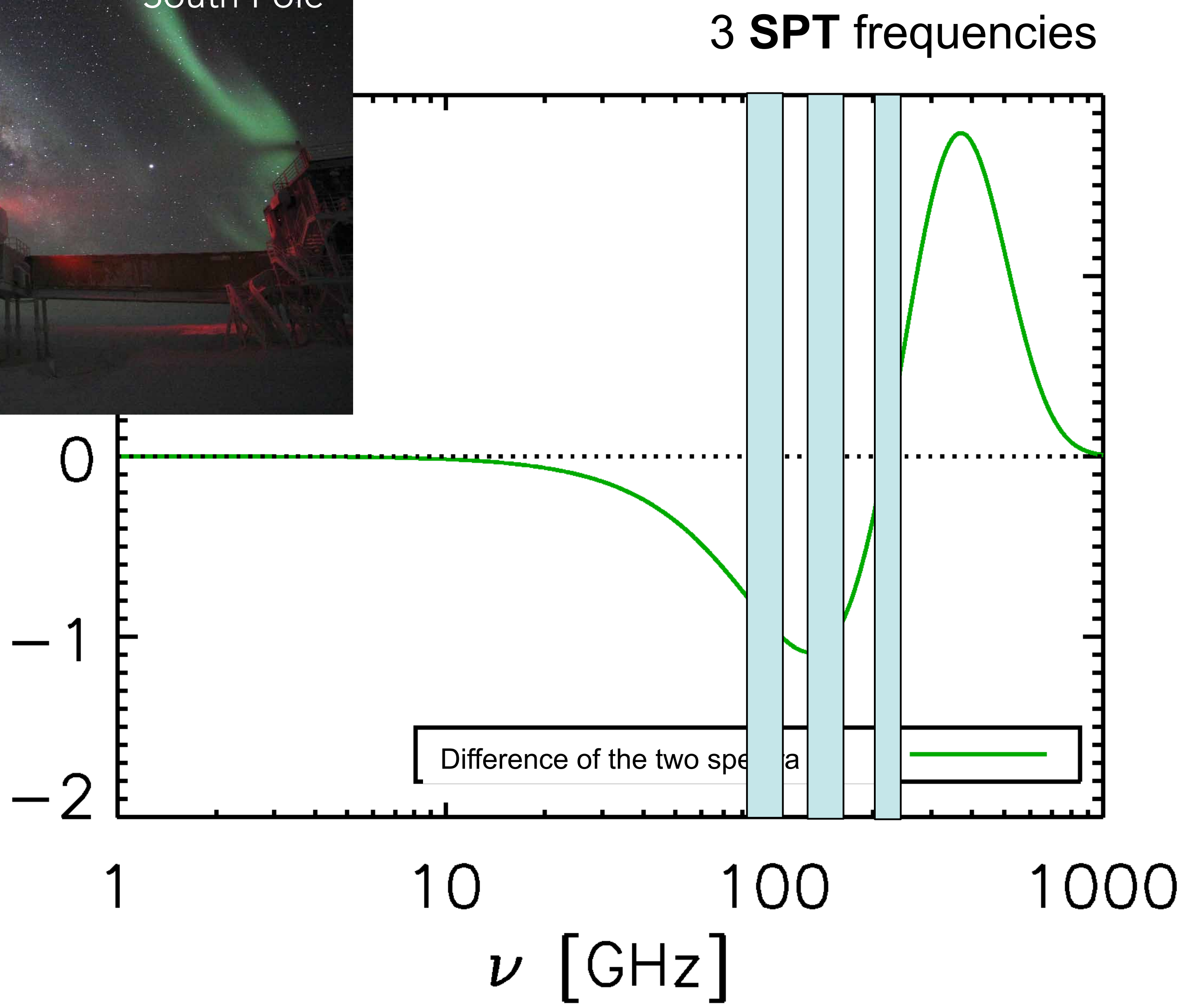


Credit: ACT

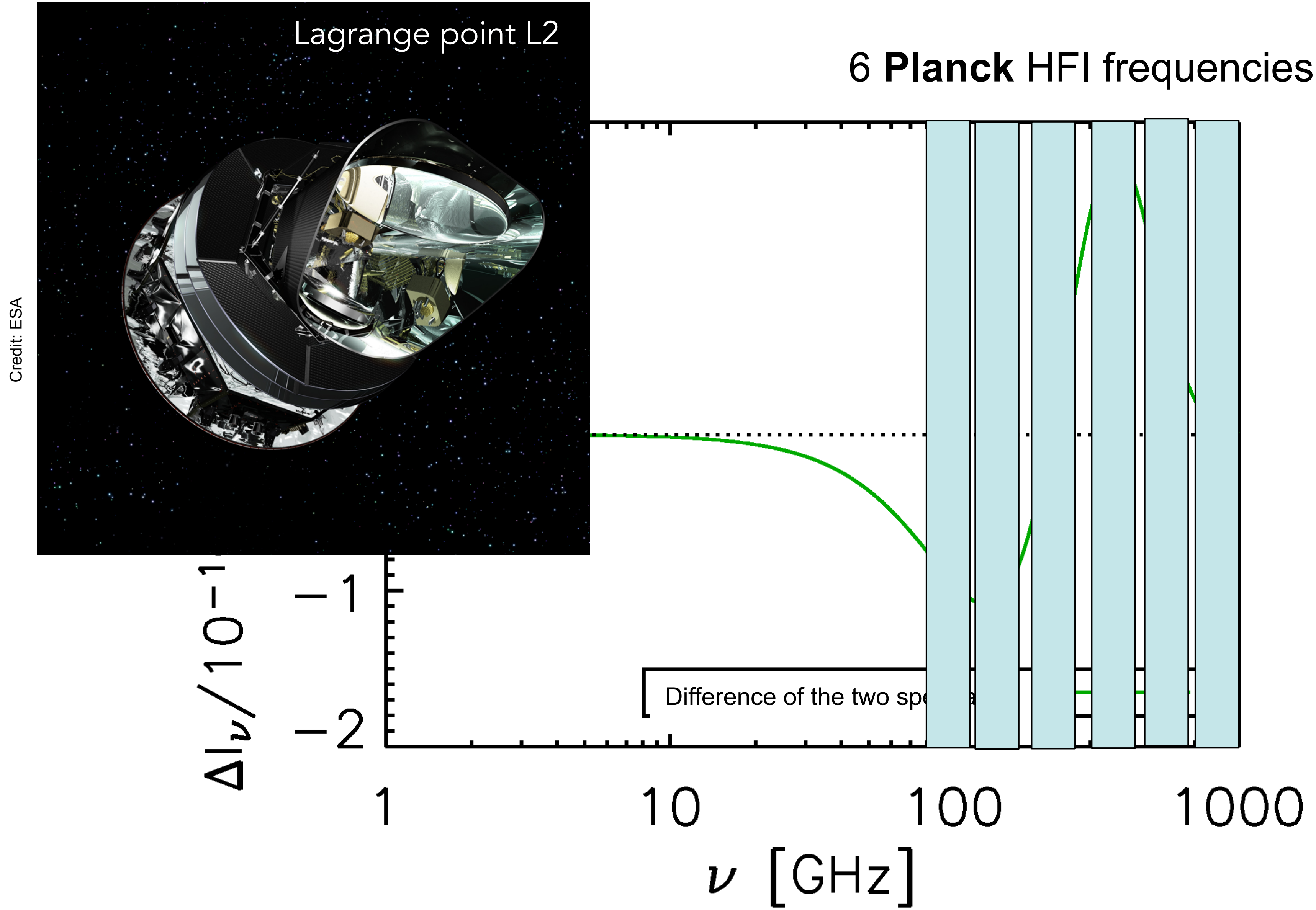


Detecting the hot gas in halos with the SZ effect

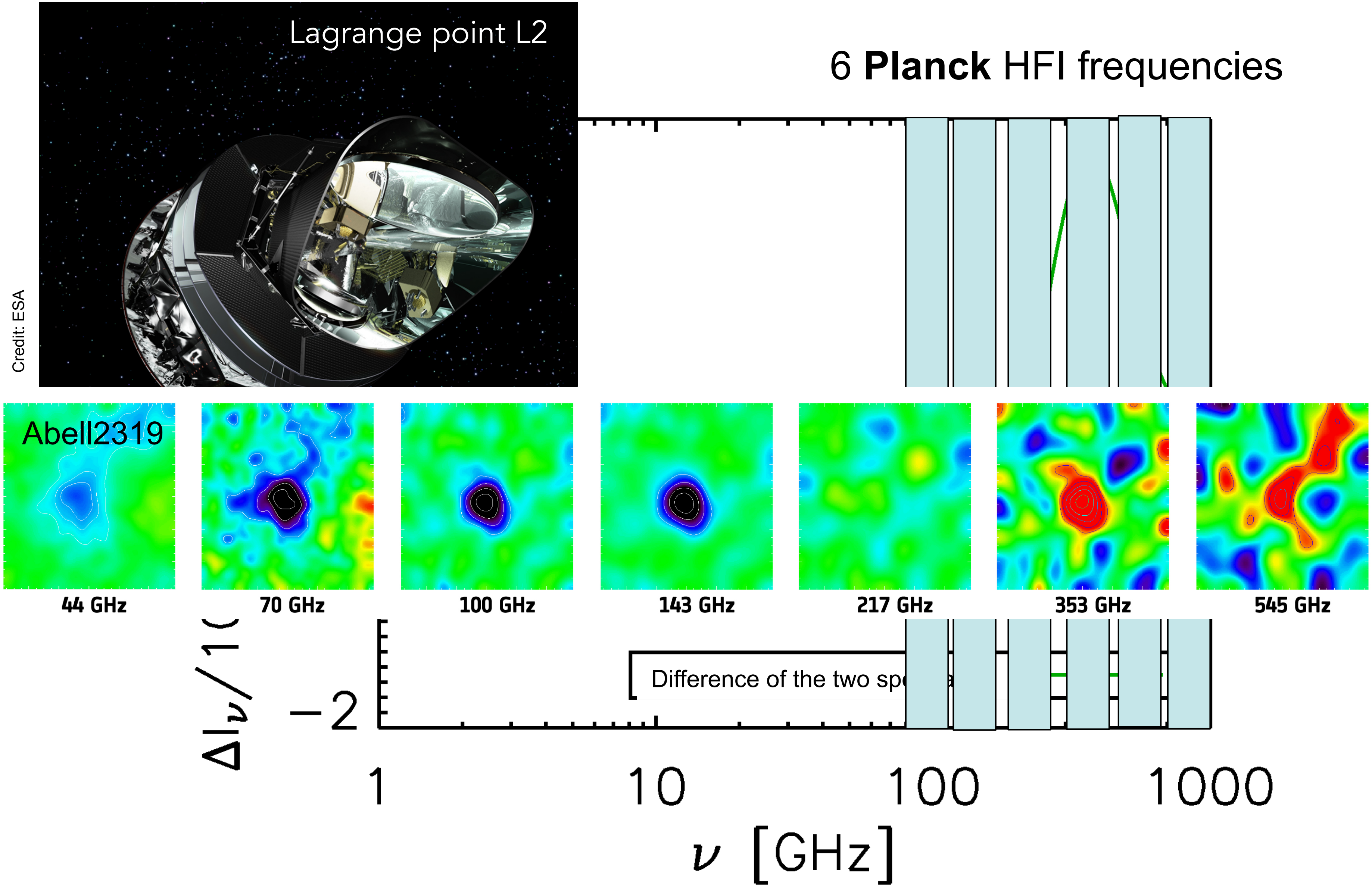
Credit: SPT, K. Vanderlinde



Detecting the hot gas in halos with the SZ effect



Detecting the hot gas in halos with the SZ effect



Blind SZ catalogues

ACT — **91** optically confirmed clusters (504 deg^2)

Hasselfield et al. 2013

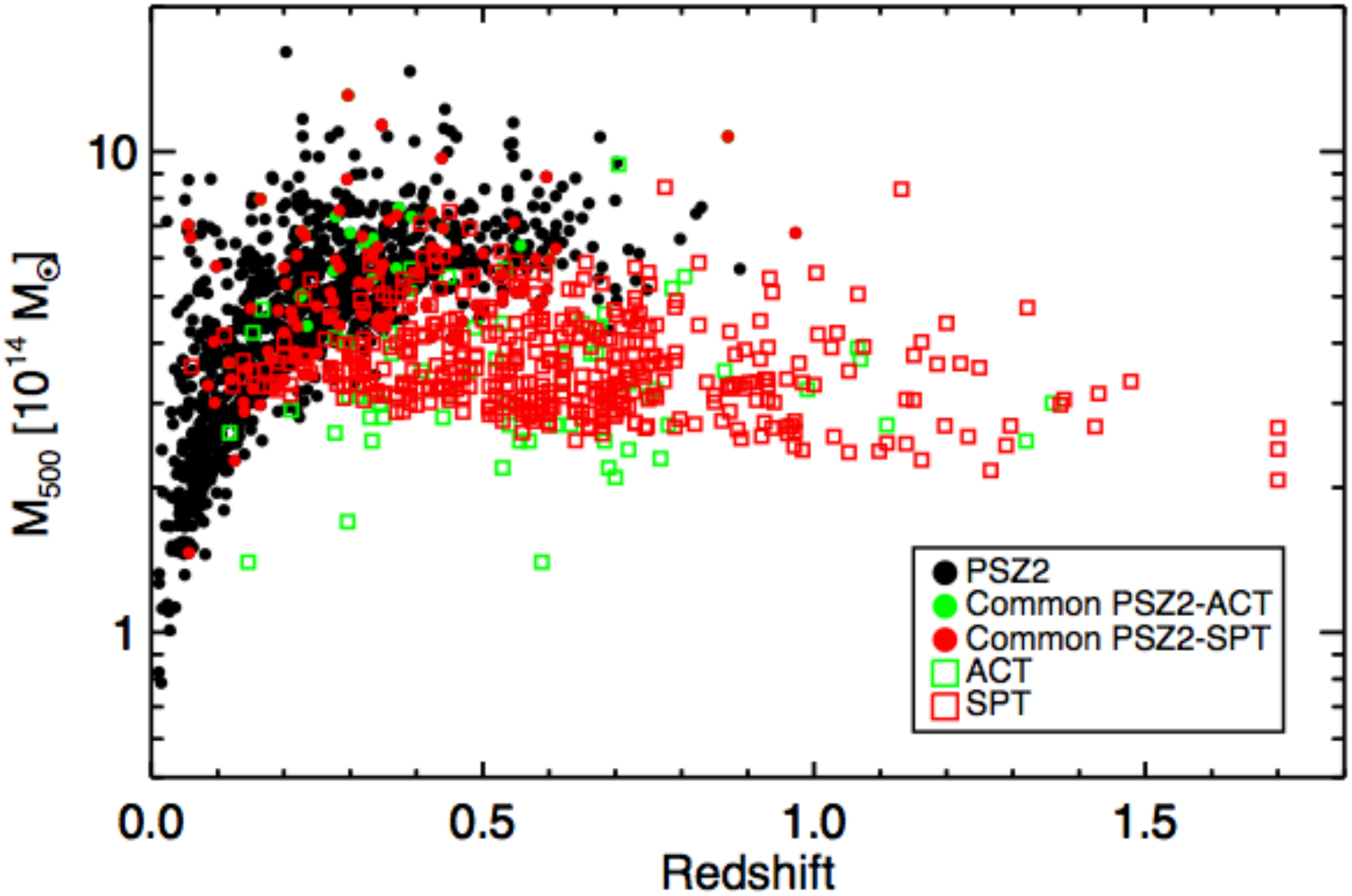
SPT — **677** SZ sources at S/N>4.5 (2,500 deg^2)

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

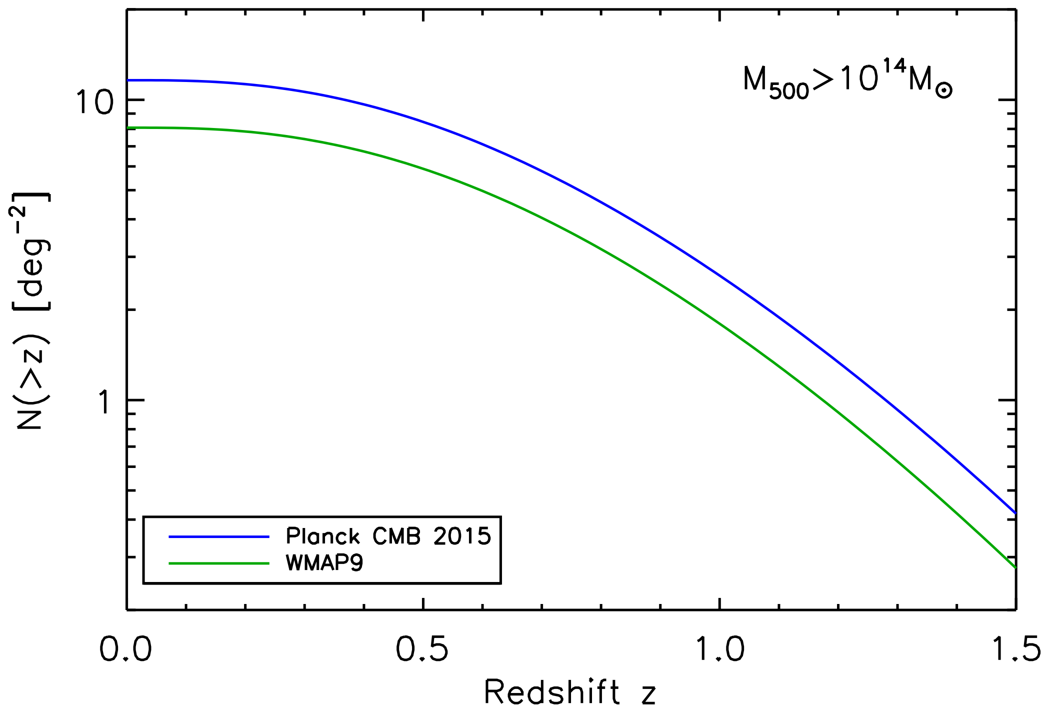
Outline

- Sunyaev-Zeldovich (SZ) catalogues

- Cosmology from SZ cluster counts
  ➔ tension & possible solutions

- Future directions

Cosmology from cluster counts



See also
G. Schellenberger talk

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

Scaling laws

Important slide !

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

$$\bar{\theta}_{500} = \theta_* \left[\frac{h}{0.7}\right]^{-2/3} \left[\frac{(1-b)\,M_{500}}{3\times 10^{14}\mathrm{M_{sol}}}\right]^{1/3} E^{-2/3}(z) \left[\frac{D_\mathrm{A}(z)}{500\,\mathrm{Mpc}}\right]^{-1},$$

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

Scaling laws

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

Important slide !

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

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

α, Y* determined on X-ray data

Scaling laws

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

Important slide !

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

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

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

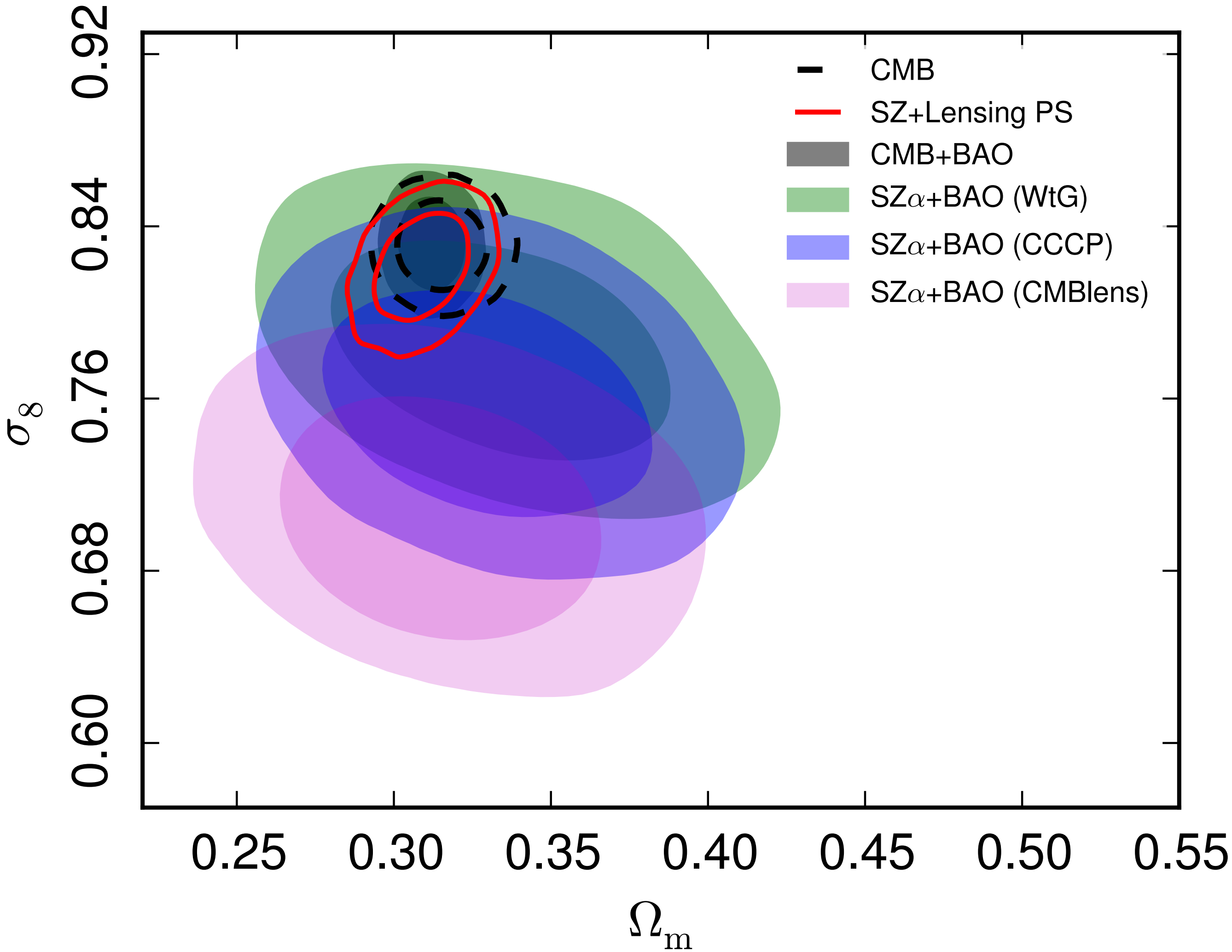
Hoekstra et al. 2015

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 ± 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.

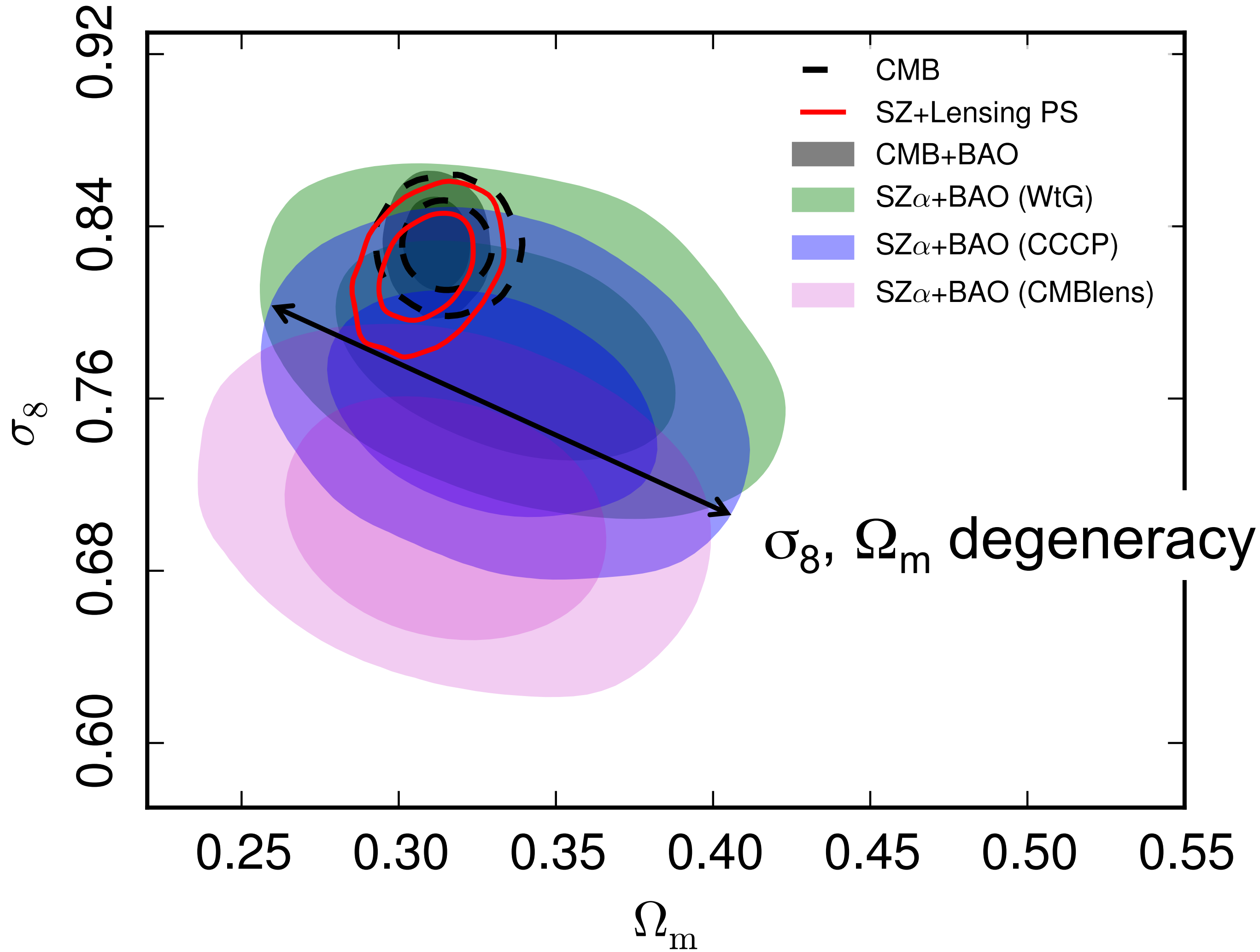
NEW (CMB halo lensing) !!!

Planck cluster cosmology 2015



Planck Results XXIV 2015

Planck cluster cosmology 2015



Planck Results XXIV 2015

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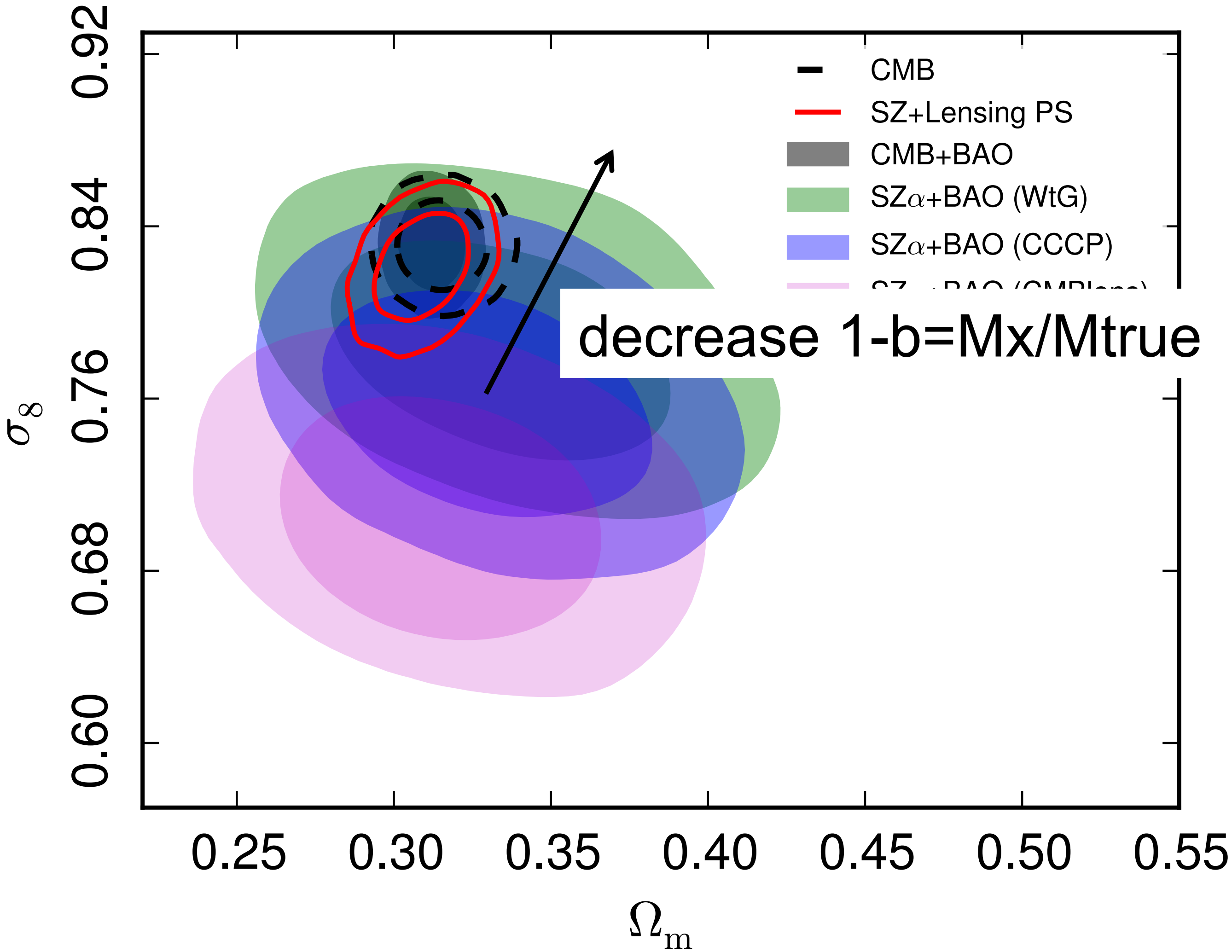
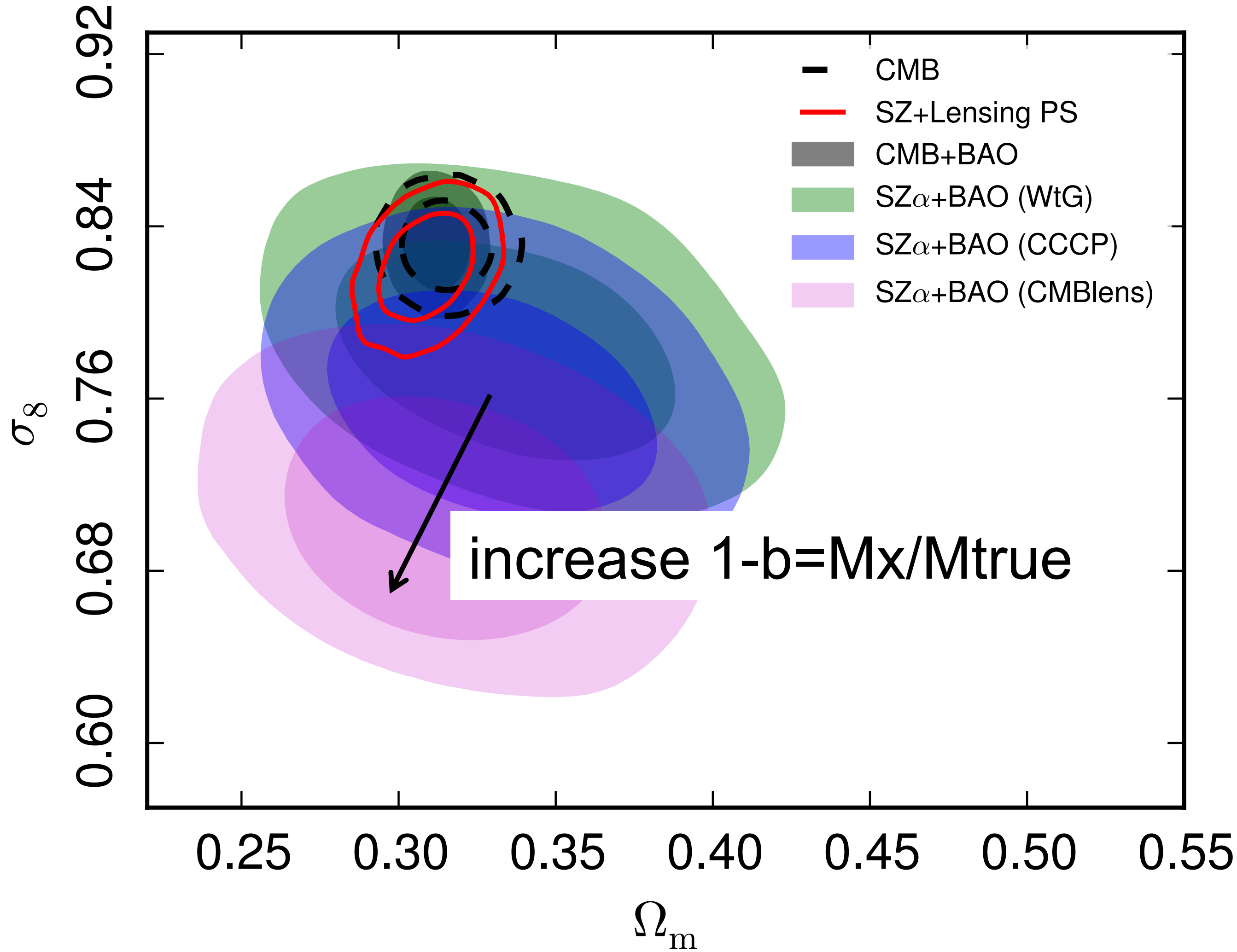


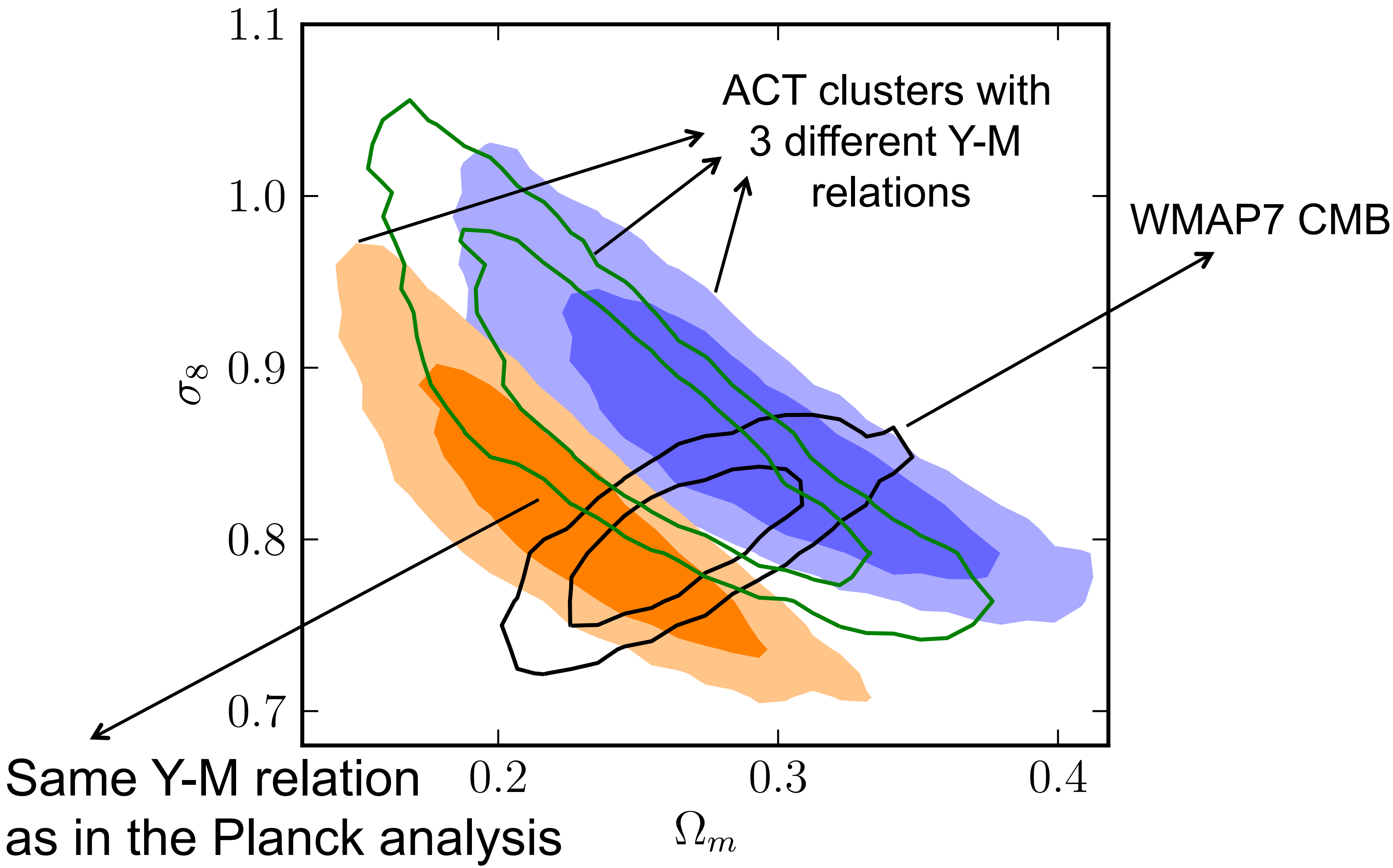
Planck Results XXIV 2015

Planck cluster cosmology 2015



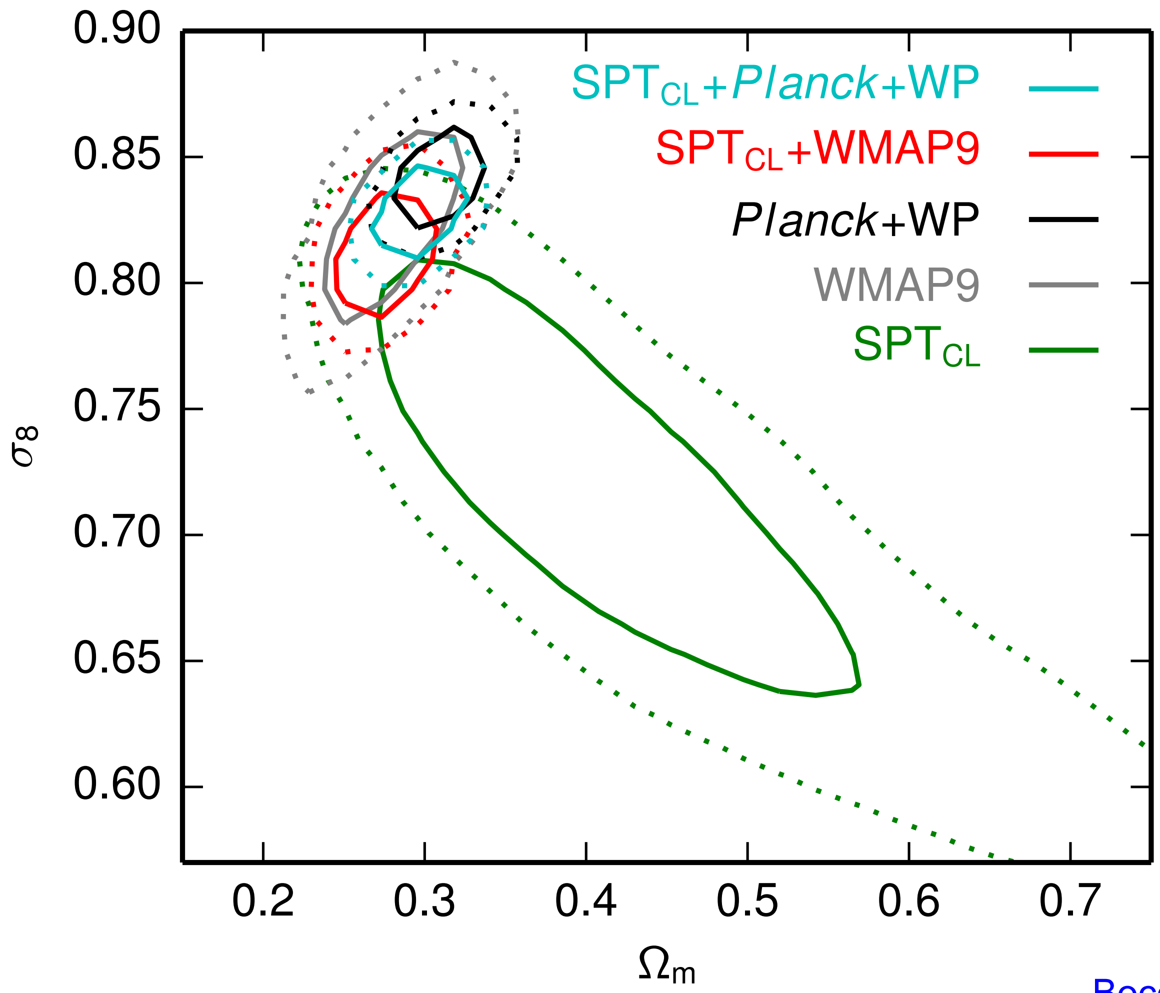
Planck Results XXIV 2015

ACT cluster cosmology 2013



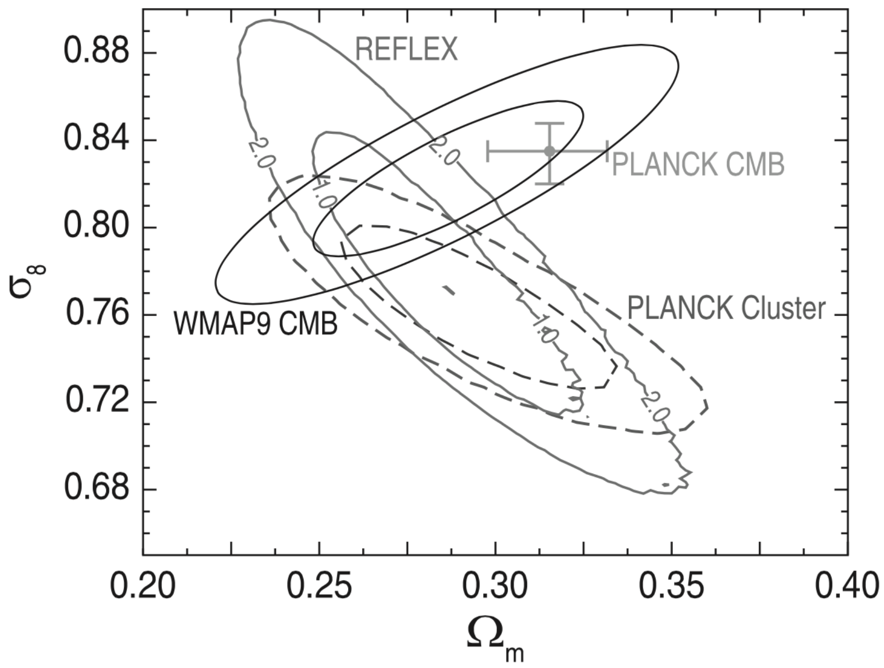
Hasselfield et al. 2013

SPT cluster cosmology 2015

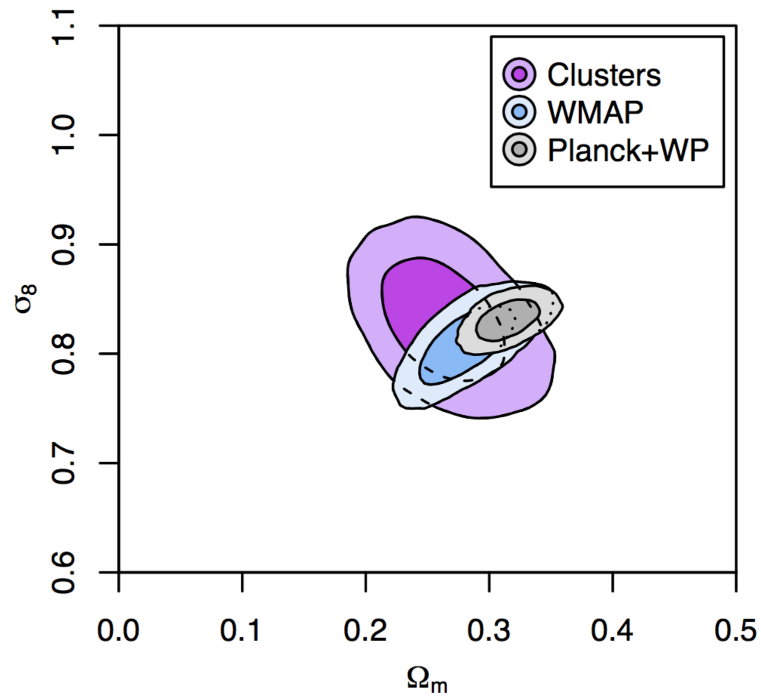


Bocquet et al. 2015

X-ray cluster analyses?



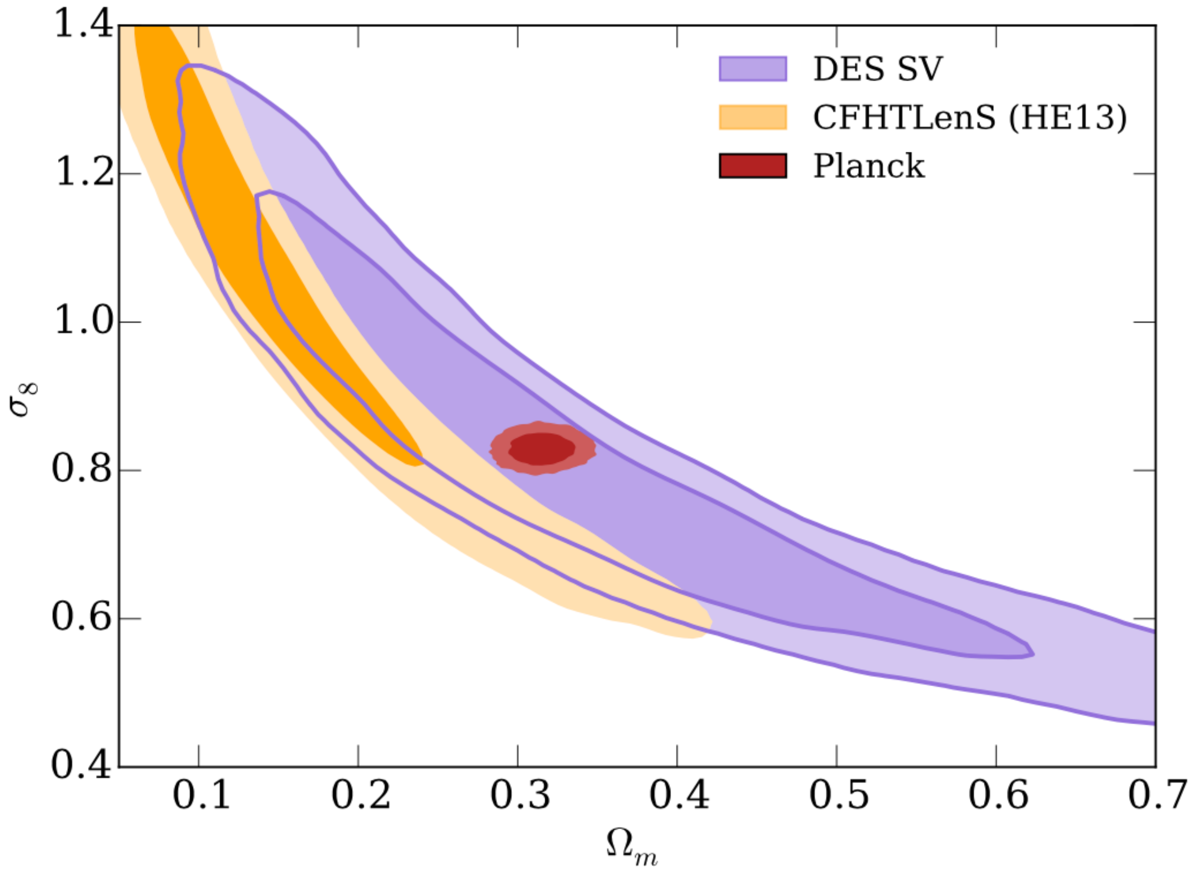
Böhringer et al. 2014



Mantz et al. 2015

See also
F. Pacaud talk on preliminary XXL-100-GC counts

CFHTLens and DES cosmic shear?



The DES Collaboration 2015

How to reconcile Planck CMB and SZ counts?

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- Baryonic effects in the mass function? $\frac{dN}{dz\, dM_{500}\, d\Omega}$
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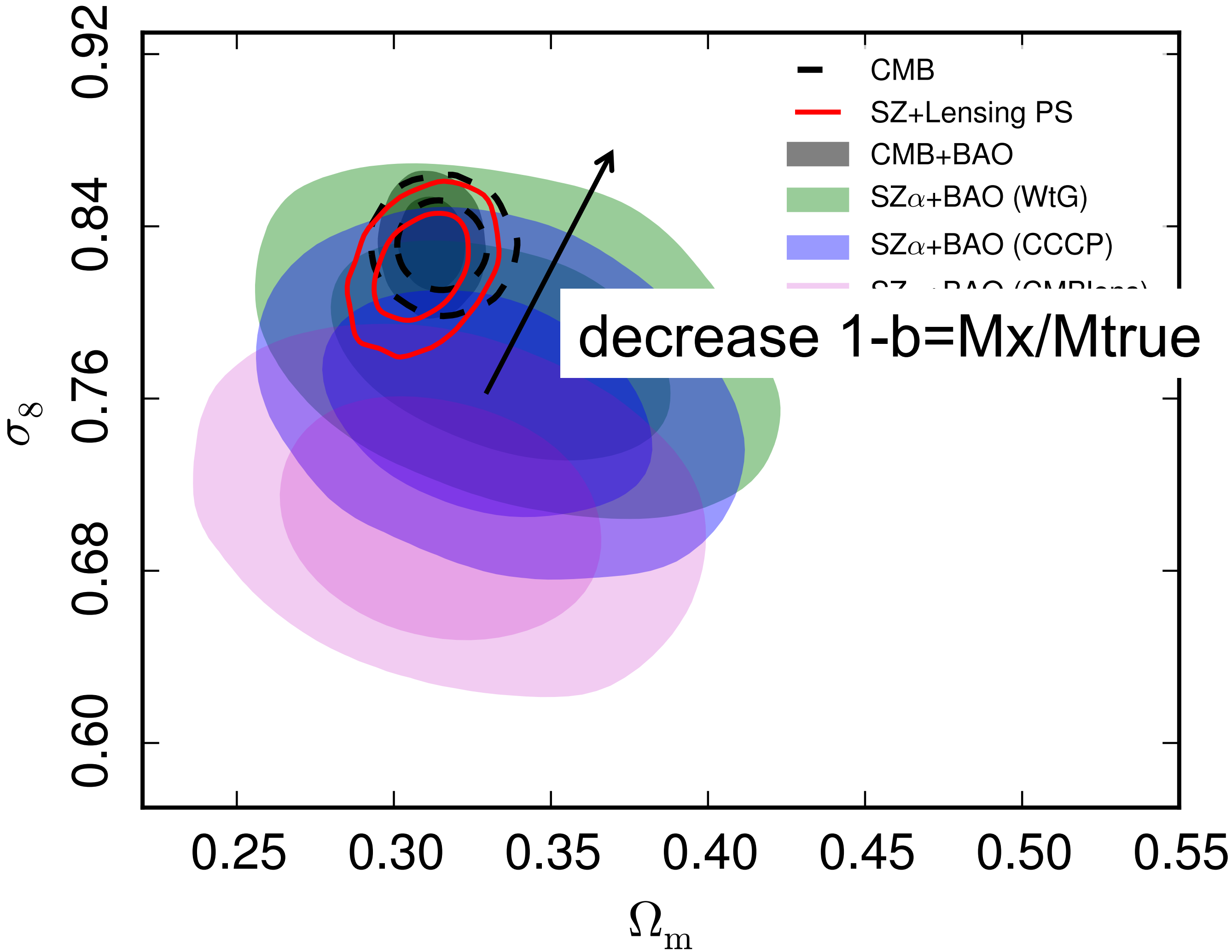
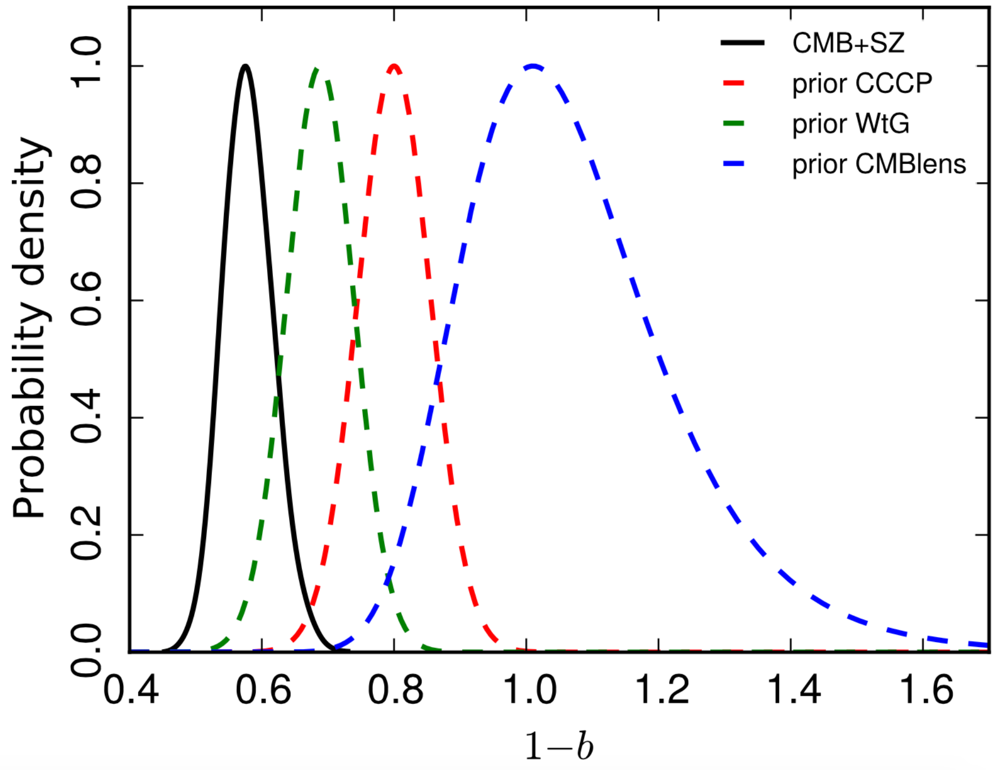
Planck cluster cosmology 2015



Planck Results XXIV 2015

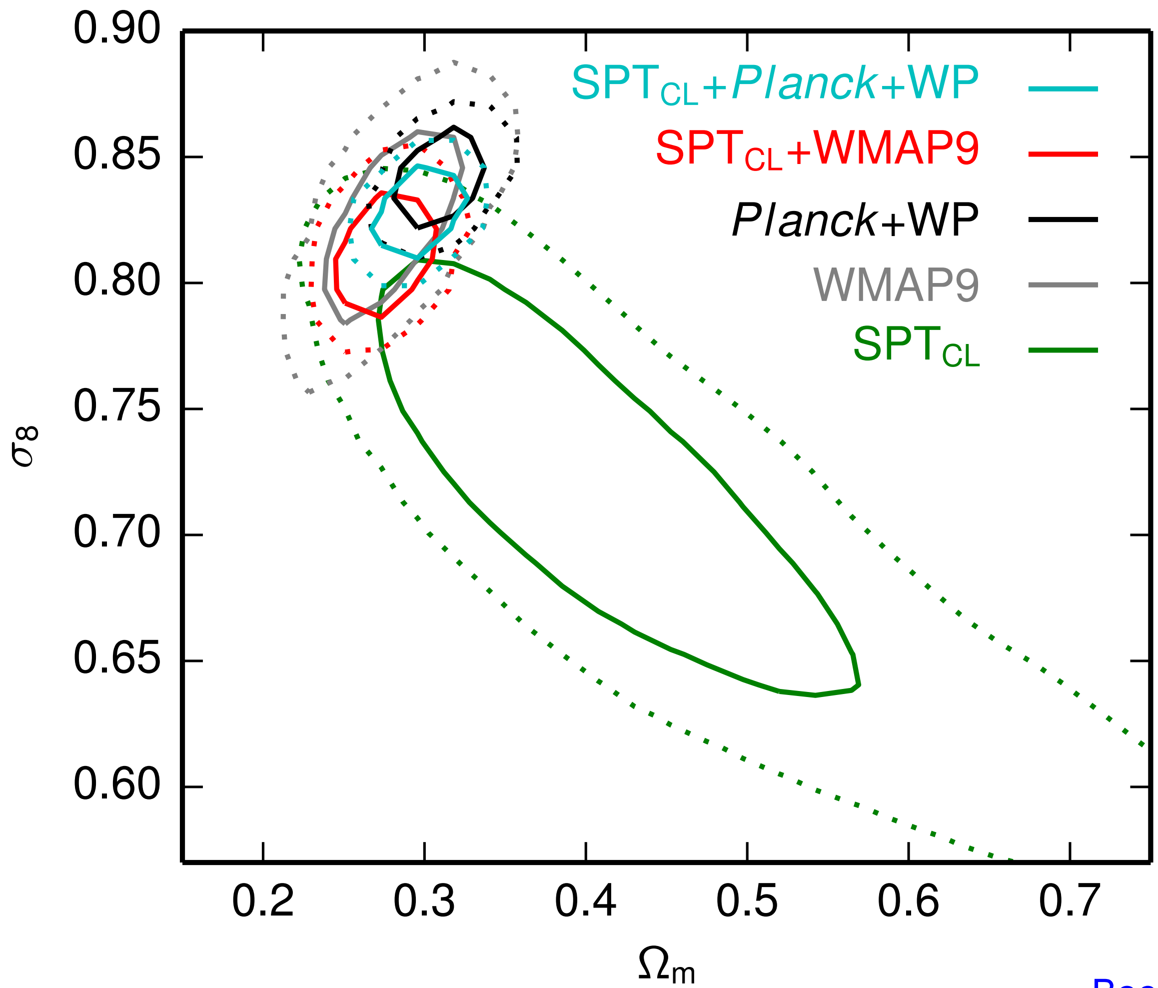
Planck cluster cosmology 2015

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

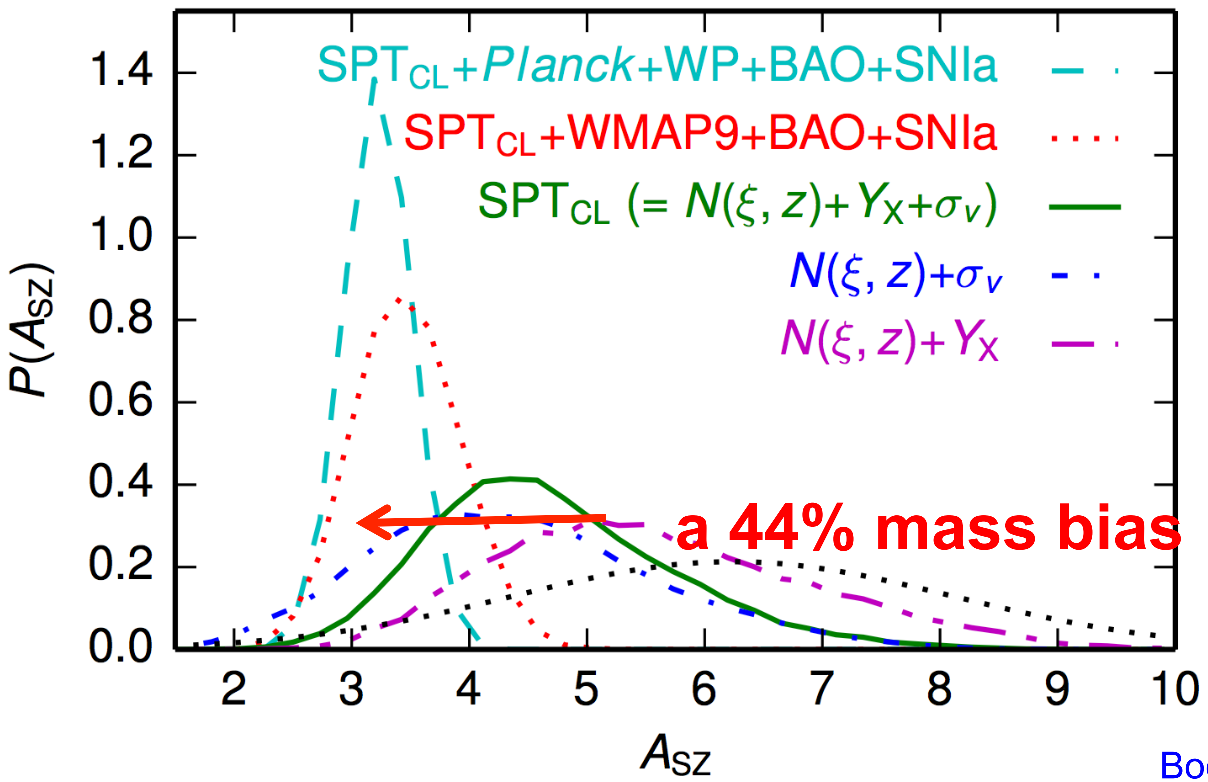


Bocquet et al. 2015

SPT cluster cosmology 2015

≈1.5

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

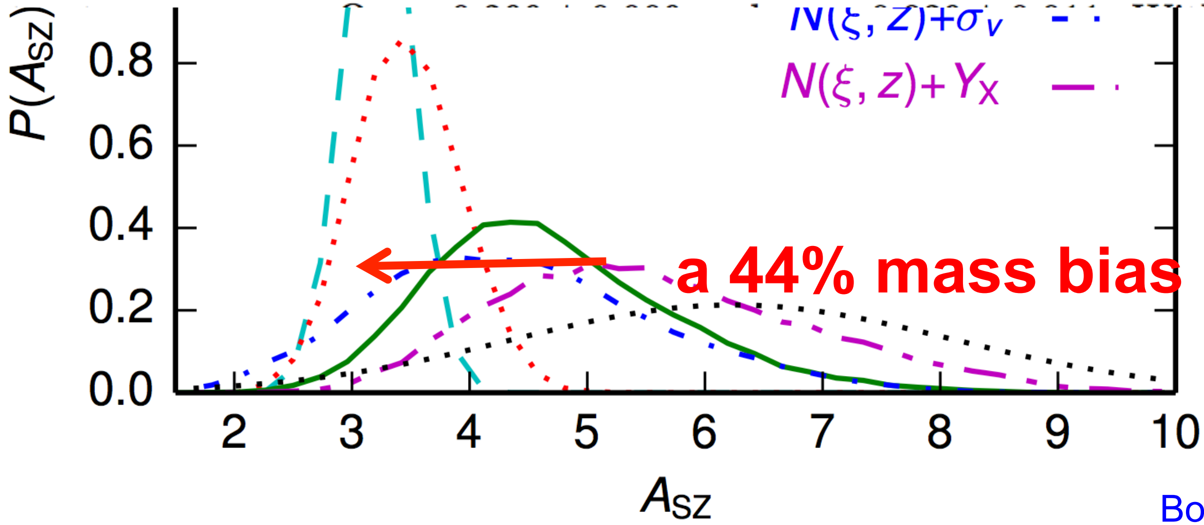


Bocquet et al. 2015

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 SPT$_{\rm CL}$ 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 (∼44% and ∼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

How to reconcile Planck CMB and SZ counts?

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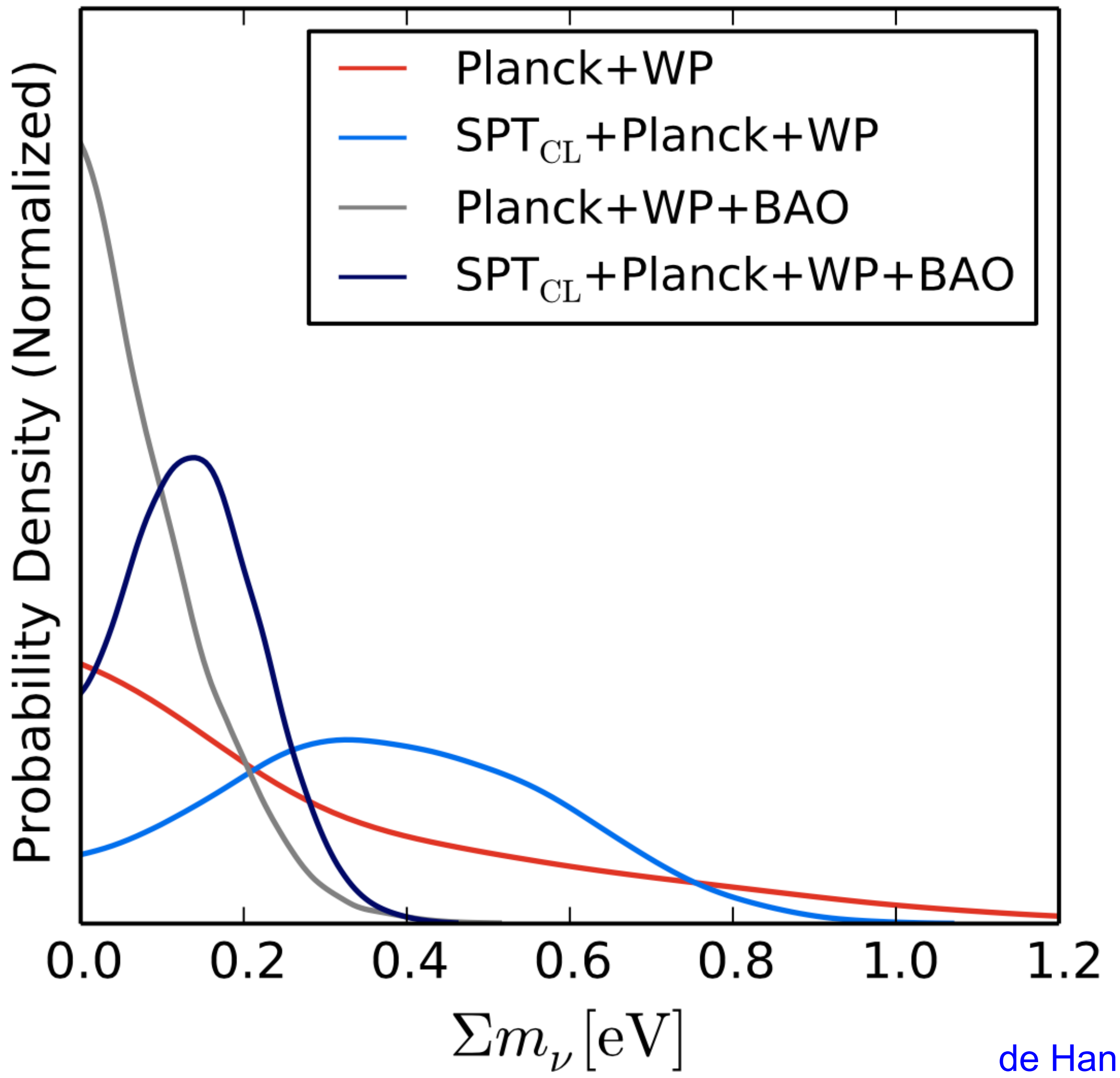
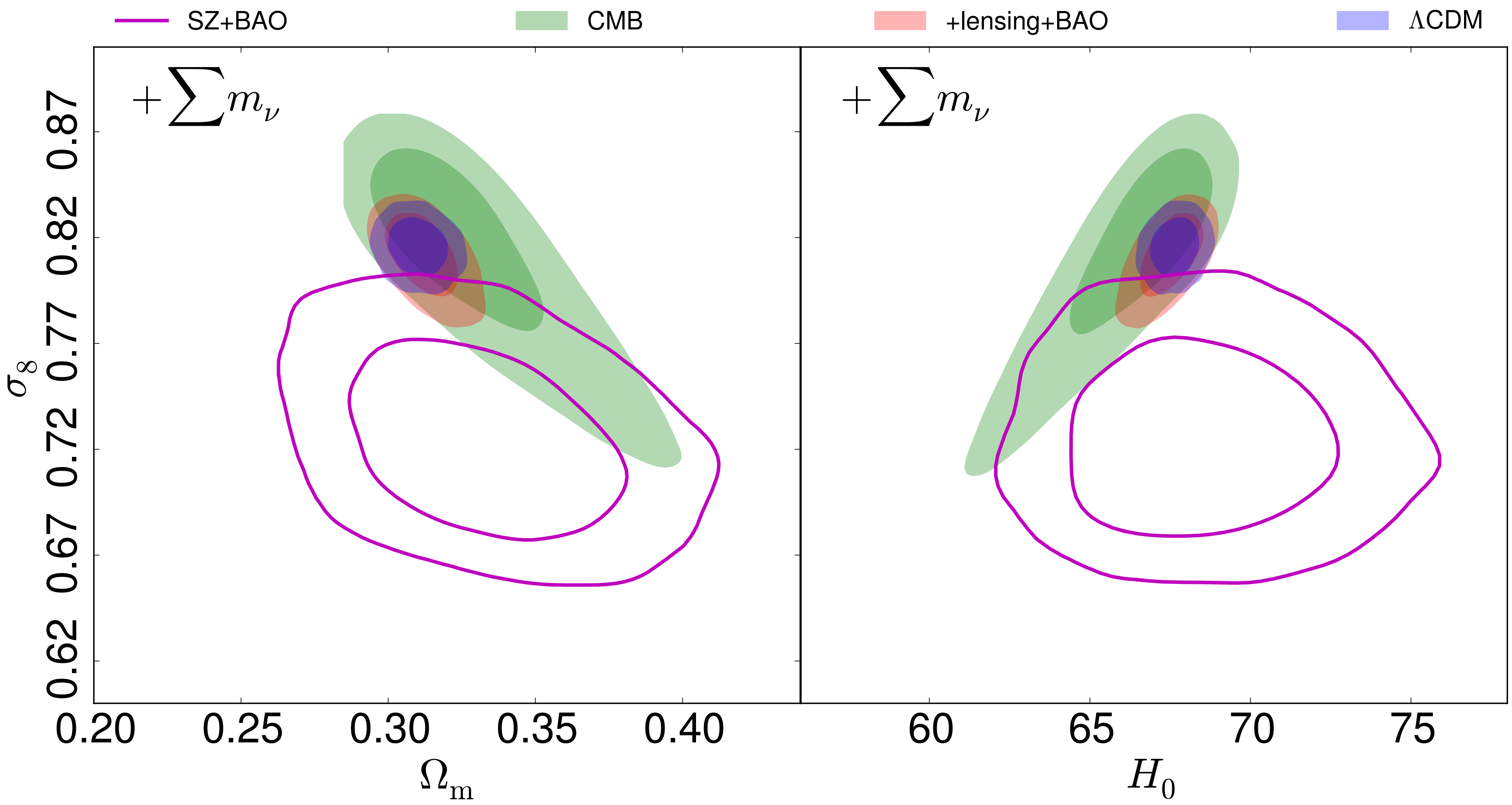
- Baryonic effects in the mass function? $\frac{dN}{dz\, dM_{500}\, d\Omega}$
- Selection function of SZ surveys? $\chi(Y_{500}, \theta_{500}, l, b)$
- Primary CMB?

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

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  See
  I. McCarthy talk
- Selection function of SZ surveys? $\chi(Y_{500}, \theta_{500}, l, b)$
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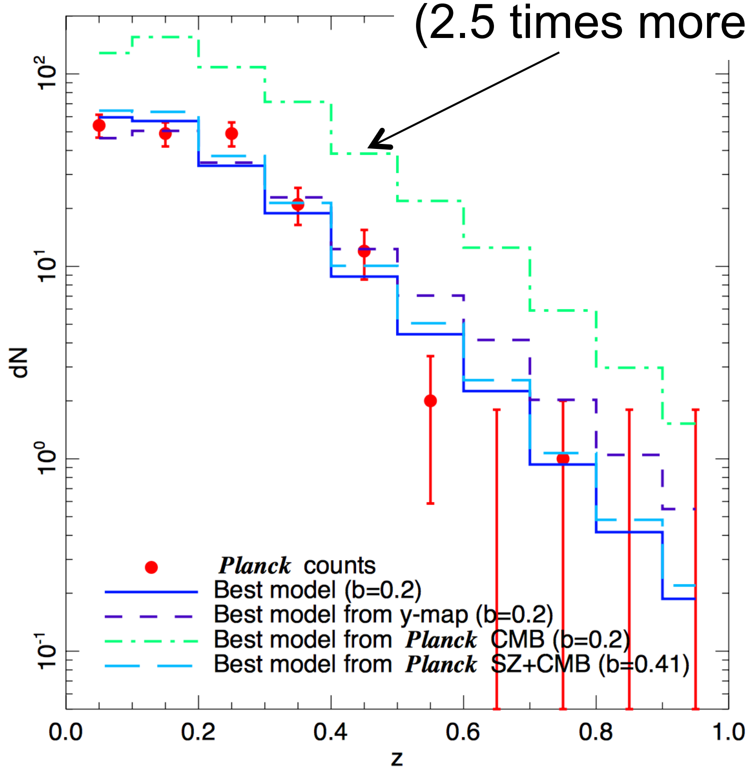
- Primary CMB?

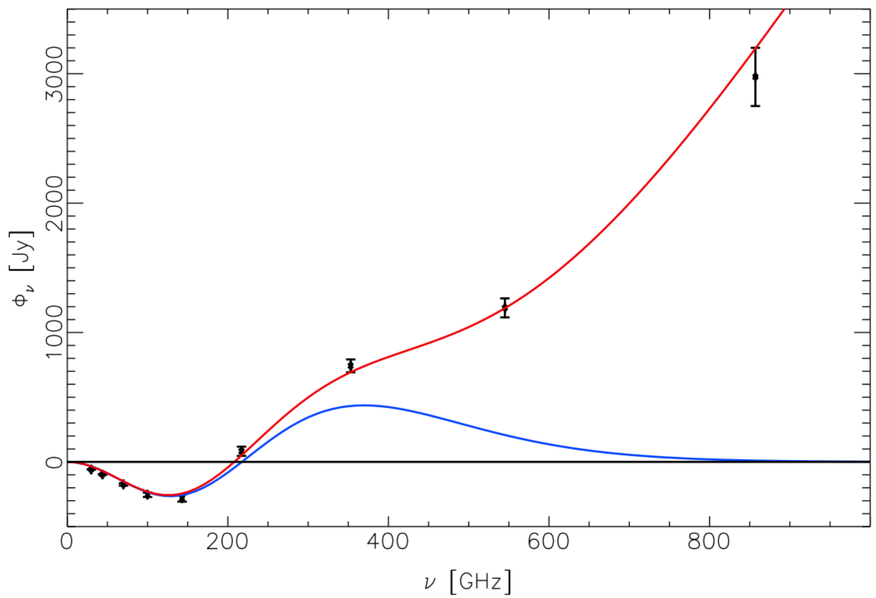
Selection function of SZ surveys?

CMB prediction
(2.5 times more clusters than observed)



Planck Results XX 2013

Impact of dust in clusters?



Planck Results XXIII 2015

How to reconcile Planck CMB and SZ counts?

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

Primary CMB?

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

Parameter	*Planck* Best fit	*Planck* 68% limits	*Planck*+lensing Best fit	*Planck*+lensing 68% limits	*Planck*+WP Best fit	*Planck*+WP 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**

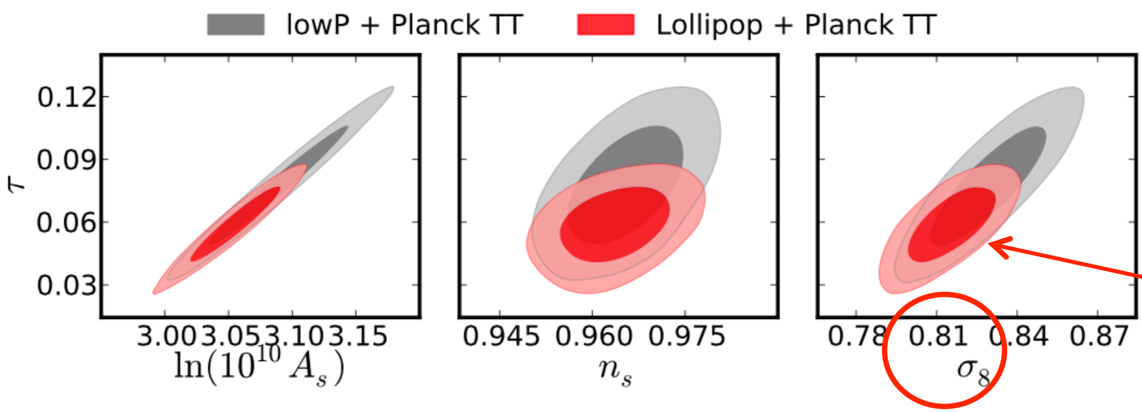
Primary CMB?

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**

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



Planck+WP 68% limits
0.02205 ± 0.00028
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$0.089^{+0.012}_{-0.014}$
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Planck Results XVI **2013**

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- Cosmology from SZ cluster counts
  ➔ tension & possible solutions

- Future directions

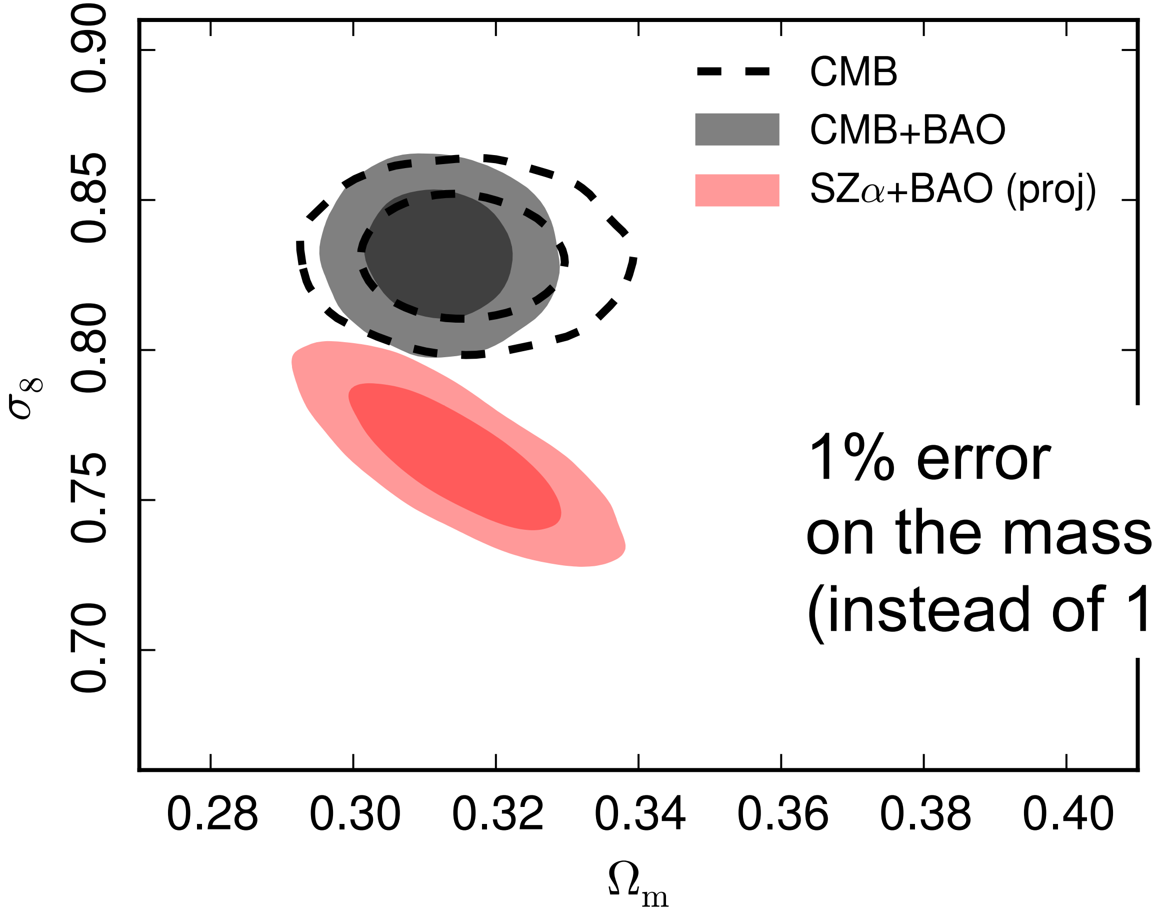
Mass calibration!

Weak lensing → See E. Rozo talk
Caustics → See B. Maughan talk
Velocity dispersion → See S. Amodeo talk

We must continue our effort…

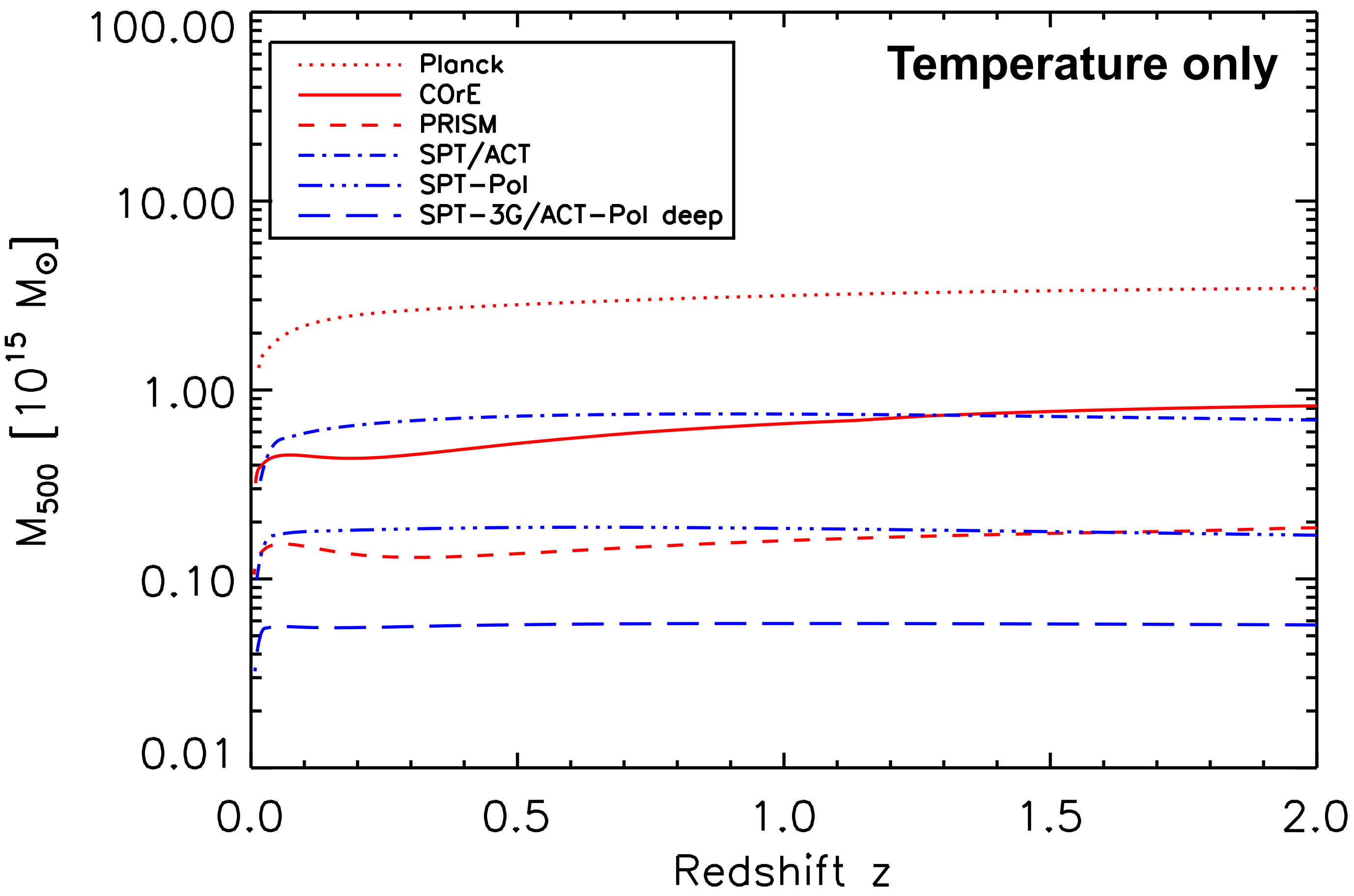
Future?
Planck SZ alone vs. primary CMB

…until...



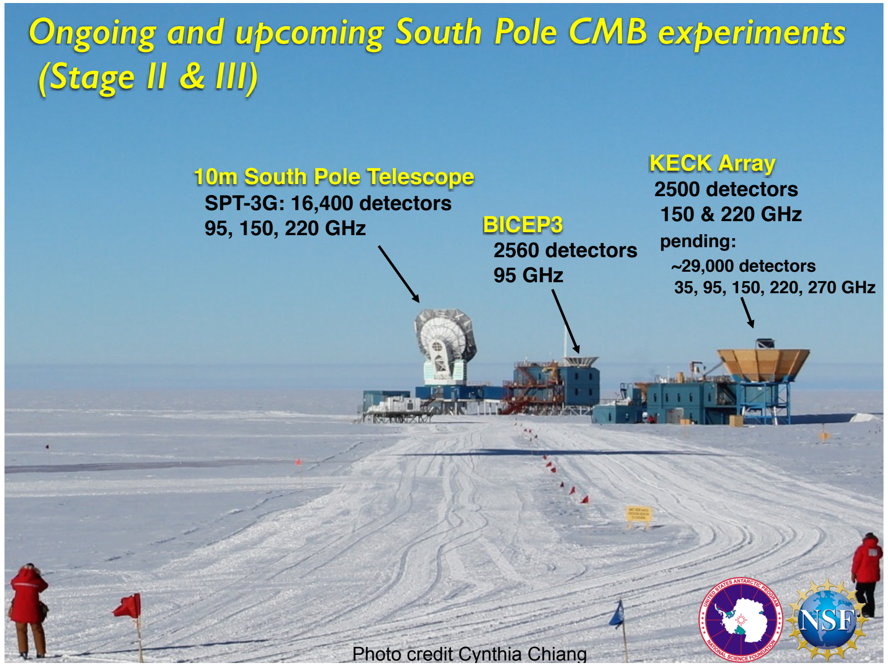
1% error
on the mass bias
(instead of 10%)

CMB halo lensing



Melin & Bartlett 2015
A&A 578,A21 (arXiv:1408.5633)

CMB-S4

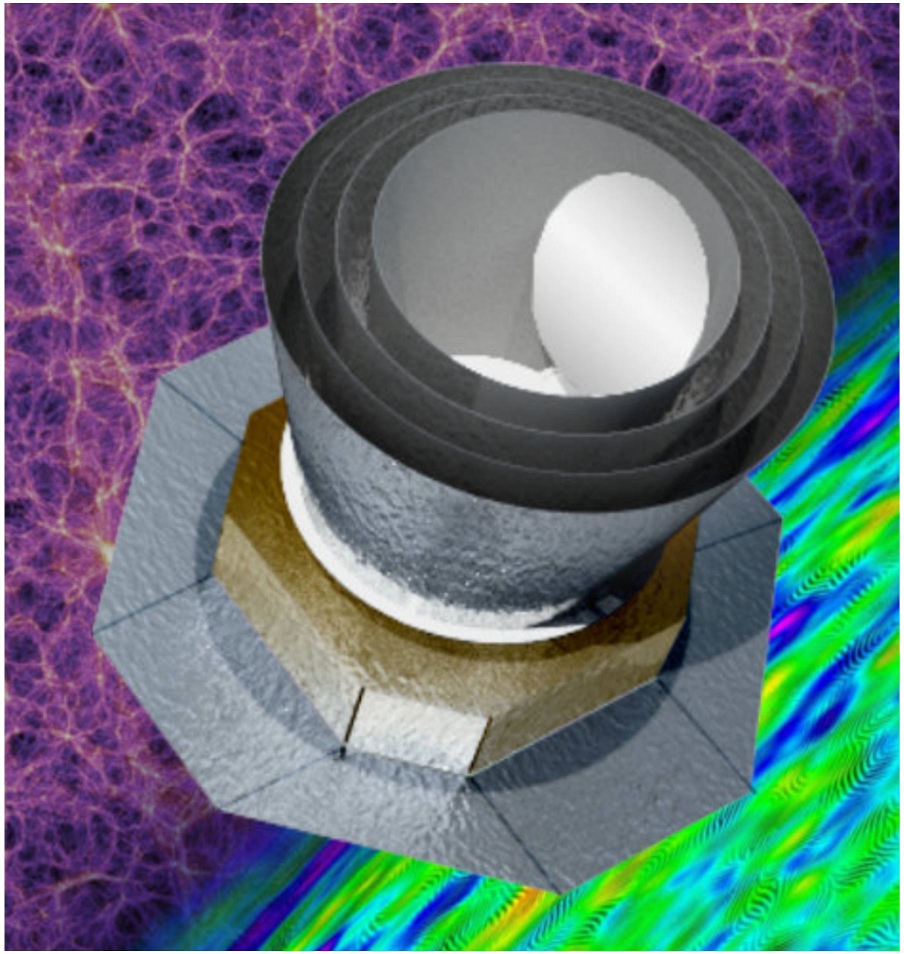


Credit: J. Carlstrom

A joint ground-based US CMB "experiment"
~2025

- ~500,000 detectors
- Arcmin to a few arcmin resolution
- Low frequencies (<300 GHz)

CORE



Answer to ESA call M5
(due Oct. 2016)
Launch 2025-2030

- 2,500 detectors (Planck 50)
- ~Planck (a few arcmin) resolution
- 15-20 frequencies (Planck 9)
  from 60 to 600 GHz

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)

- But the situation is continually improving with multi-frequency observations of large cluster catalogues (optical, X-ray, SZ)

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

- Future experiments (eROSITA 2016, Euclid 2020) will provide additional data which will allow a ~1% mass scale calibration and bring cluster cosmology to the front.

- SZ future: **CMB-S4** 2025 and **CORE** 2025-2030