SZ counts: a review

J.-B. Melin
CEA Saclay, France

Rencontres du Vietnam 2015 – Cosmology 50 years after CMB discovery 2015 August 21

Outline

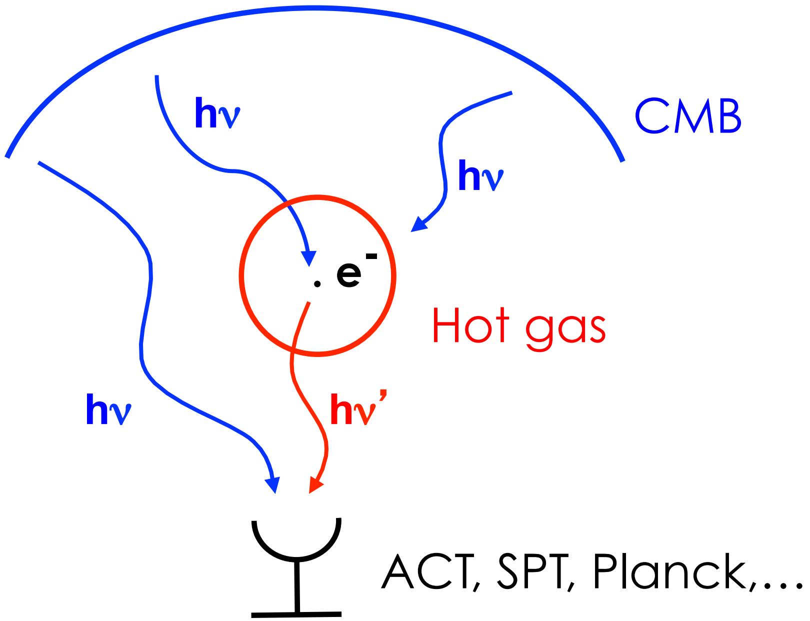
- The Sunyaev-Zeldovich (SZ) effect
- Blind SZ catalogues
- Cosmological constraints from SZ cluster counts

Outline

- The Sunyaev-Zeldovich (SZ) effect
- Blind SZ catalogues
- Cosmological constraints from SZ cluster counts

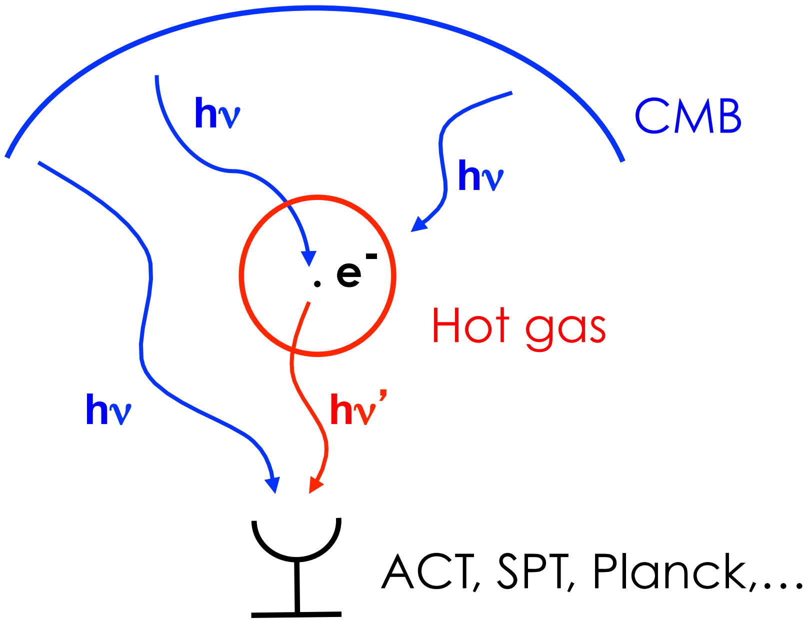
Detecting the hot gas in halos with the SZ effect

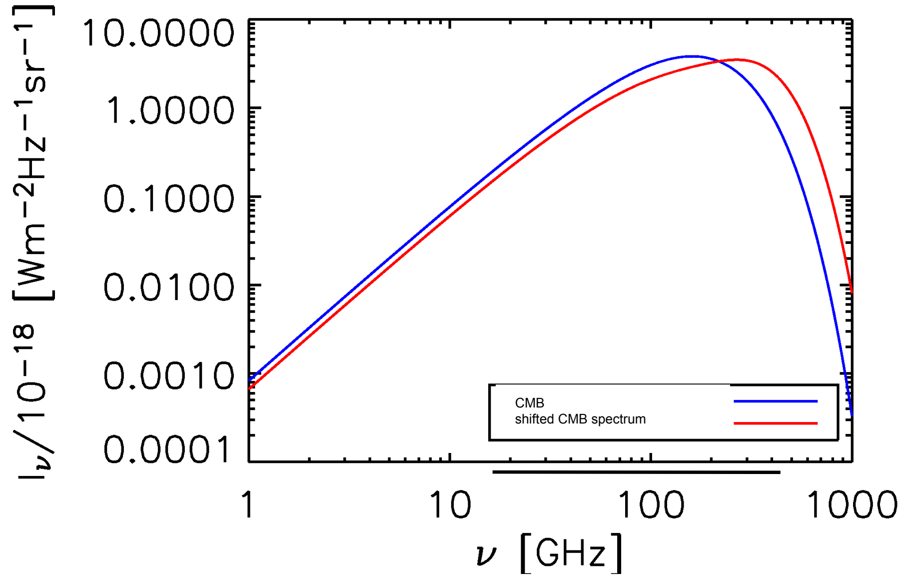
Sunyaev and Zeldovich 1970,1972



Detecting the hot gas in halos with the SZ effect

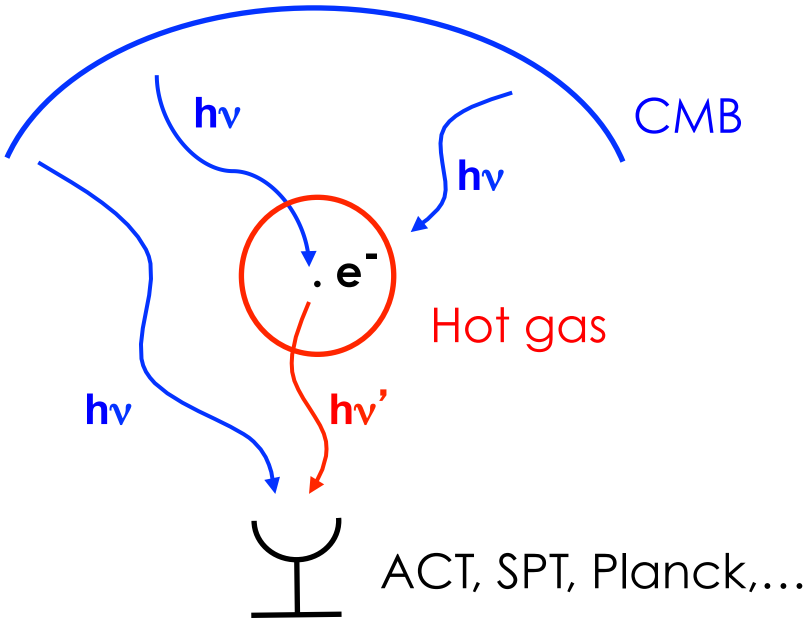
Sunyaev and Zeldovich 1970,1972

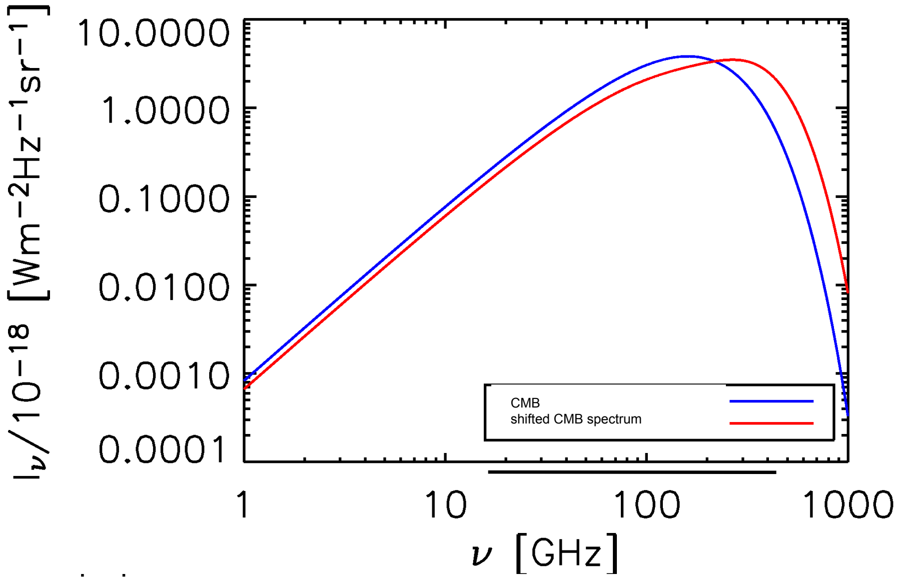


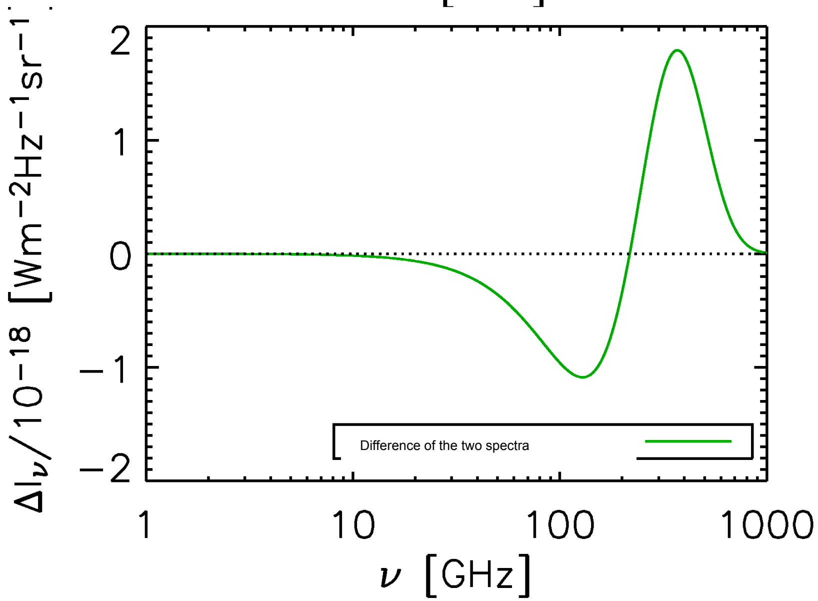


Detecting the hot gas in halos with the SZ effect

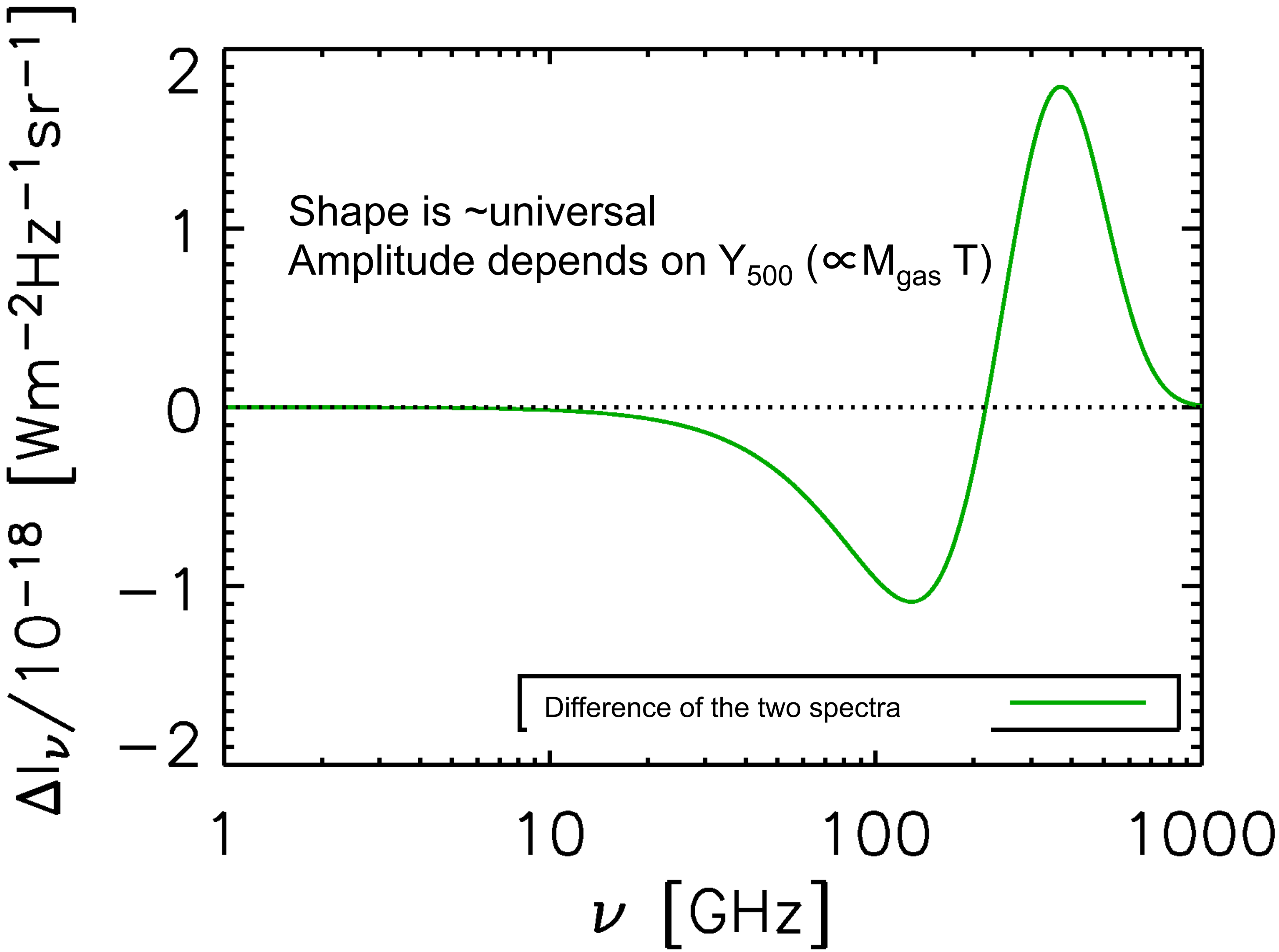
Sunyaev and Zeldovich 1970,1972



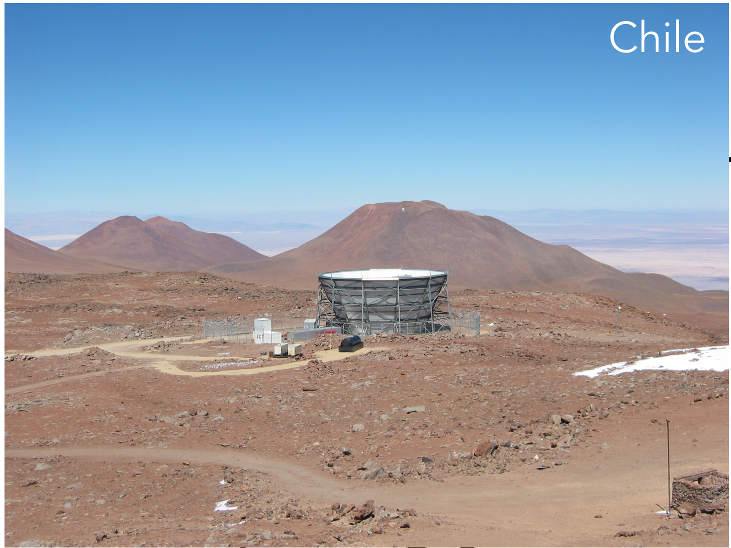




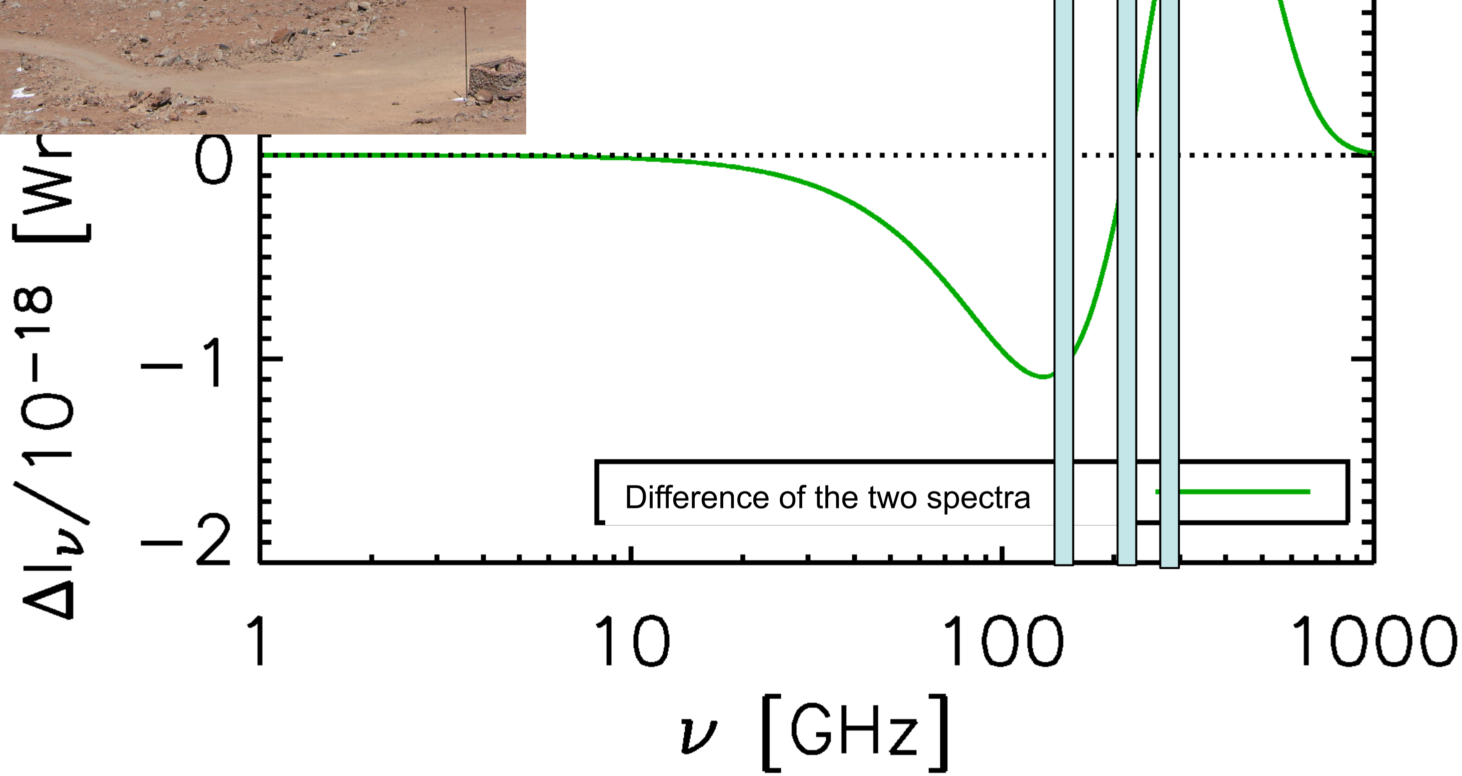
Detecting the hot gas in halos with the SZ effect



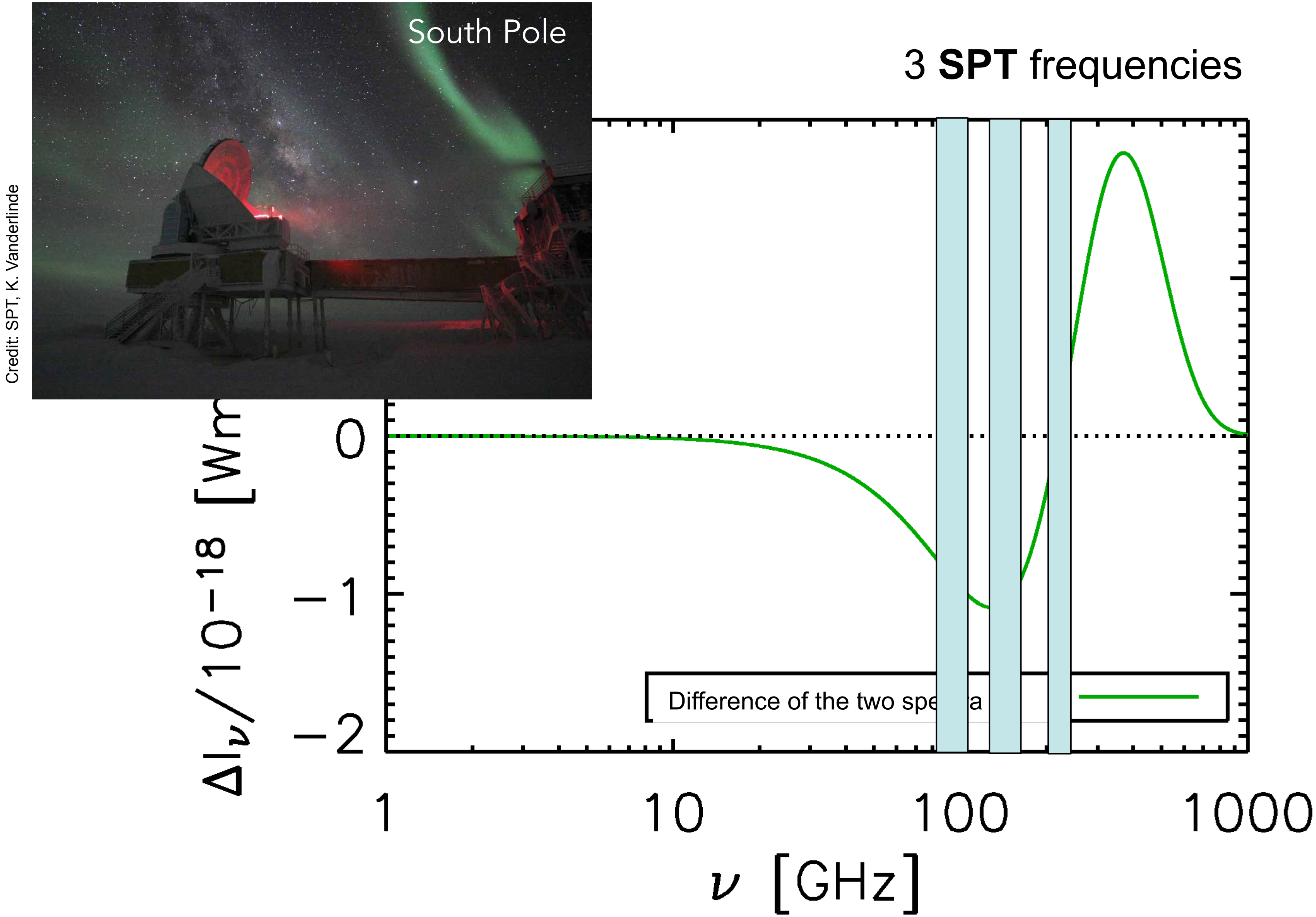
Detecting the hot gas in halos with the SZ effect



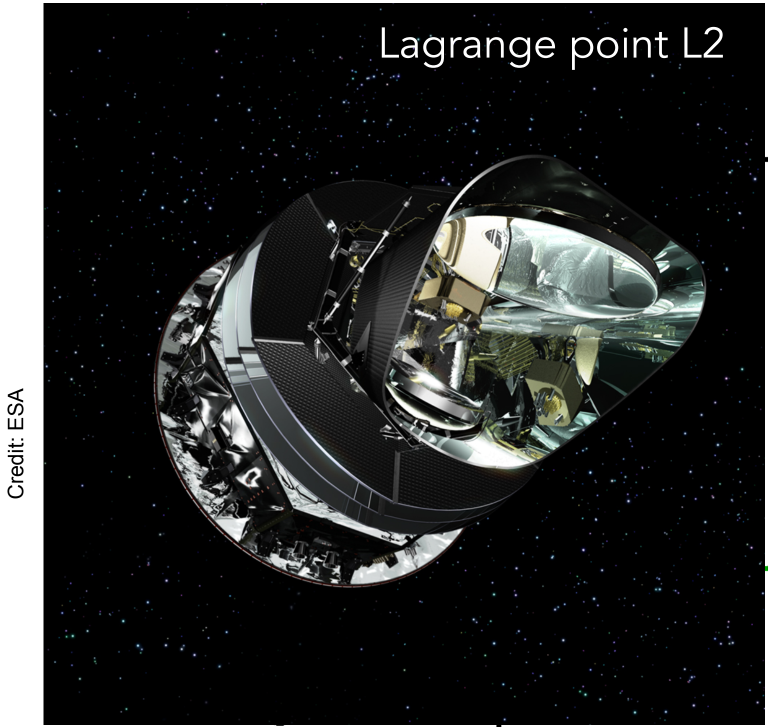
Credit: ACT

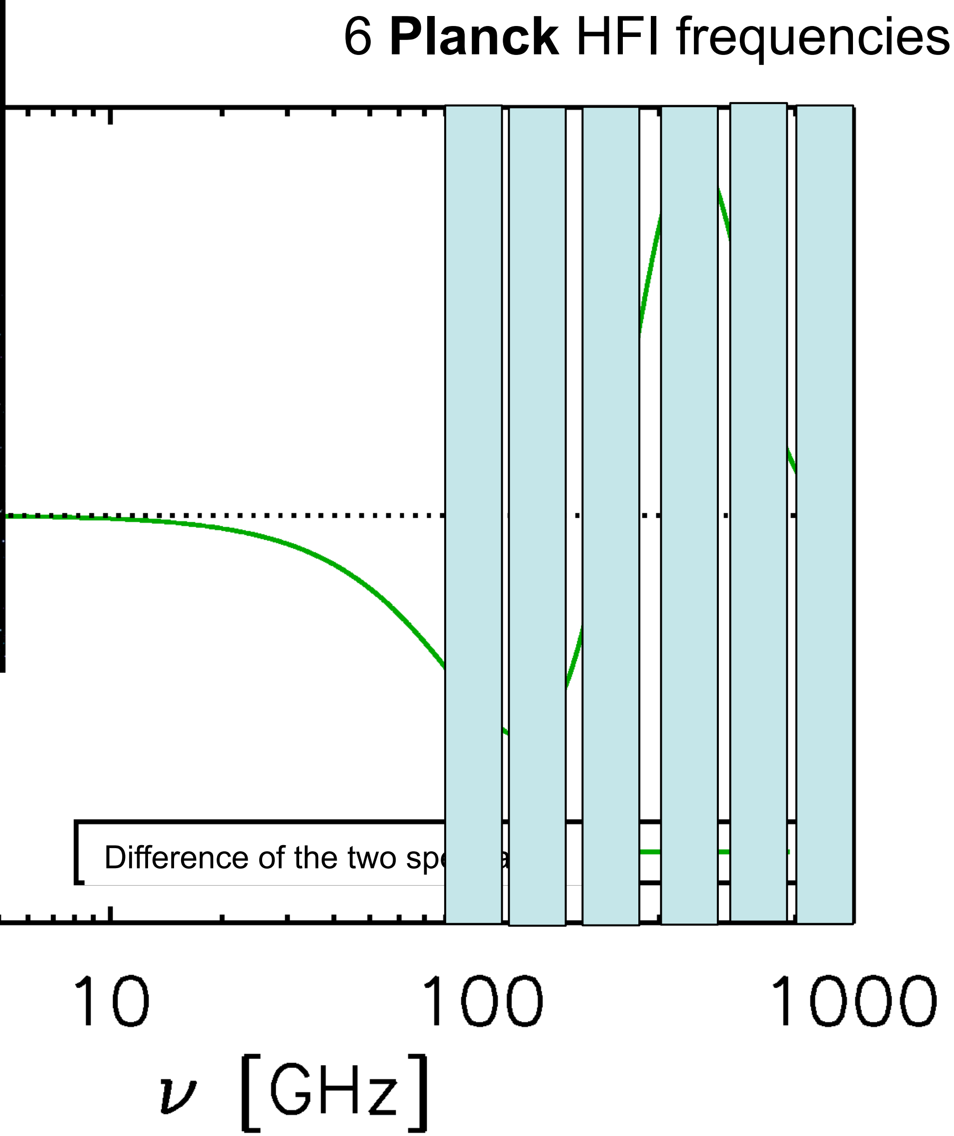


Detecting the hot gas in halos with the SZ effect

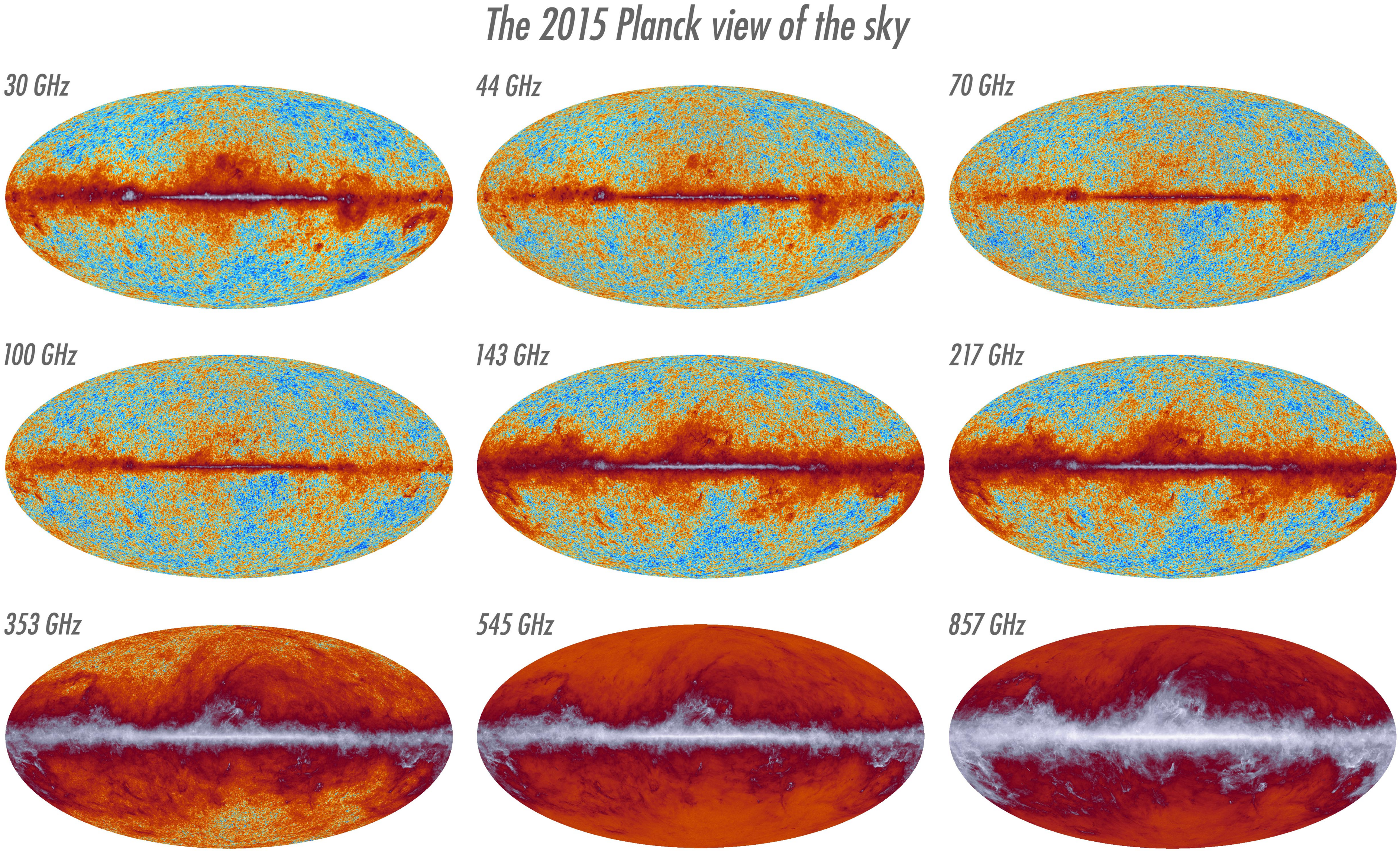


Detecting the hot gas in halos with the SZ effect

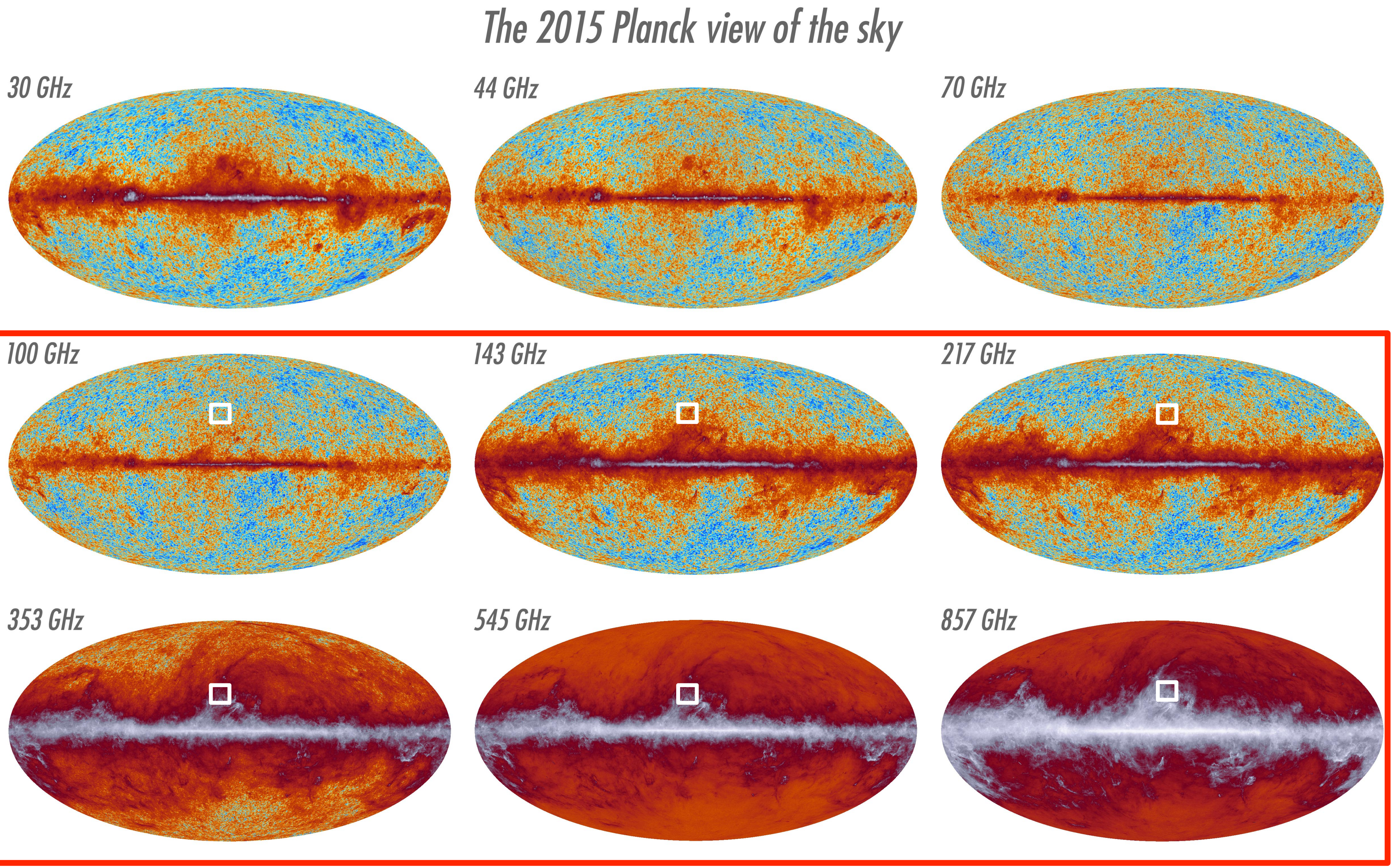




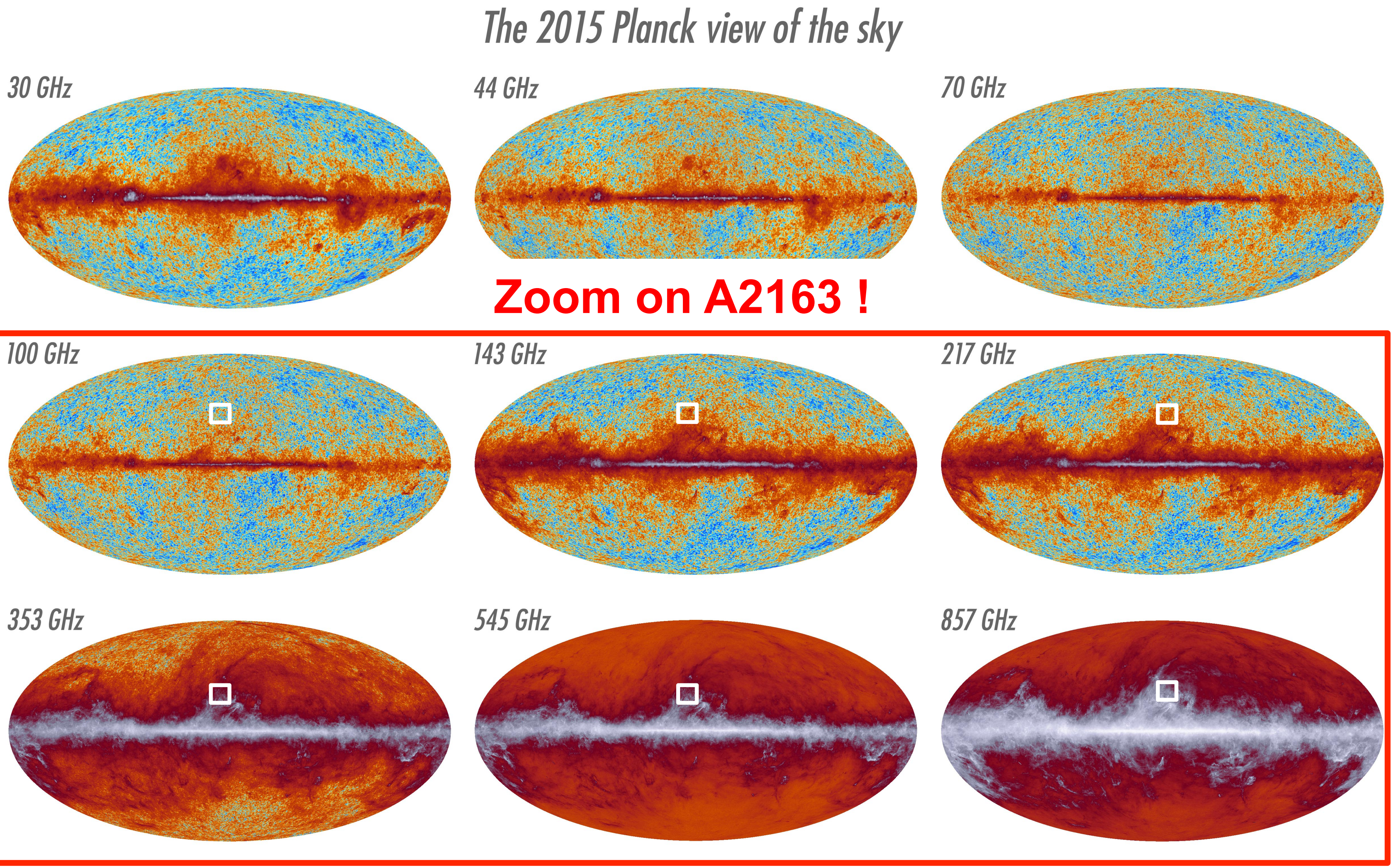
The Planck maps



The Planck maps

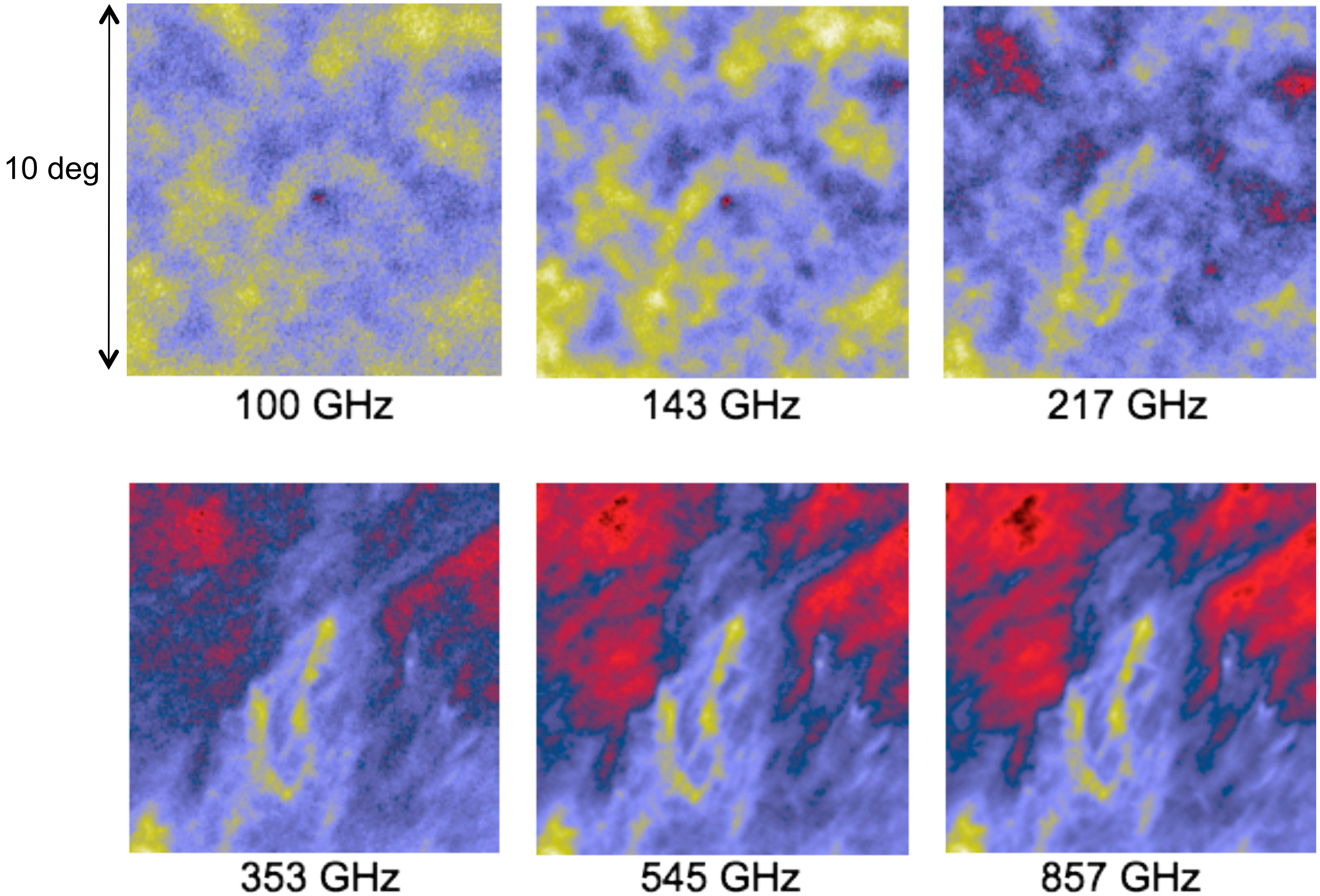


The Planck maps

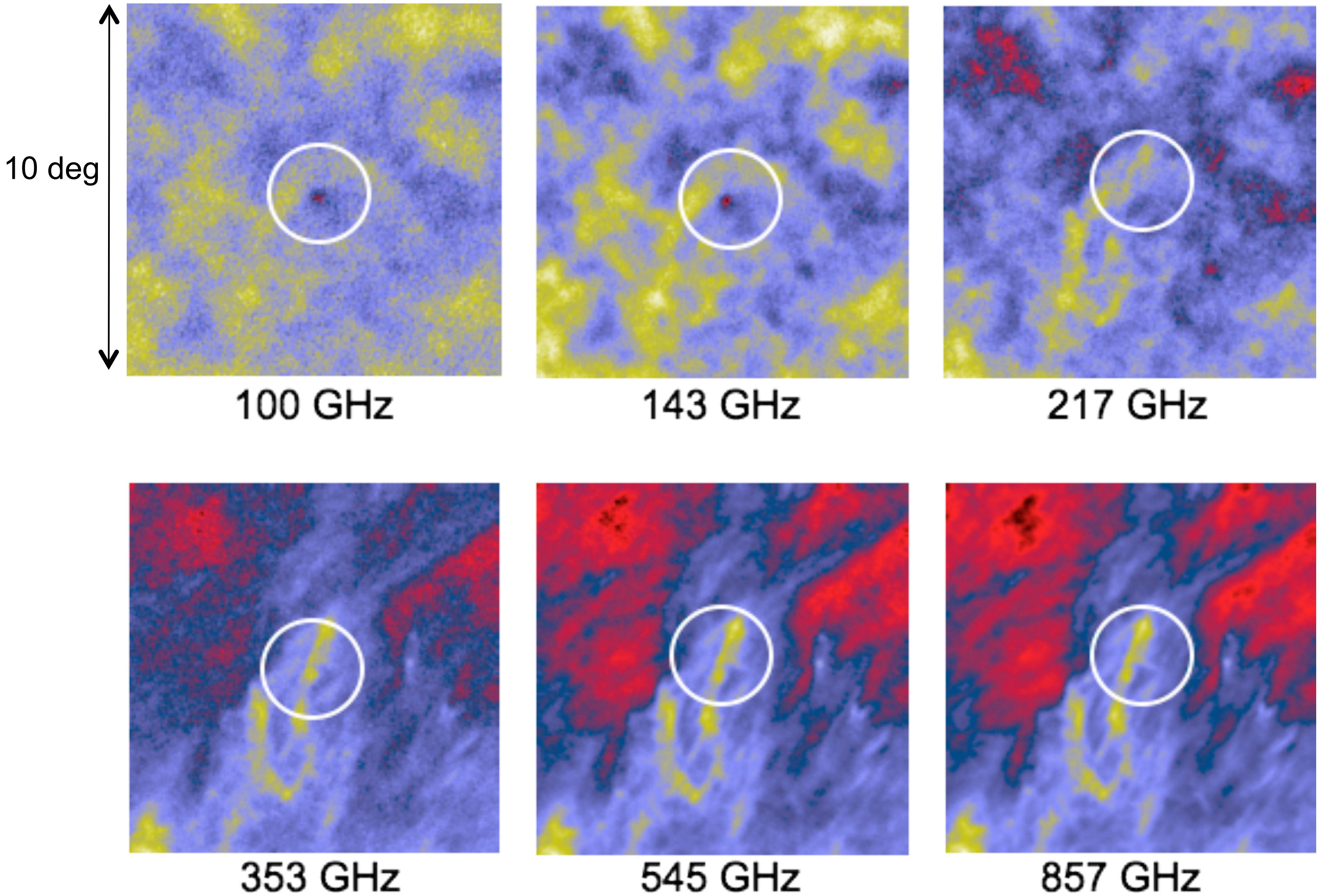


Zoom on A2163 !

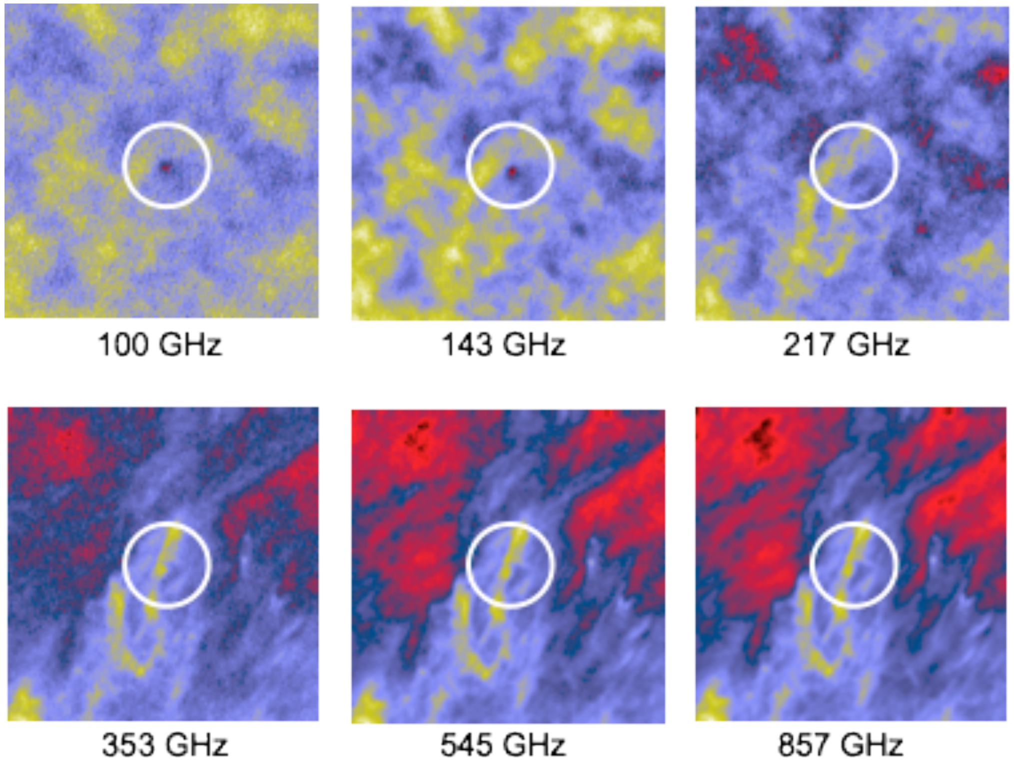
Abell 2163

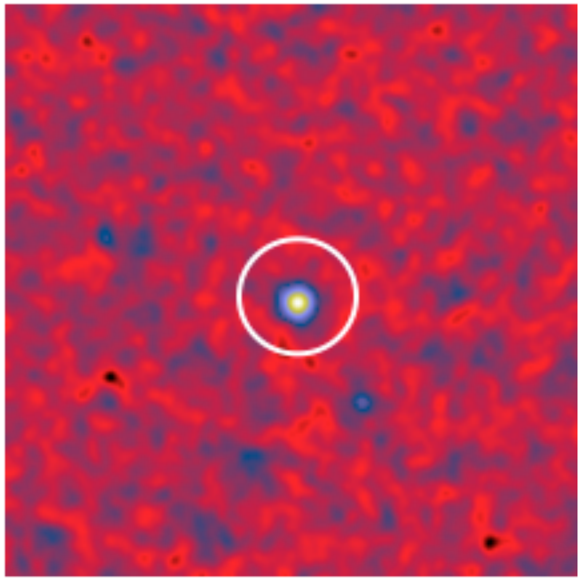


Abell 2163



Abell 2163





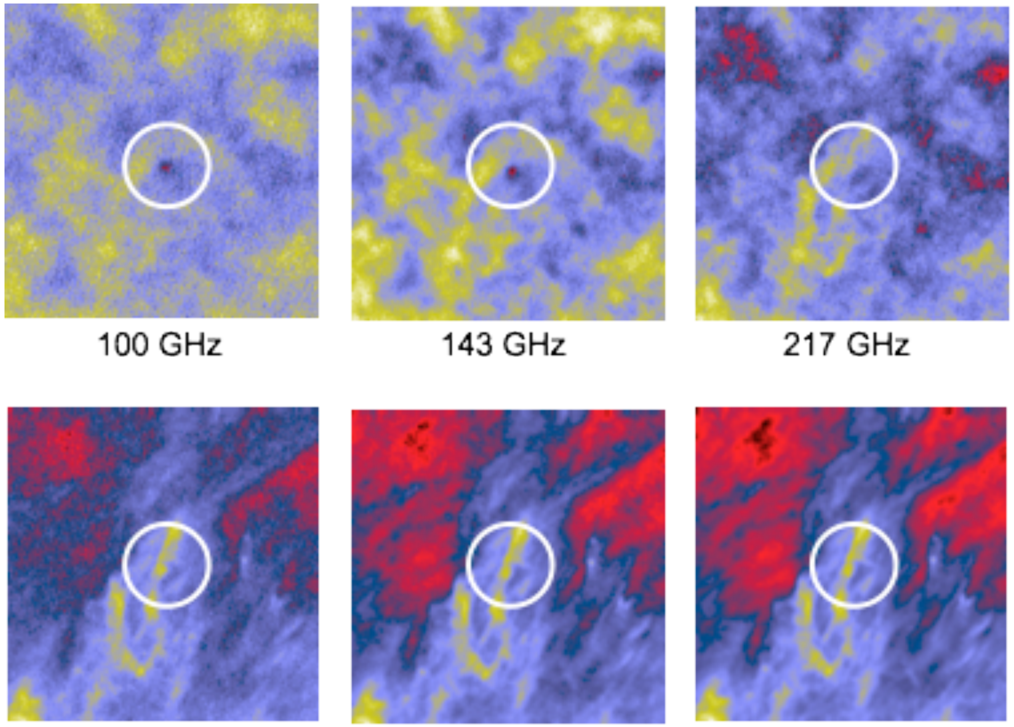
MMFiltered map

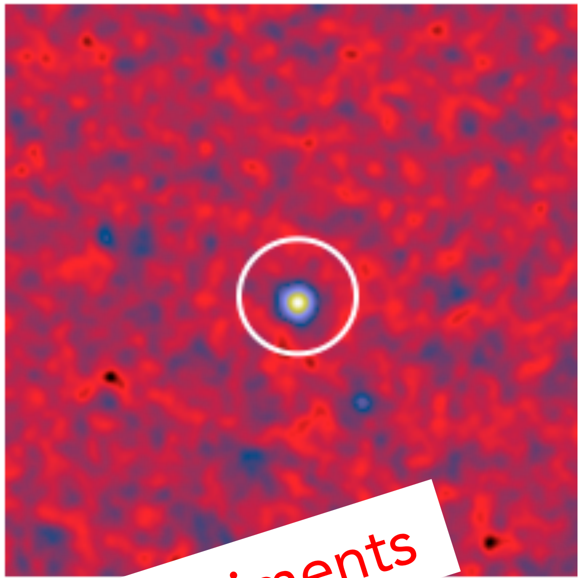
The Matched Multi Filters assume

- SZ frequency spectrum
- cluster profile
- noise crosspower spectra

Herranz et al. 2002
Melin, Bartlett, Delabrouille 2006

Abell 2163





…ed map

The Mat… …l Filters

…frequency spectrum
• cluster profile
• noise crosspower spectra

The Matched filters are used by the three experiments

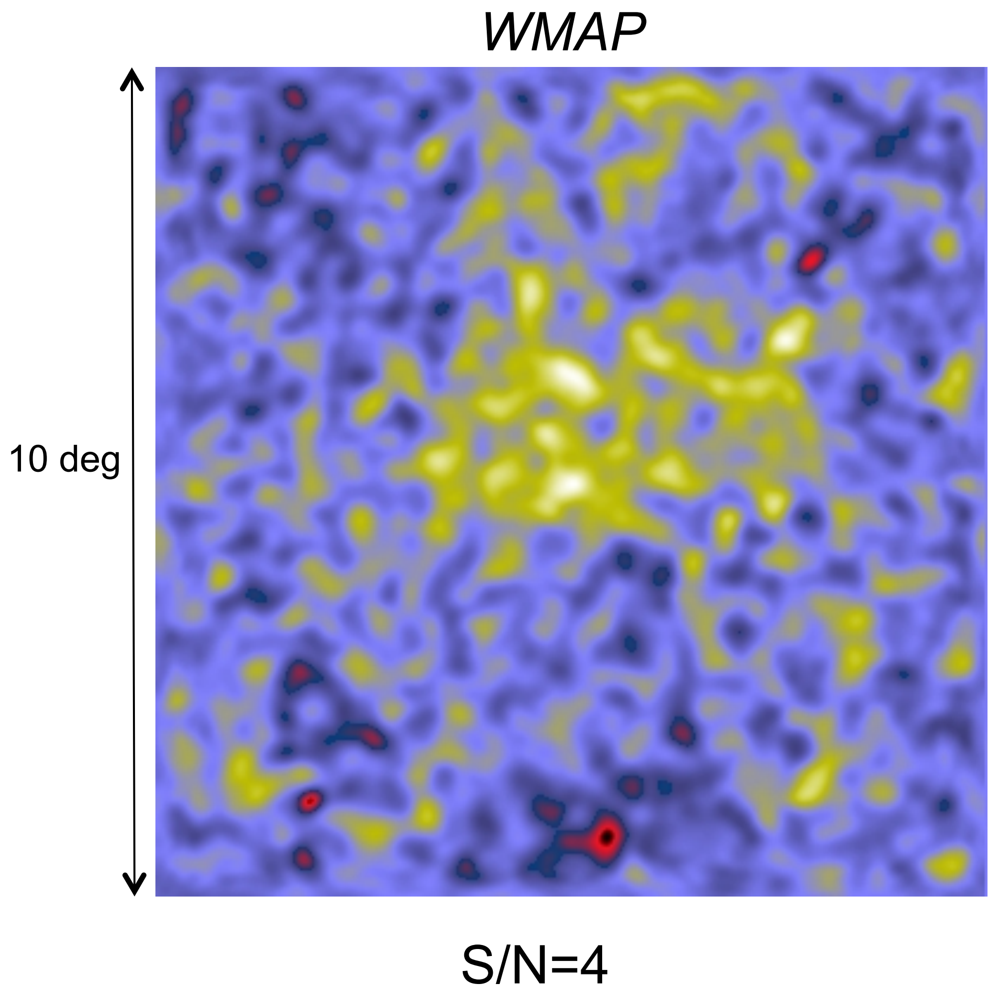
Herranz et al. 2002
Melin, Bartlett, Delabrouille 2006

A short pre-”Planck launch” story
(circa 2007-2008)

Competition for the first SZ blind detection

Competition for the first SZ blind detection

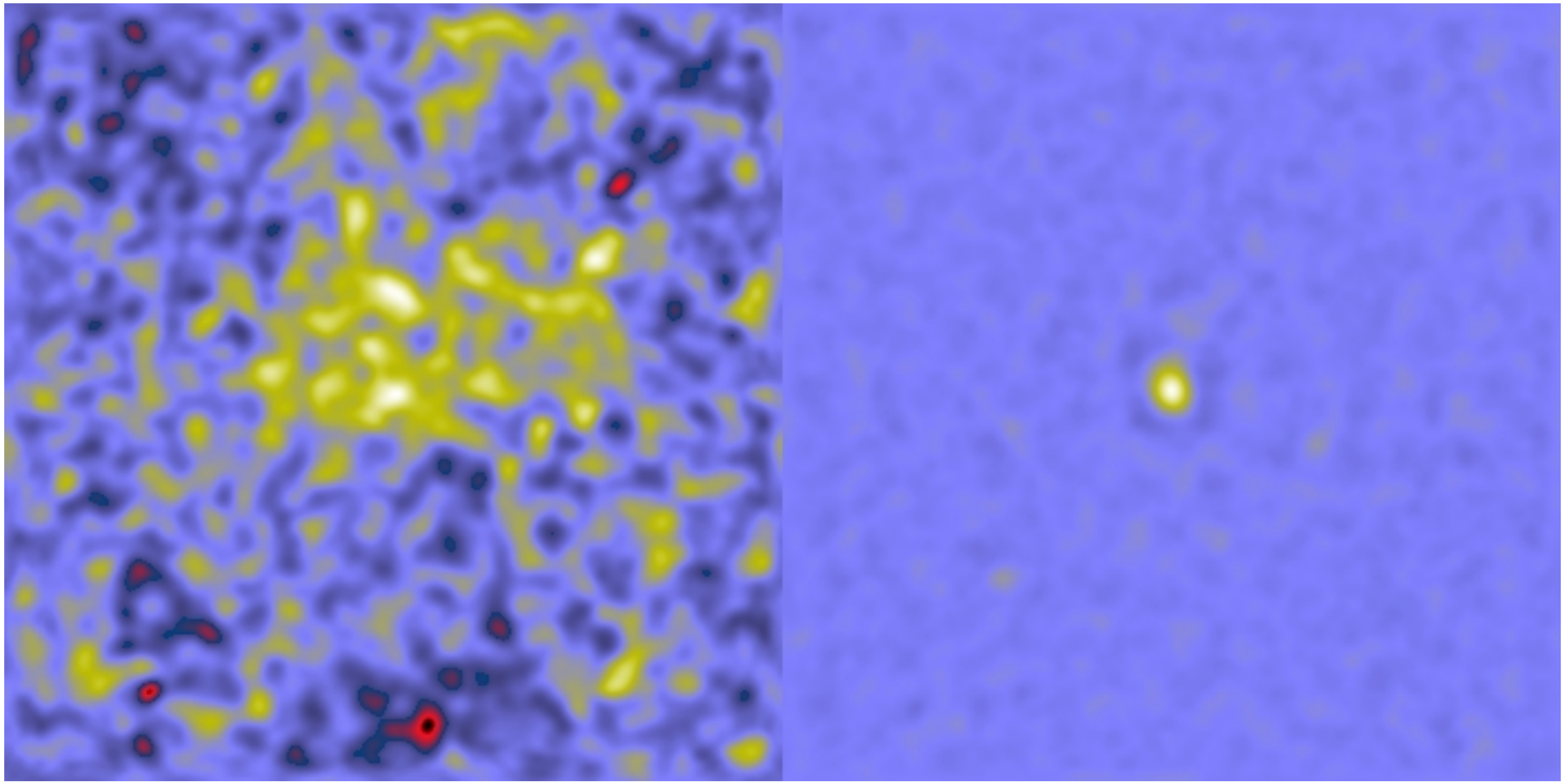
Coma



Competition for the first SZ blind detection

Coma

WMAP *Planck*

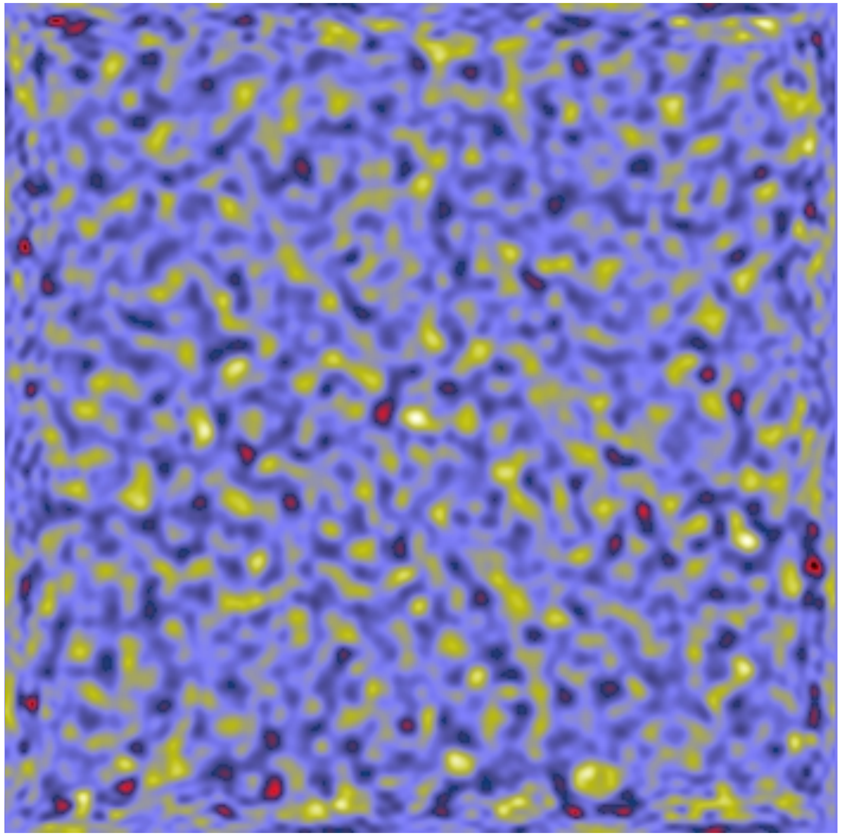


S/N=4 S/N=29

Competition for the first SZ blind detection

A2163

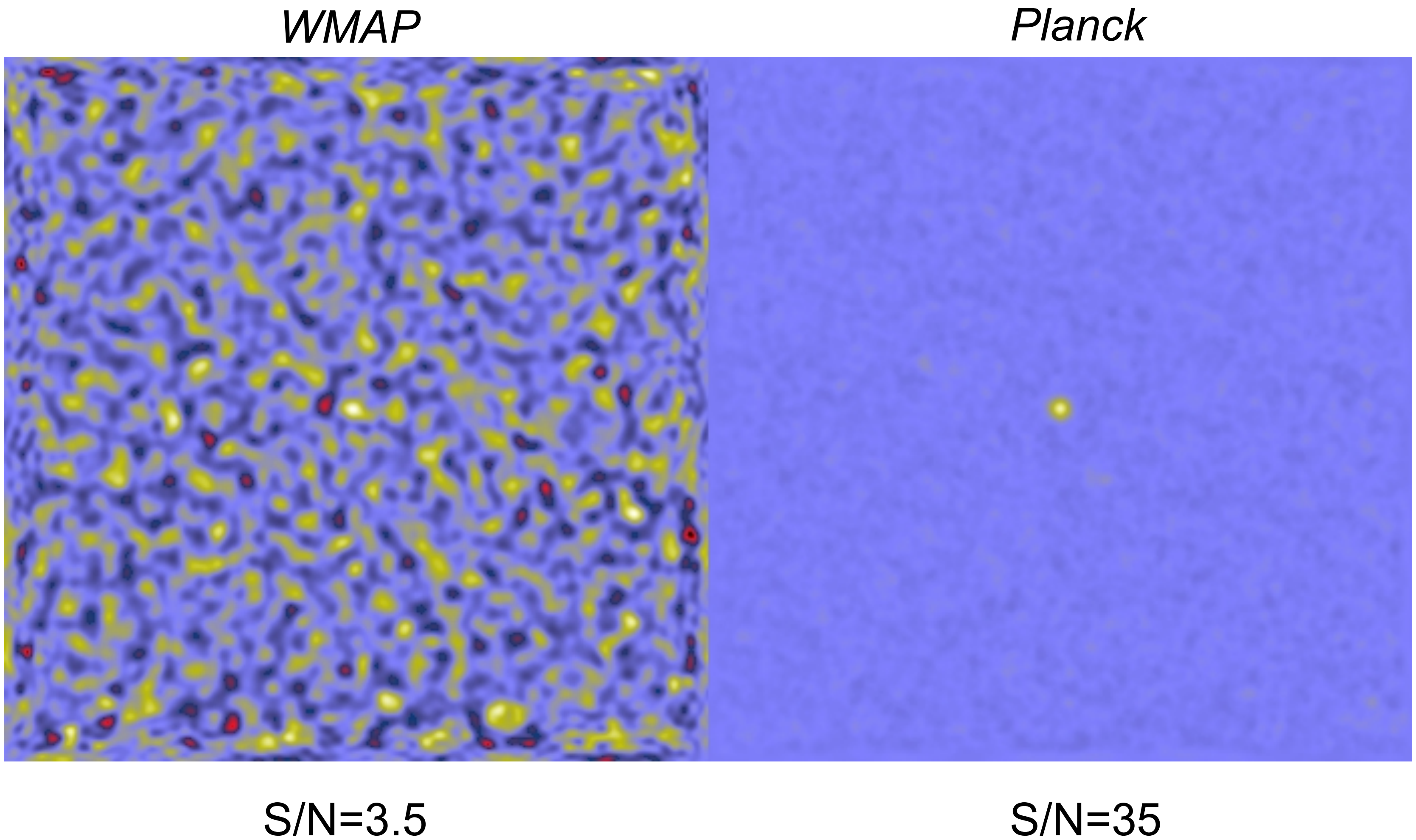
WMAP



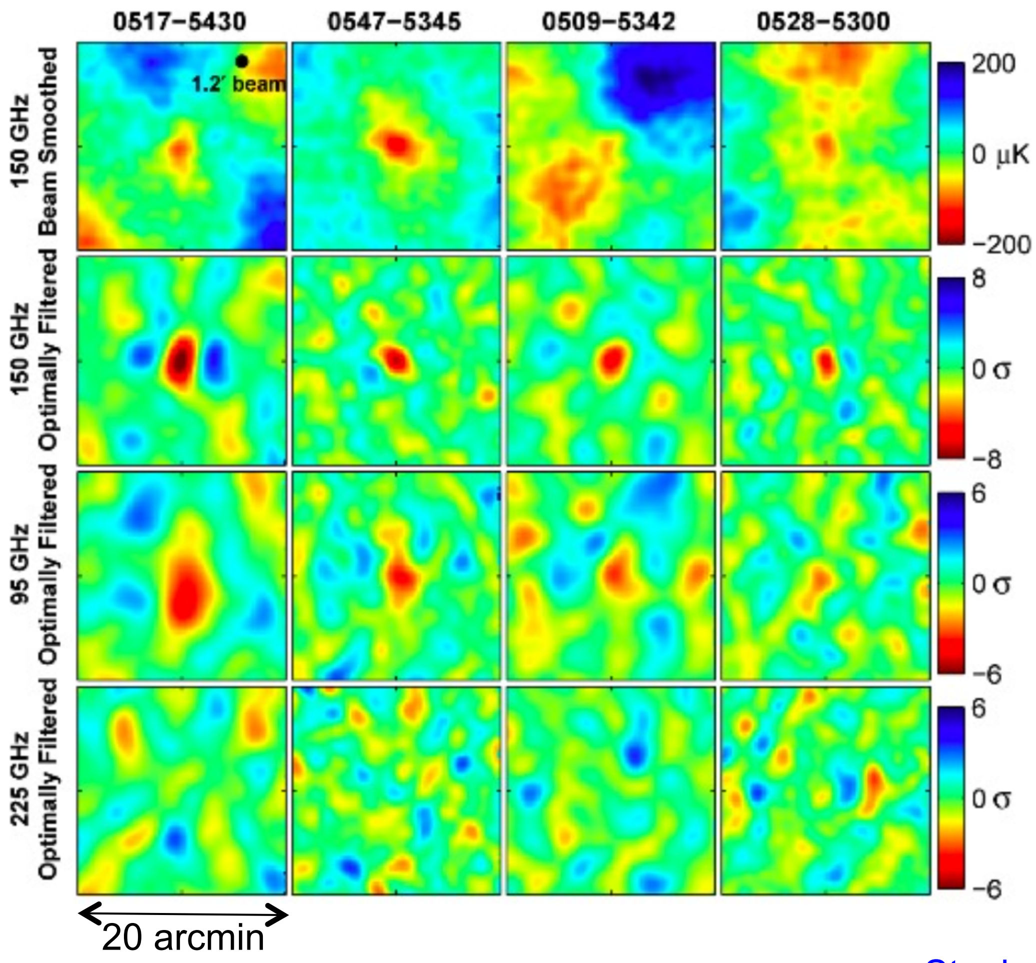
S/N=3.5

Competition for the first SZ blind detection

A2163



Competition for the first SZ blind detection



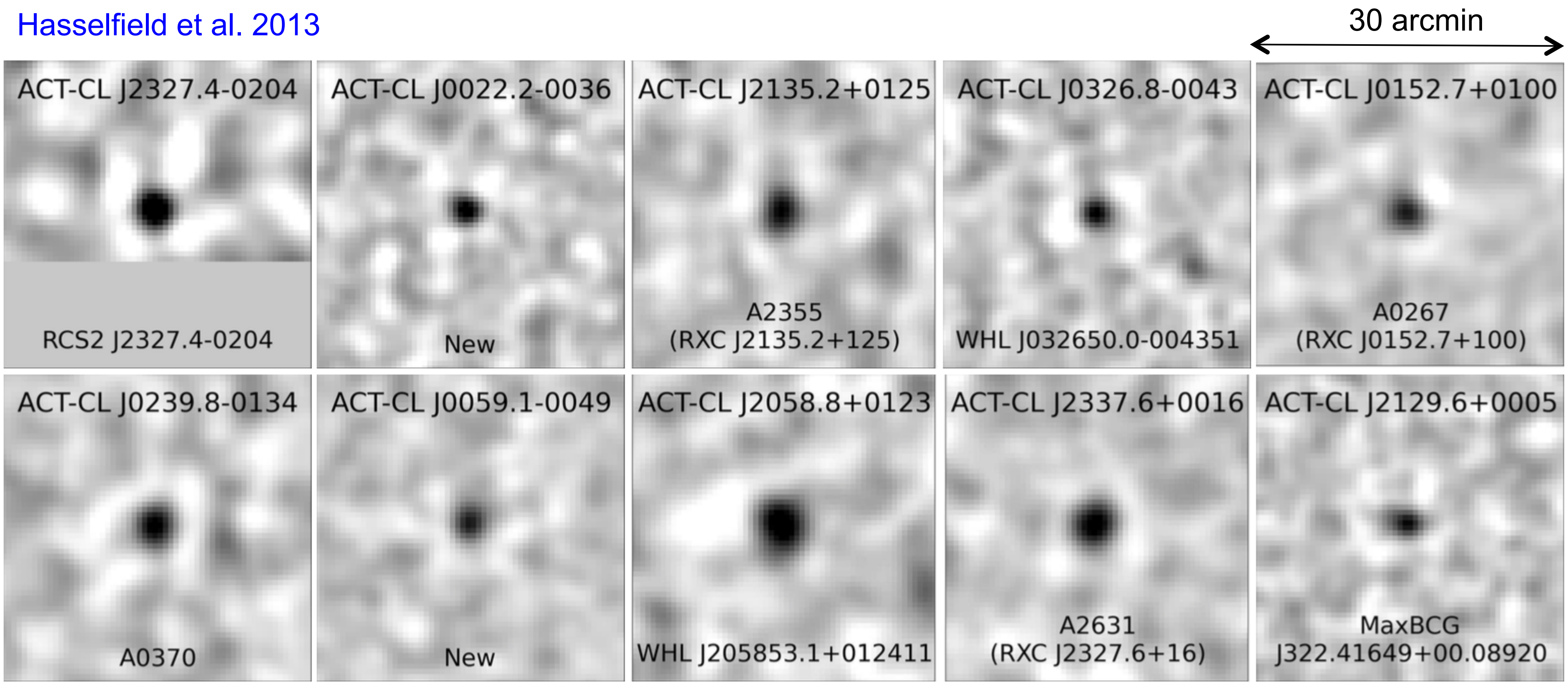
Staniszewski et al. 2008

Outline

- The Sunyaev-Zeldovich (SZ) effect
- Blind SZ catalogues
- Cosmological constraints from SZ cluster counts

The ACT catalogue

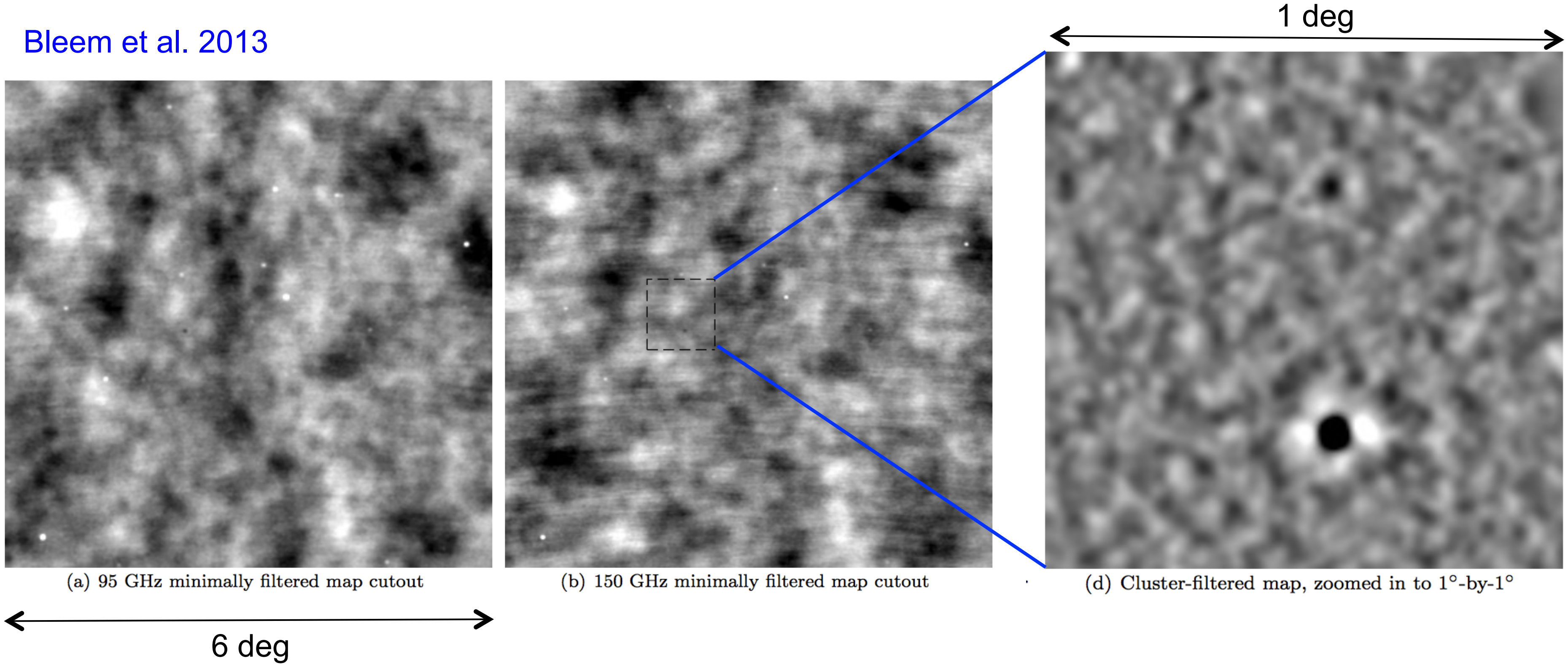
Hasselfield et al. 2013



91 optically confirmed clusters (504 deg^2)

The SPT catalogue

Bleem et al. 2013



(a) 95 GHz minimally filtered map cutout

(b) 150 GHz minimally filtered map cutout

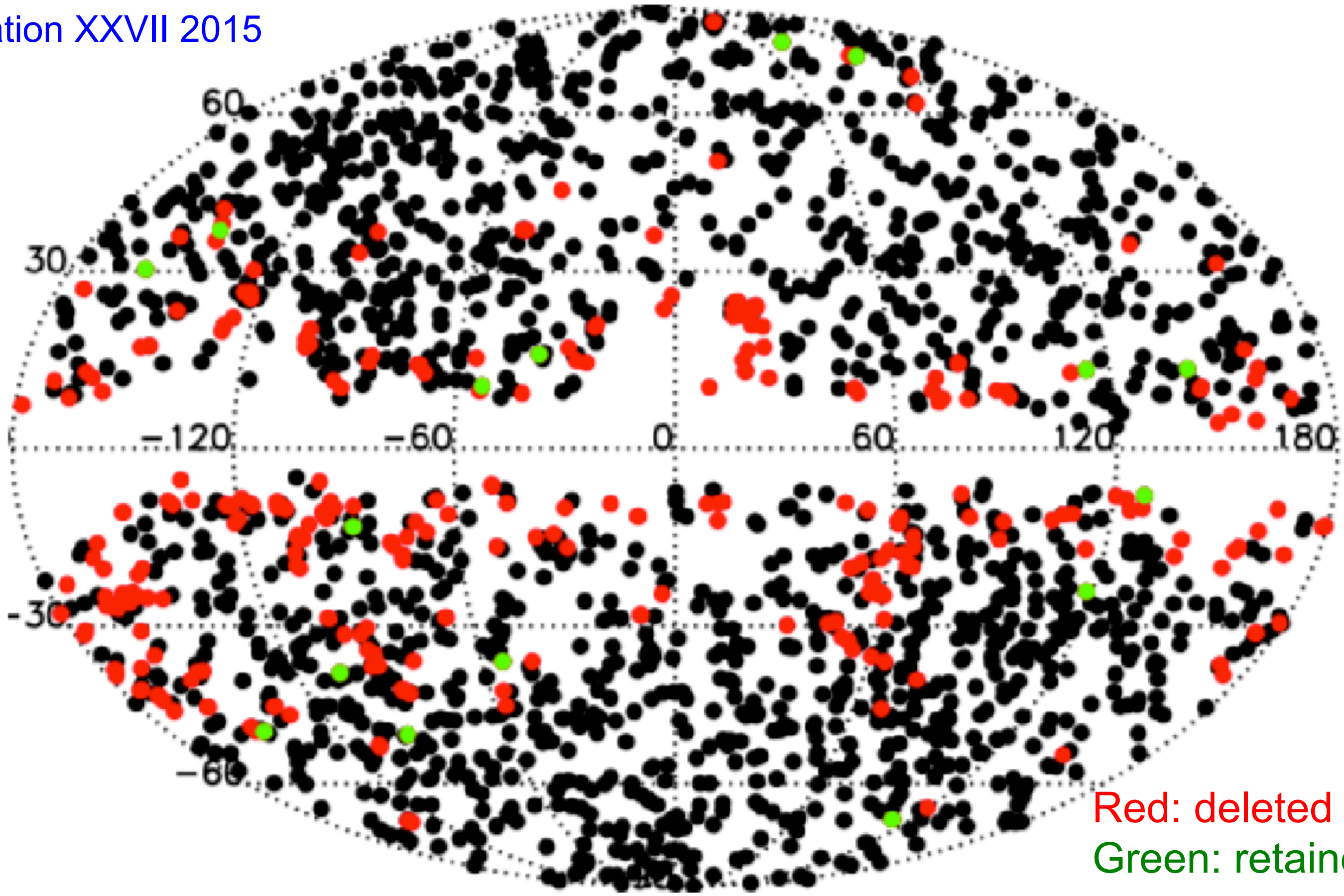
(d) Cluster-filtered map, zoomed in to 1°-by-1°

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

The PSZ2 (Planck Legacy) catalogue

Published early February 2015 (full mission data i.e. 29 months)

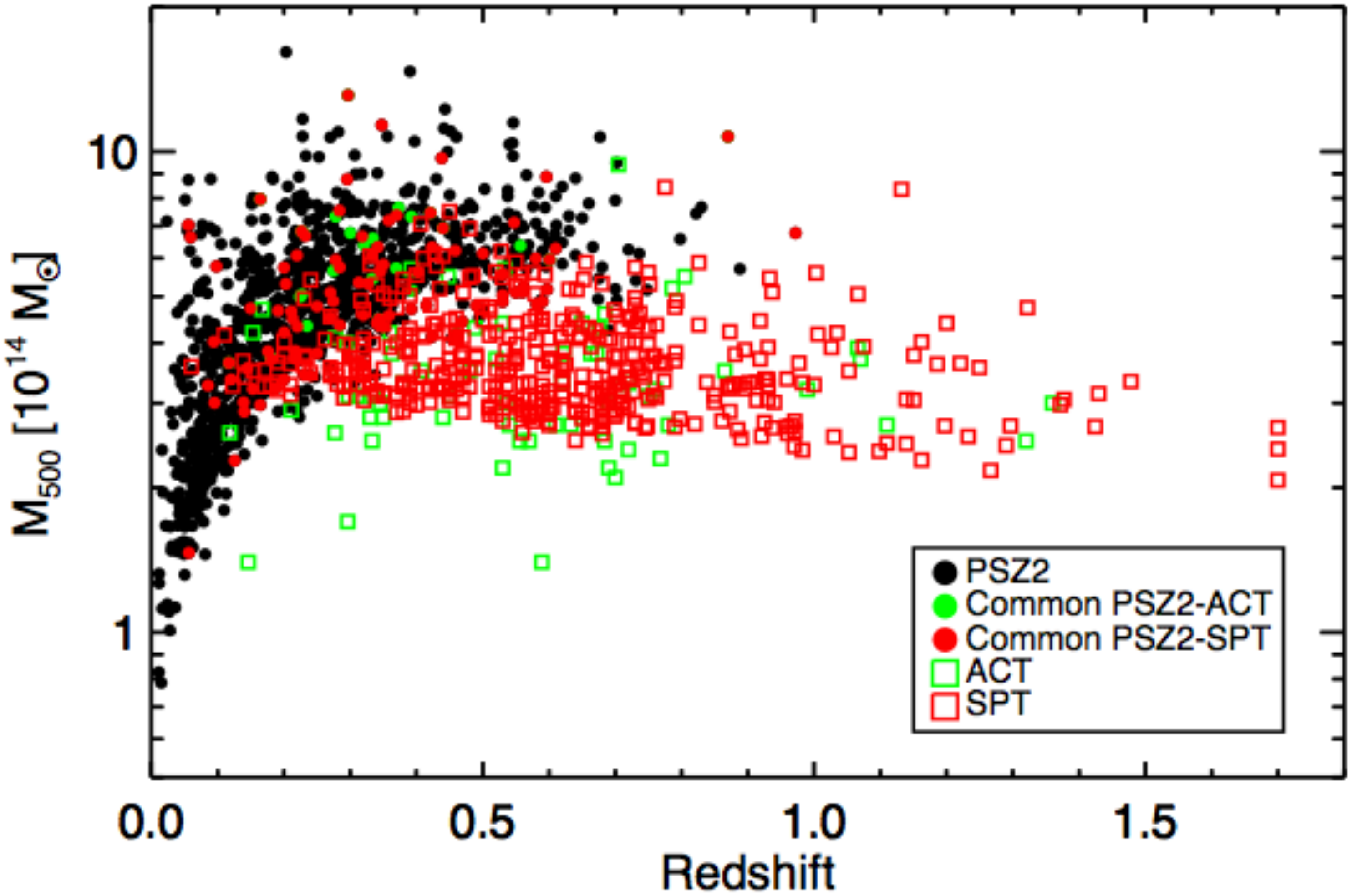
Planck Collaboration XXVII 2015



Red: deleted IR-flagged
Green: retained IR-flagged

1653 SZ sources with S/N>4.5

Main properties of the three catalogues

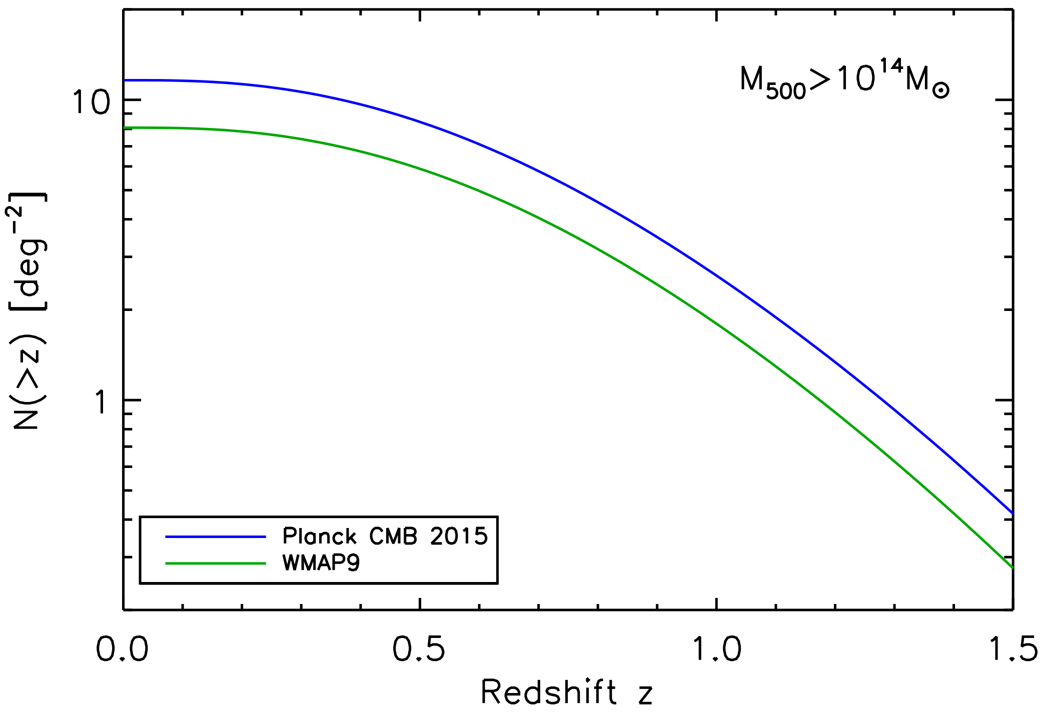


Warning: non-uniform redshift knowledge for Planck,
PSZ2 should contain z>0.6 objects not visible here

Outline

- The Sunyaev-Zeldovich (SZ) effect
- Blind SZ catalogues
- Cosmological constraints from SZ cluster counts

Cosmology from cluster counts



Cluster abundance and evolution are very sensitive to cosmological parameters $\sigma_8 \ \Omega_m$

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

The cosmological samples

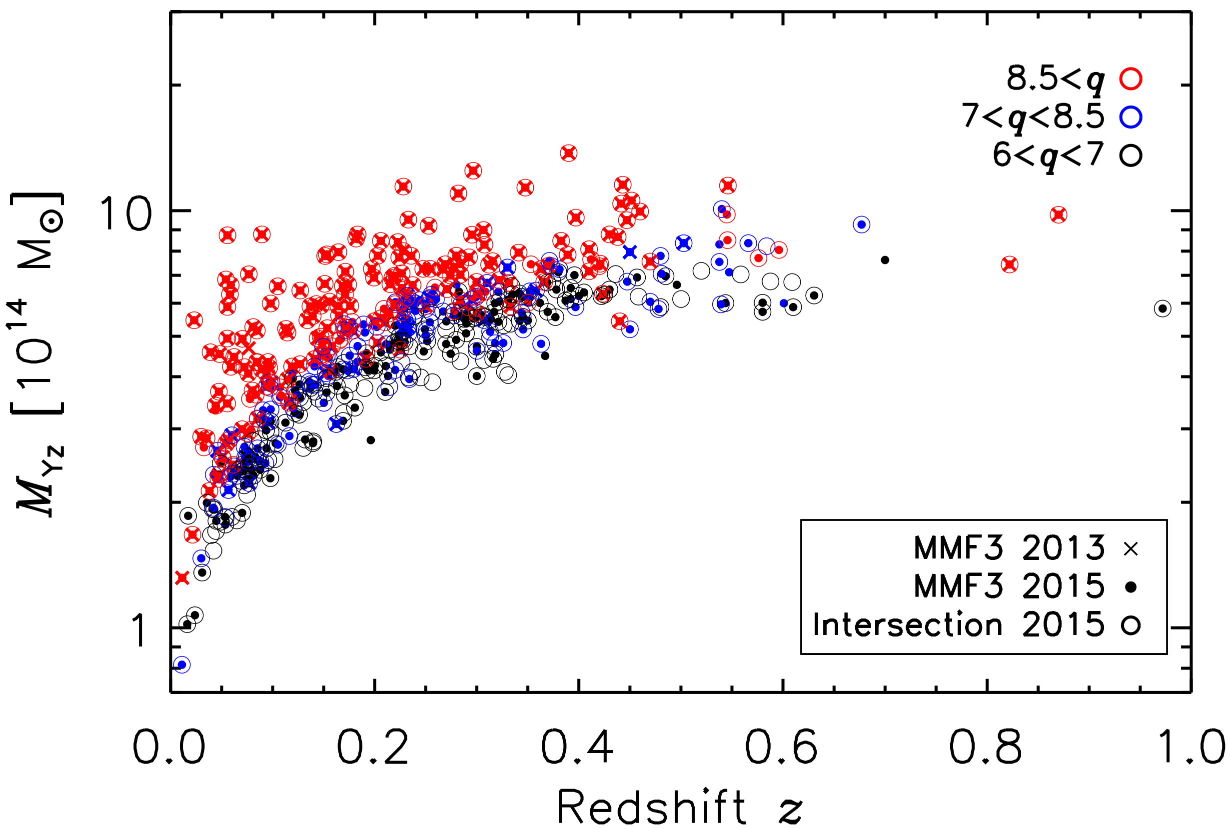
Highly reliable candidate sub-samples
+
Selection function under control

ACT S/N>5.1 ➔ 15 clusters

SPT S/N>5 ➔ 100 clusters

Planck S/N>6 ➔ 439 clusters

The Planck 2015 cosmological sample



MMF3 detections only, S/N=q>6, 65% galactic mask

439 clusters [189 clusters in 2013]

The Planck SZ cosmological analysis 2013

We used only dN/dz vs. z

189 clusters
MMF3 only
S/N=q>7

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})

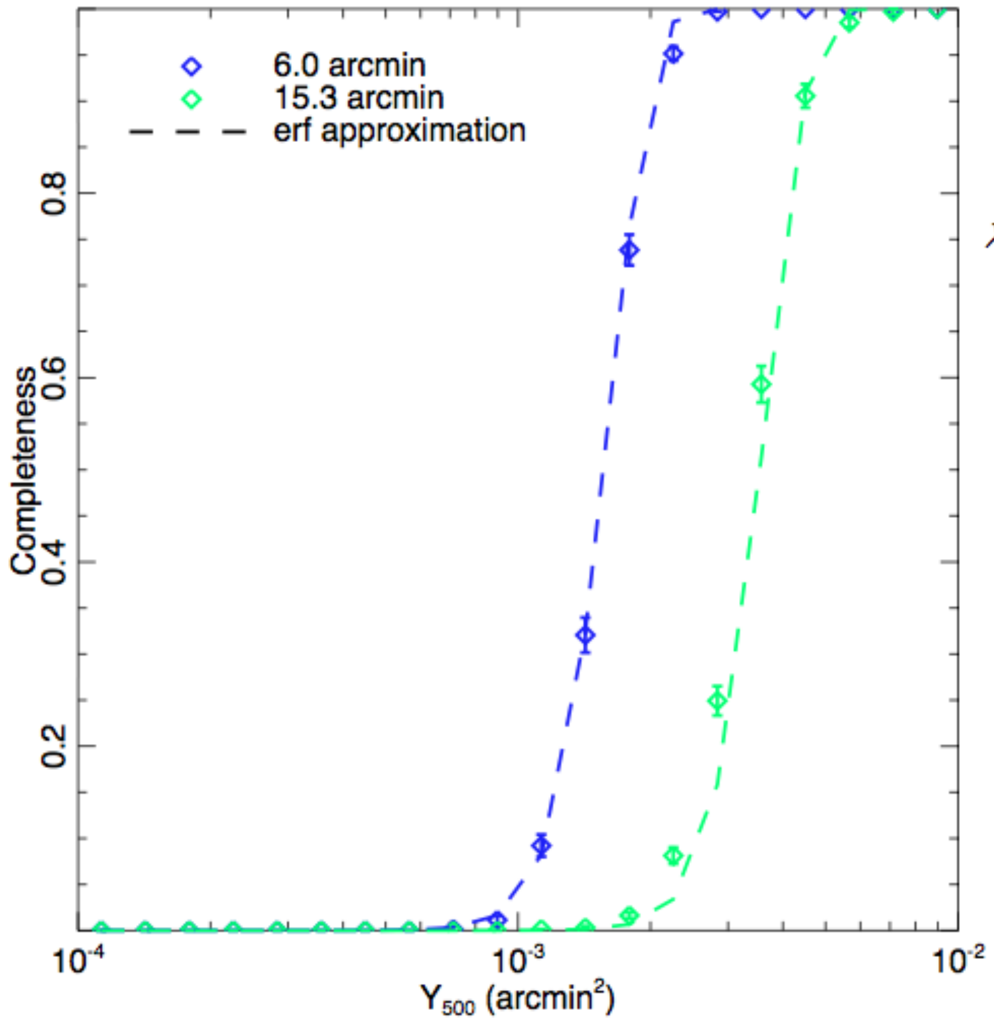
$$\hat{\chi} = \int dY_{500} \int d\theta_{500} P(z, M_{500} | Y_{500}, \theta_{500}) \chi(Y_{500}, \theta_{500}, l, b)$$

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

need scaling laws
depends on cosmology

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

Completeness (θ_{500}, Y_{500})



Noise maps

$$\chi_{\rm erf}(Y_{500},\theta_{500},l,b) = \frac{1}{2}\left[1+\mathrm{erf}\left(\frac{Y_{500} - X\,\sigma_{Y_{500}}(\theta_{500},l,b)}{\sqrt{2}\,\sigma_{Y_{500}}(\theta_{500},l,b)}\right)\right]$$

with X=7 (S/N threshold 2013)

Good agreement between
the **erf approximation**
and
the **Monte Carlo calculation**

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

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

Important slide !

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

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

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

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**

The Planck SZ cosmological analysis 2013

We used only dN/dz vs. z

189 clusters
MMF3 only
S/N=q>7

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

TO BE COMPARED WITH

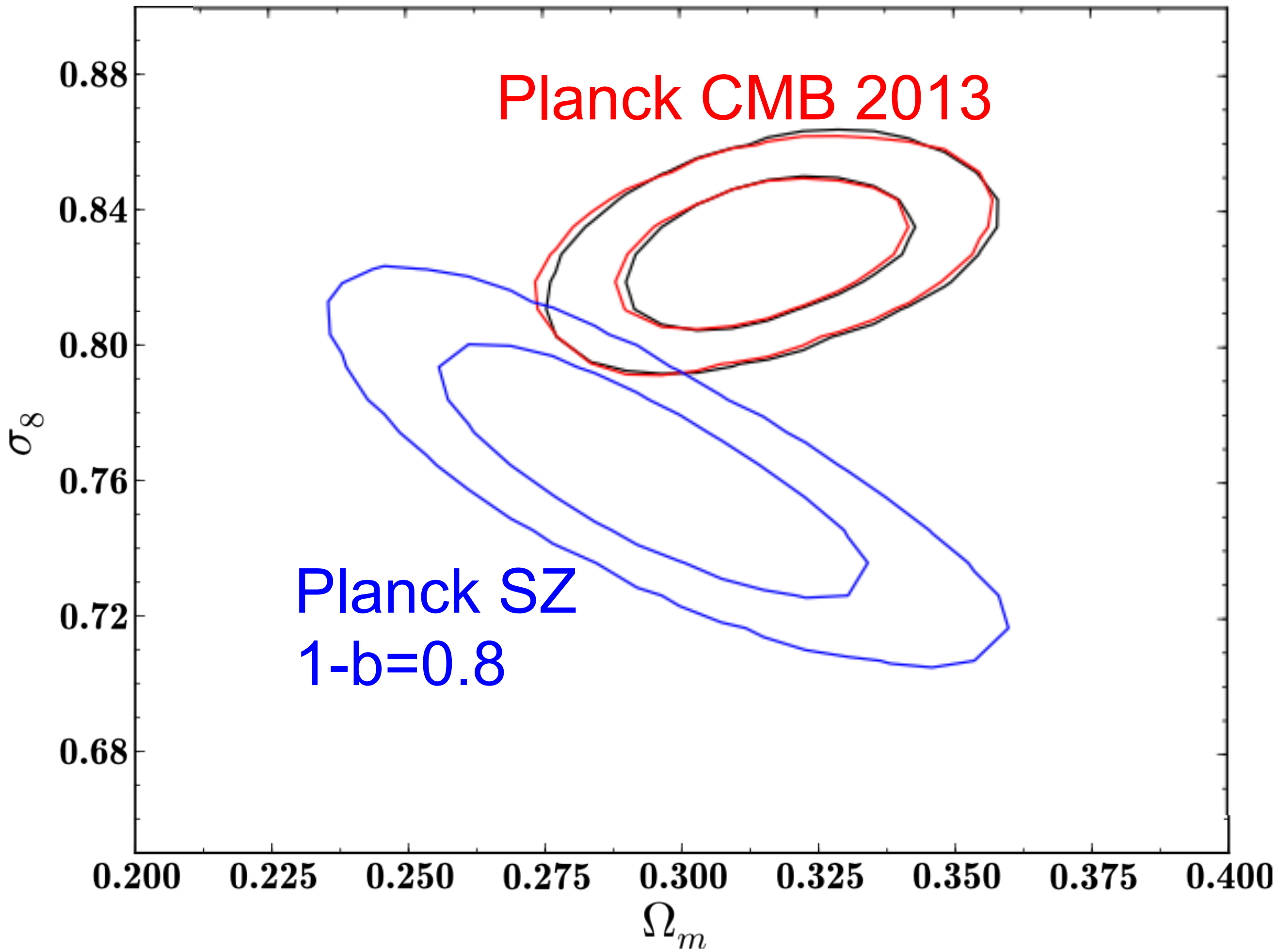
Predictions $$\frac{dN}{dz} = \int d\Omega \int dM_{500}\, \hat{\chi}(z, M_{500}, l, b)\, \frac{dN}{dz\, dM_{500}\, d\Omega}$$

↑ completeness

↑ mass function

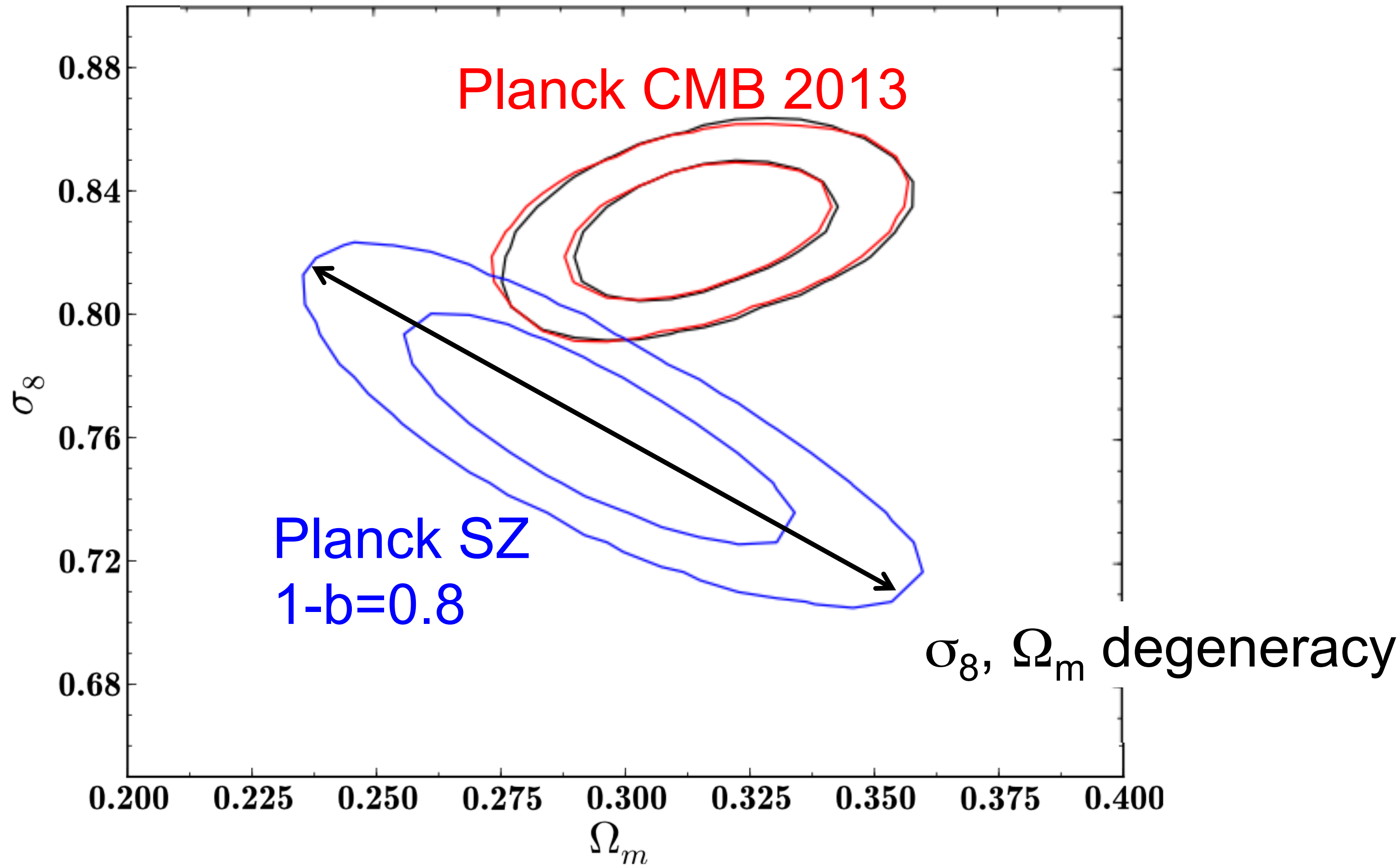
Tinker et al. 2008
Watson et al. 2013

Planck cluster cosmology 2013



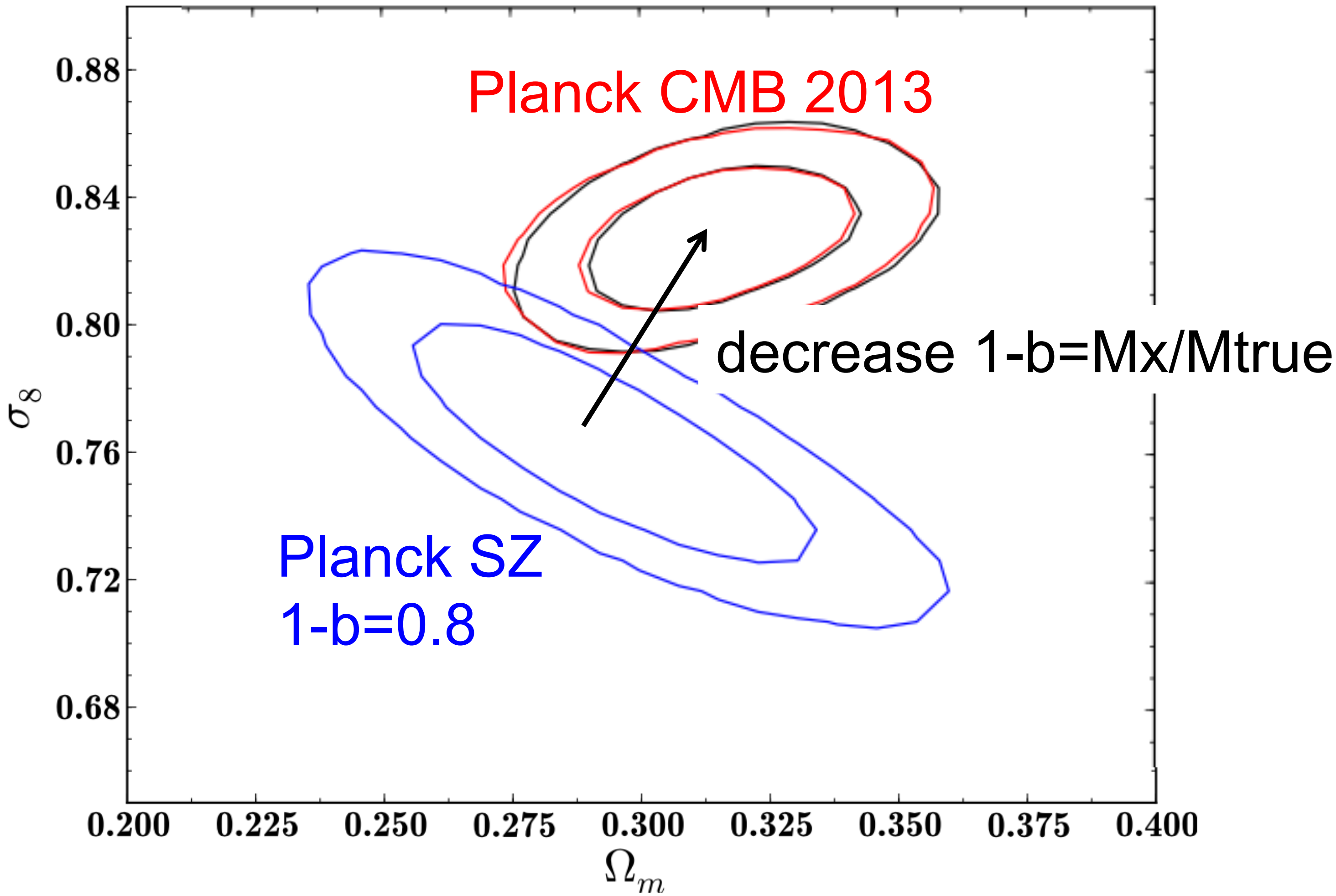
Planck Results XX 2013

Planck cluster cosmology 2013



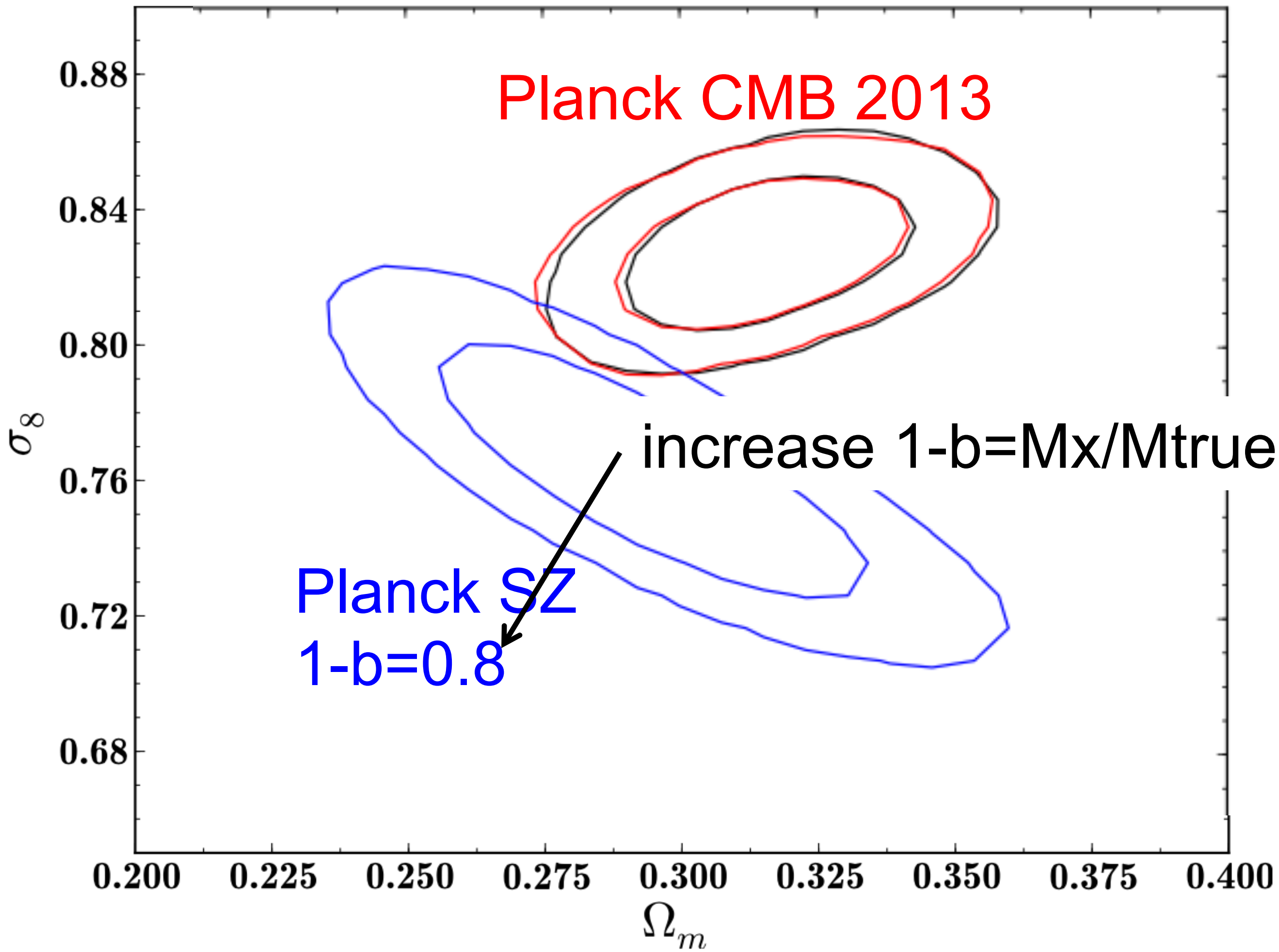
Planck Results XX 2013

Planck cluster cosmology 2013



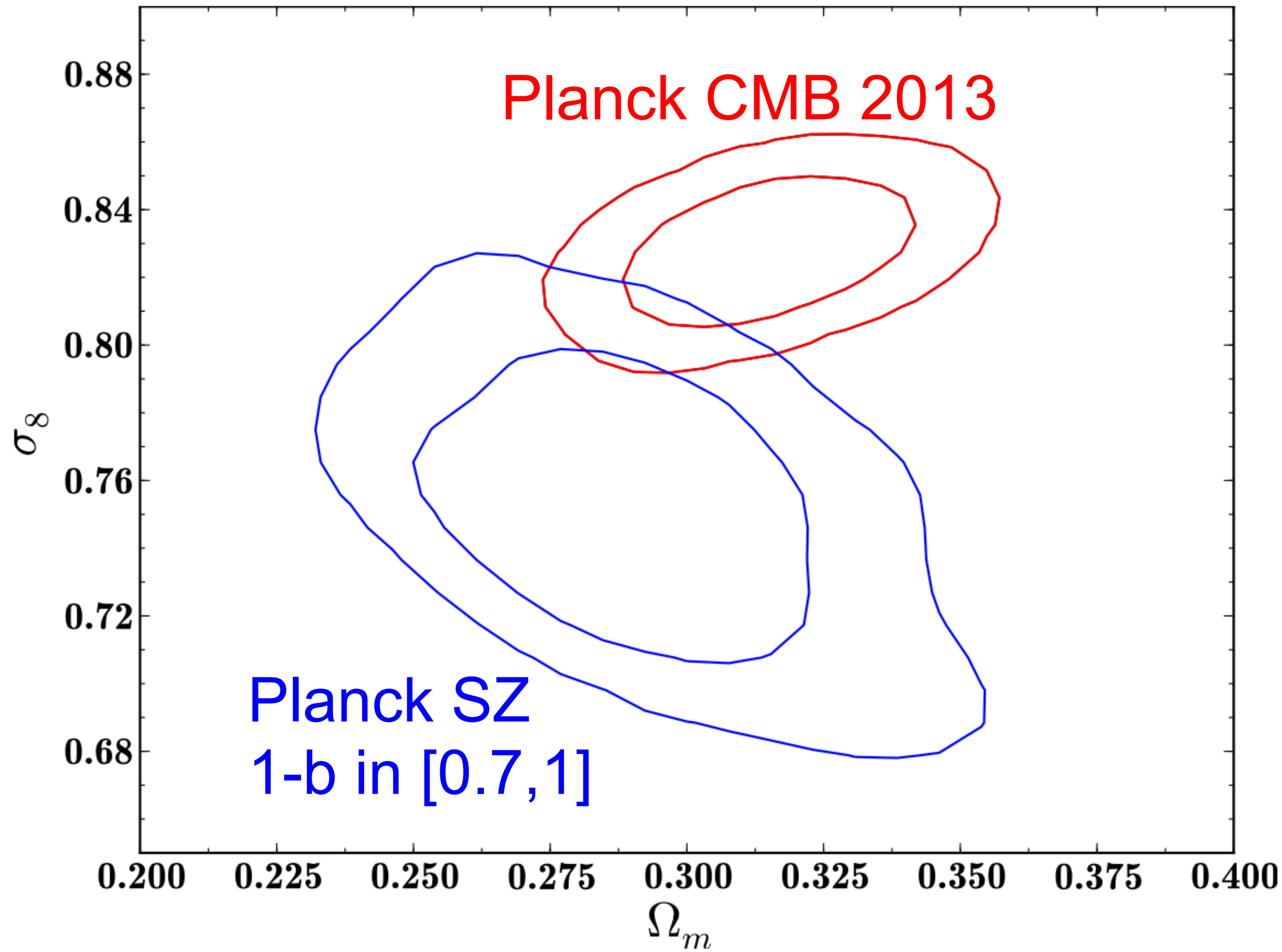
Planck Results XX 2013

Planck cluster cosmology 2013



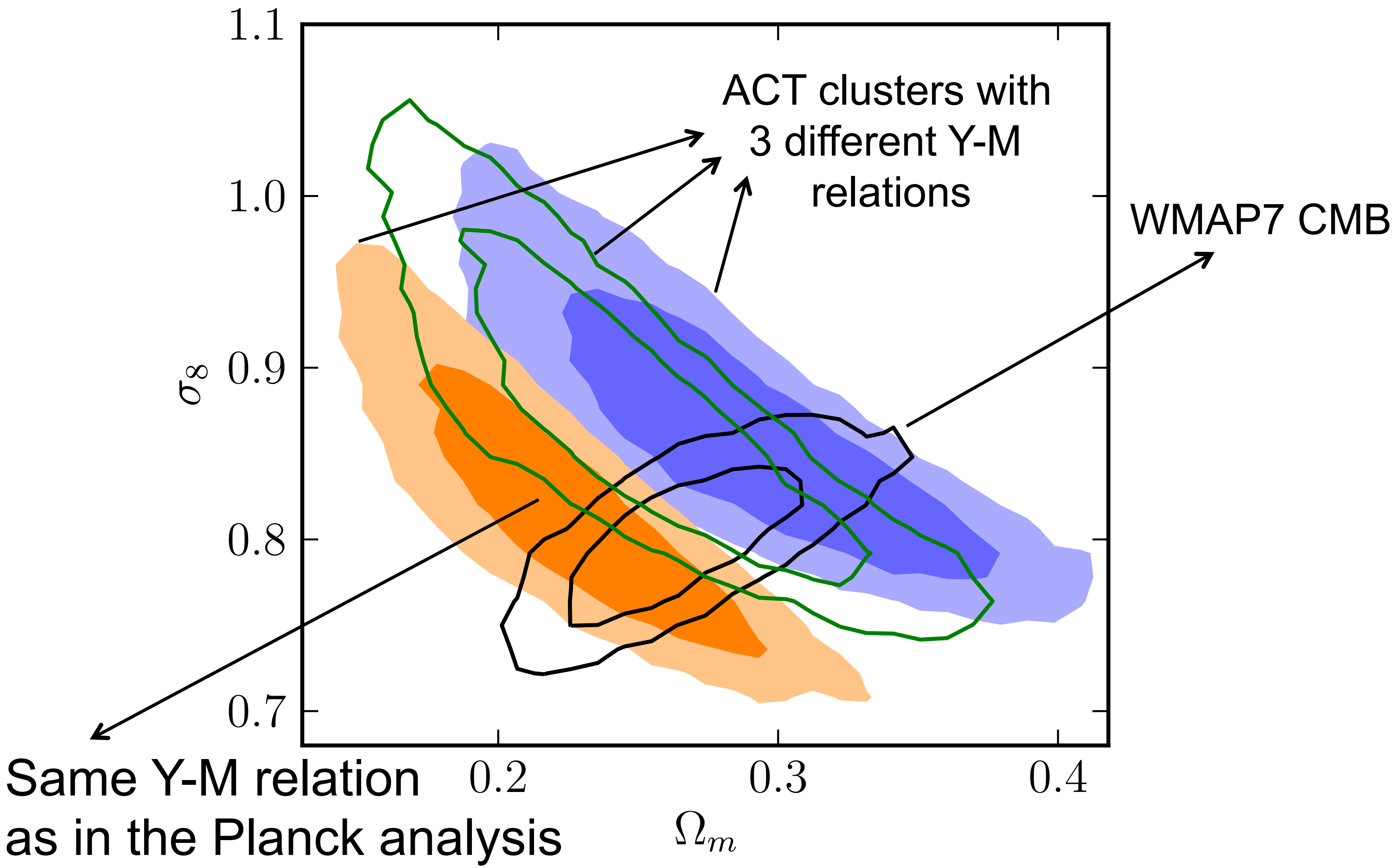
Planck Results XX 2013

Planck cluster cosmology 2013



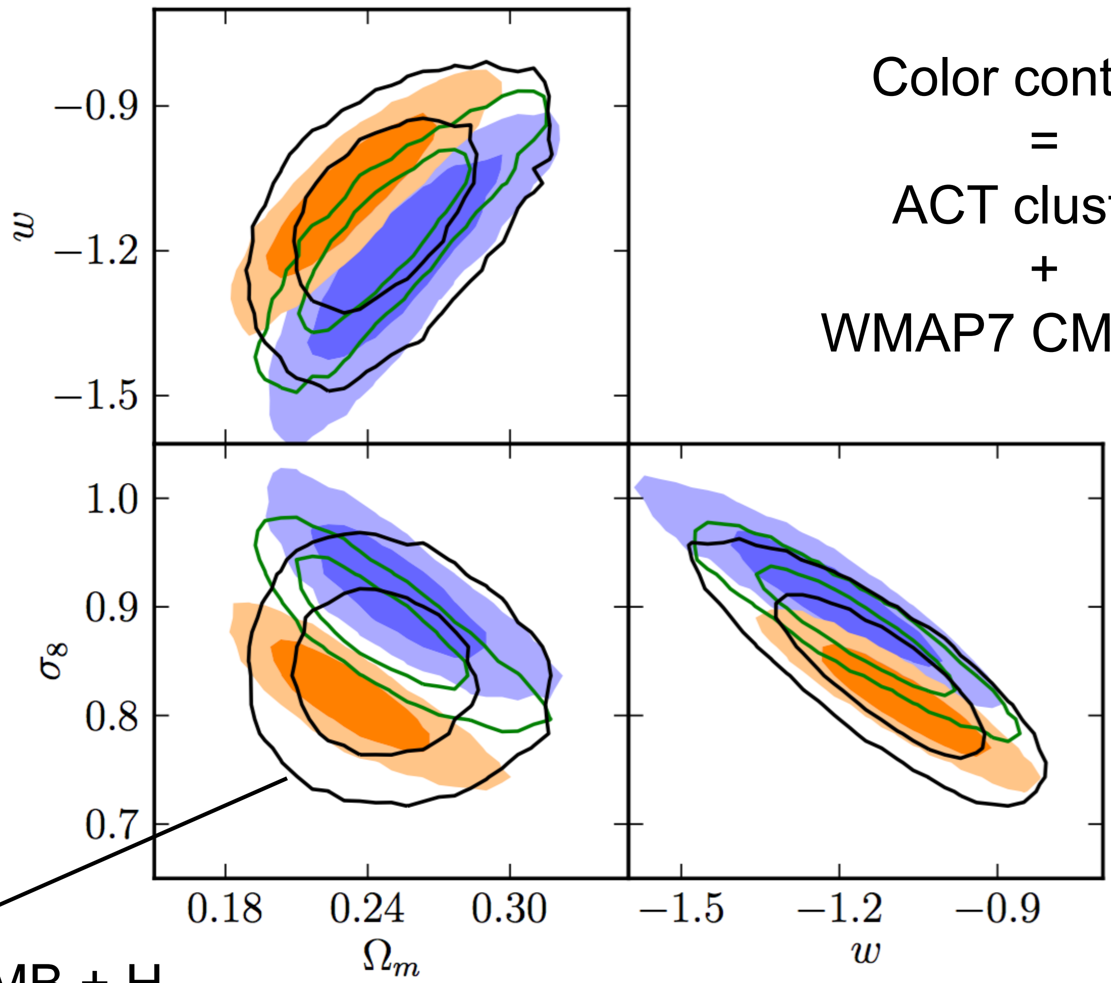
Planck Results XX 2013

ACT cluster cosmology 2013



Hasselfield et al. 2013

ACT cluster cosmology 2013

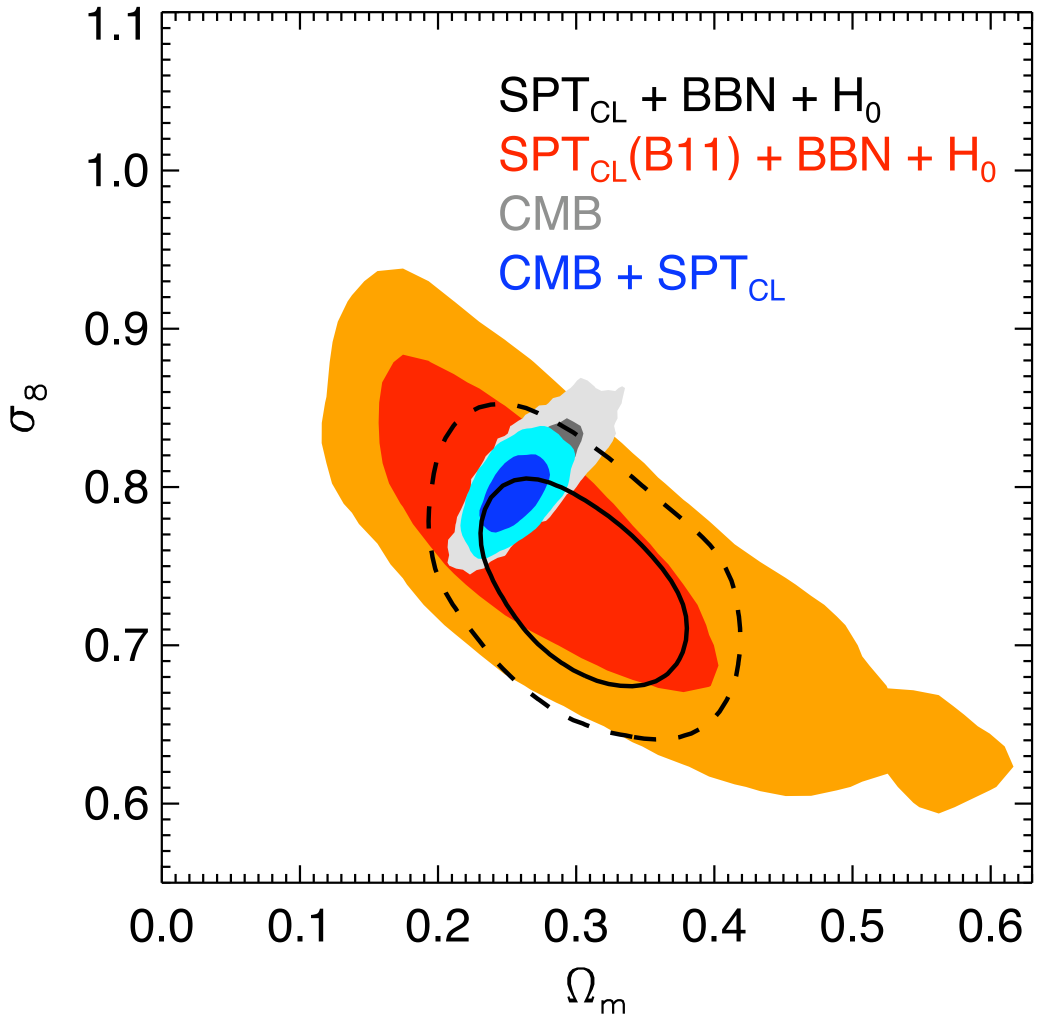


Color contours
=
ACT clusters
+
WMAP7 CMB + H_0

WMAP7 CMB + H_0

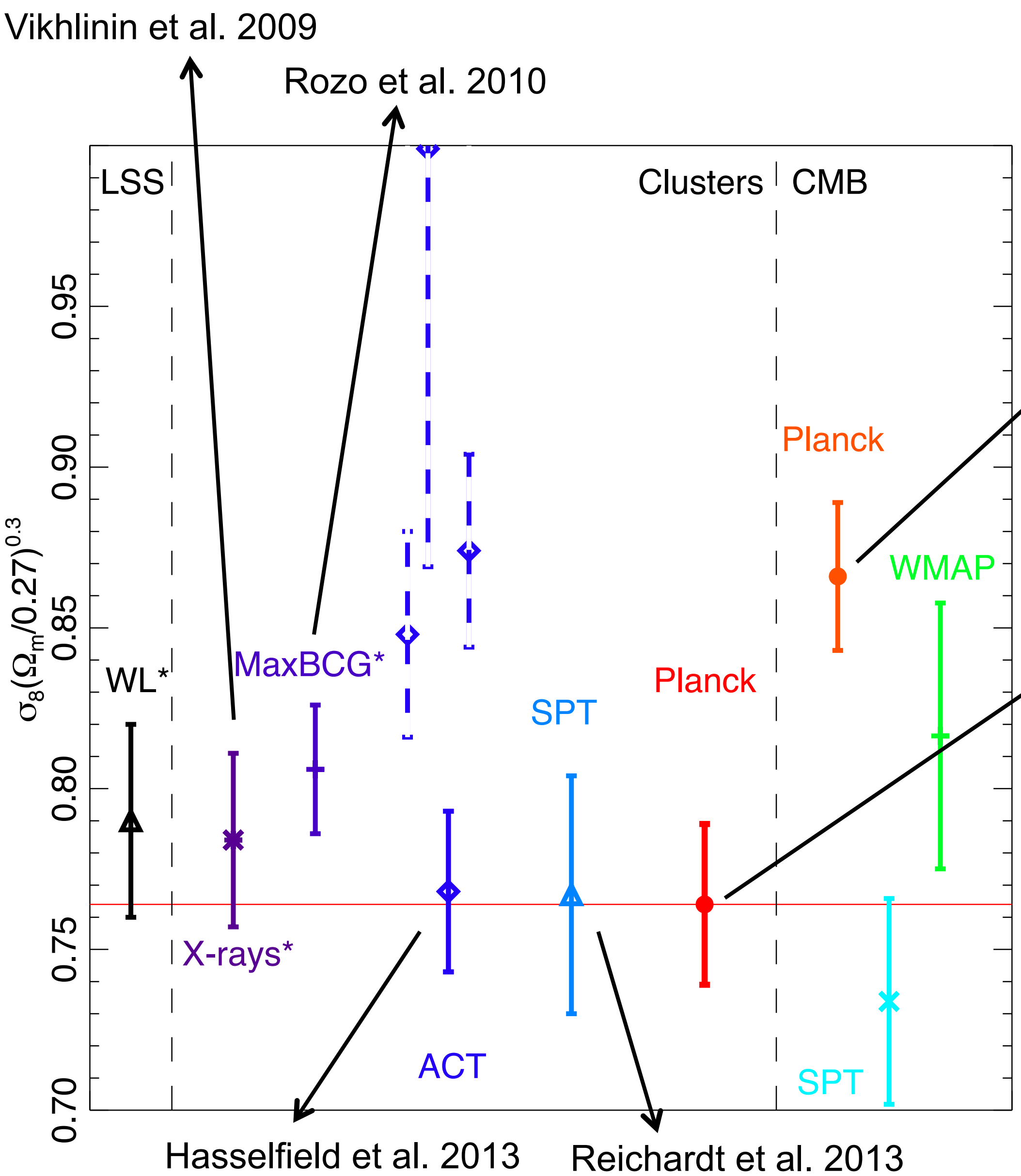
Hasselfield et al. 2013

SPT cluster cosmology 2013



Reichardt et al. 2013

Summary cluster cosmology 2013



Planck CMB predicts twice more clusters than detected

Planck Results XX 2013

Planck cluster cosmology 2015

- Use PSZ2 (q_{2015}>6) instead of PSZ1 (q_{2013}>7)

More than twice as many clusters as in 2013

- dN/dz ⇒ dN/dz/dq (similar to SPT 2013)

- Mass bias priors

based on recent lensing observations

Mass bias priors 2015

Von der linden et al. 2014

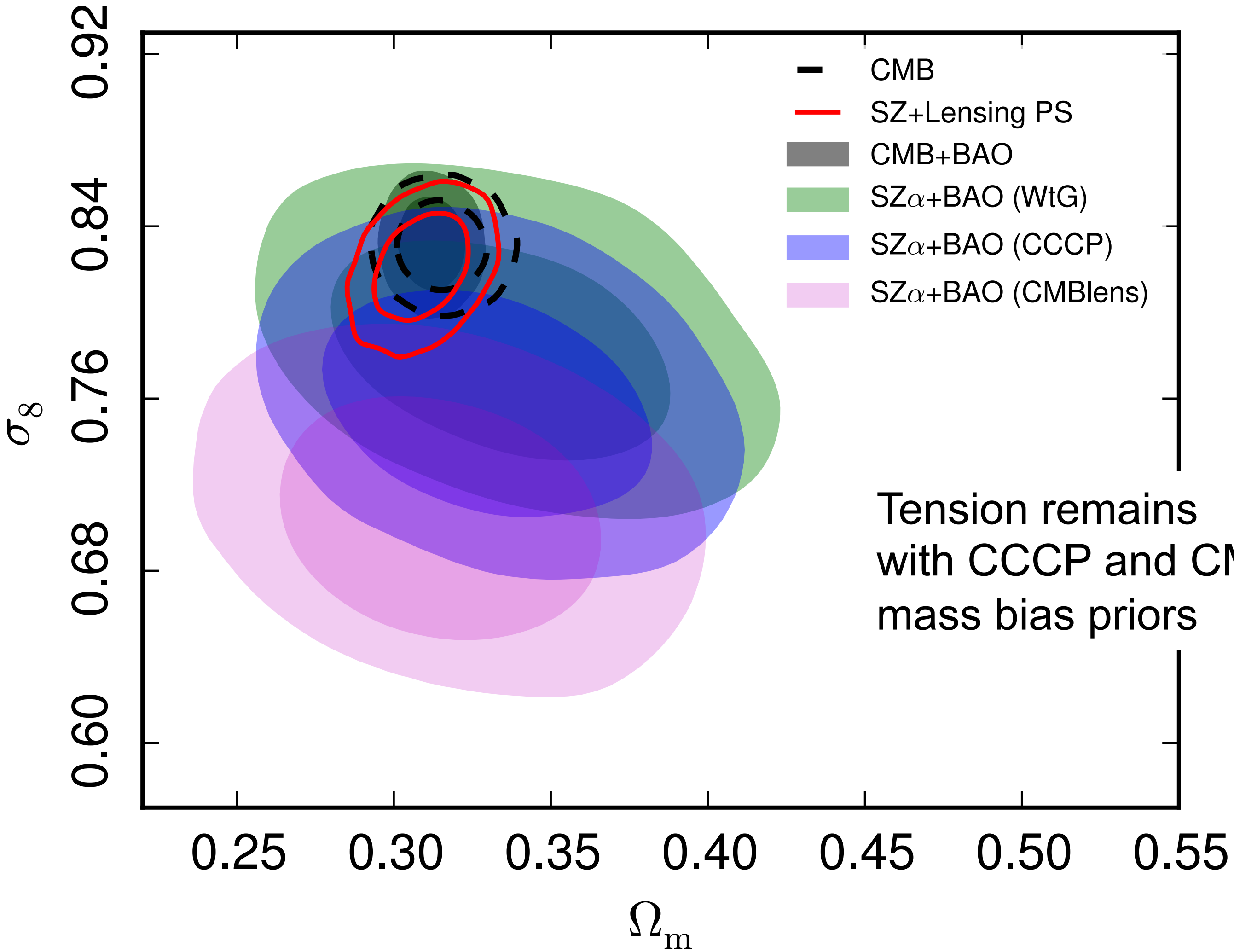
Hoekstra et al. 2015

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 !!!

Planck cluster cosmology 2015



Tension remains with CCCP and CMBlens mass bias priors

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

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

Planck cluster cosmology 2015

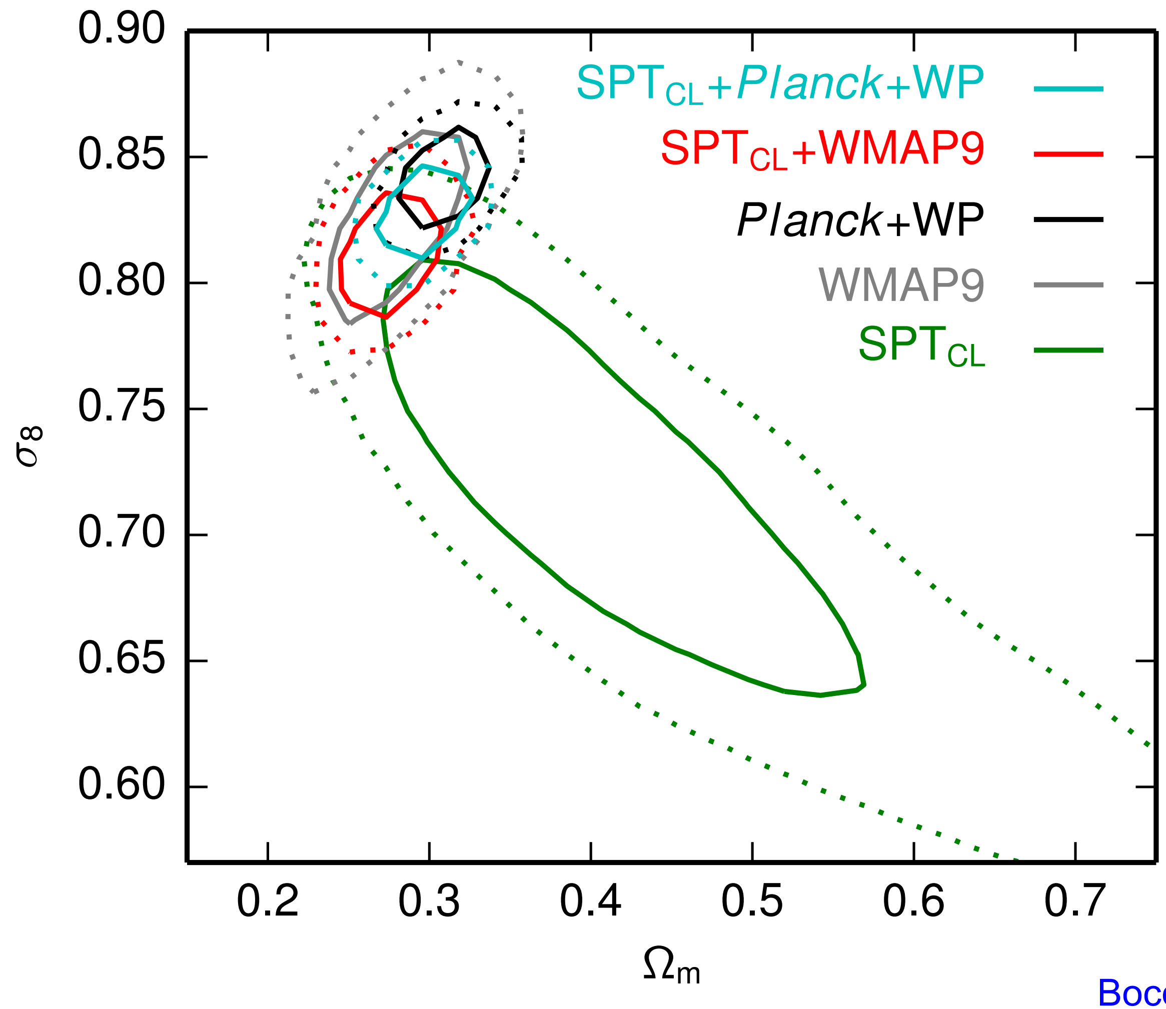
Tension can disappear
if primary CMB is used with clusters to constraint
the Y-M normalisation and cosmo parameters jointly

➔ $1\text{-}b = 0.58 \pm 0.04$

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.

SPT cluster cosmology 2015

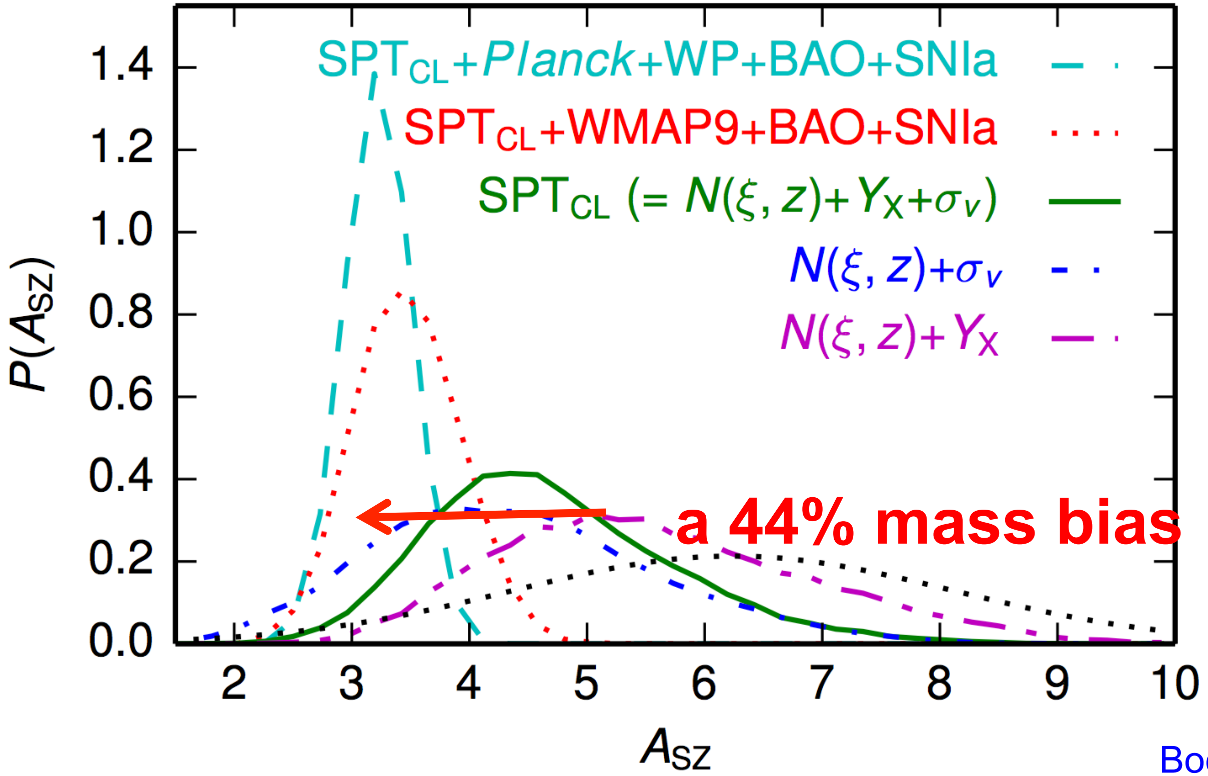


Bocquet et al. 2015

SPT cluster cosmology 2015

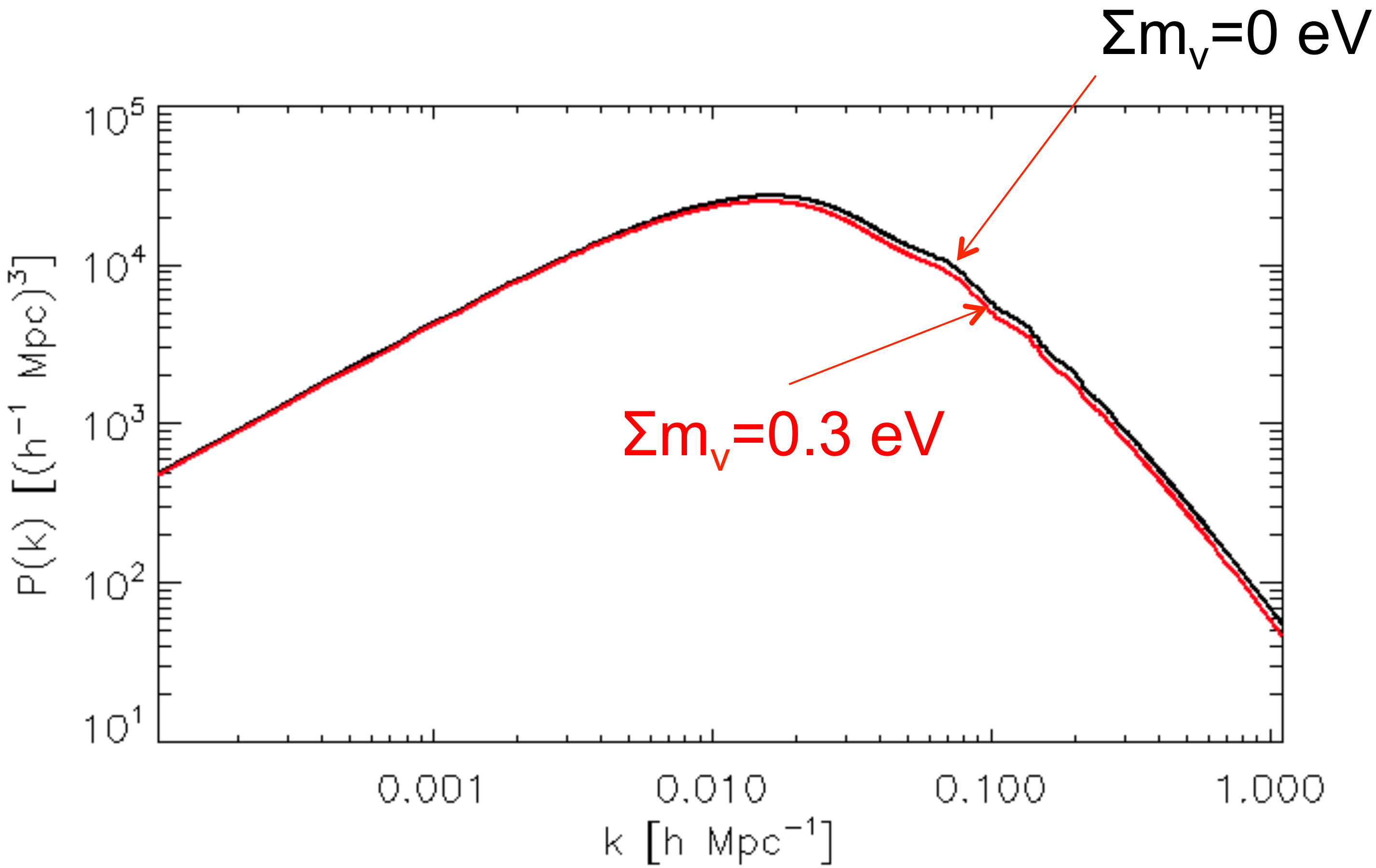
$$\zeta = A_{\rm SZ}\left(\frac{M_{500,c}}{3\times10^{14}M_\odot h^{-1}}\right)^{B_{\rm SZ}}\left(\frac{E(z)}{E(0.6)}\right)^{C_{\rm SZ}}$$

$B_{\rm SZ}$ ≈1.5



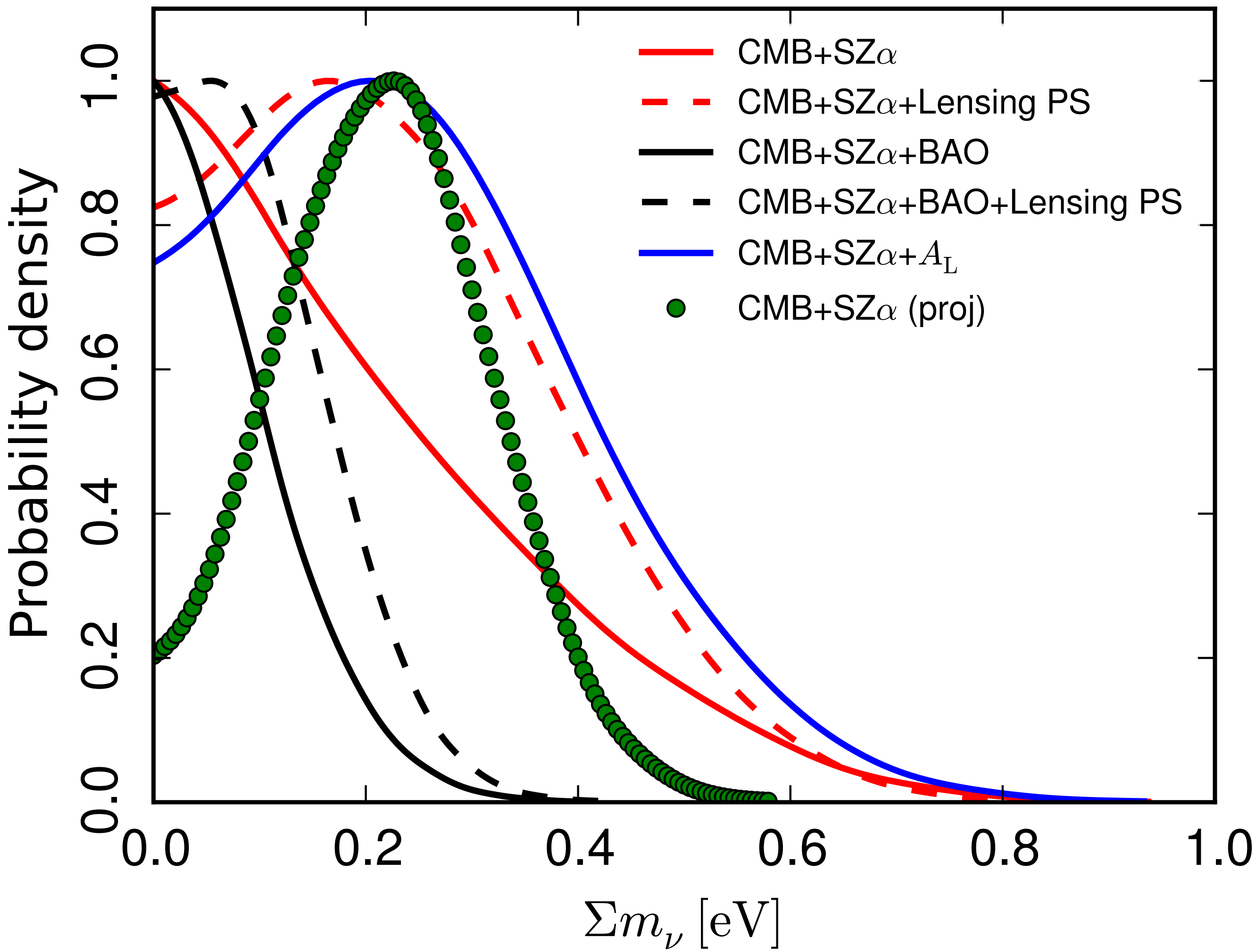
Bocquet et al. 2015

Neutrinos and the matter power spectrum

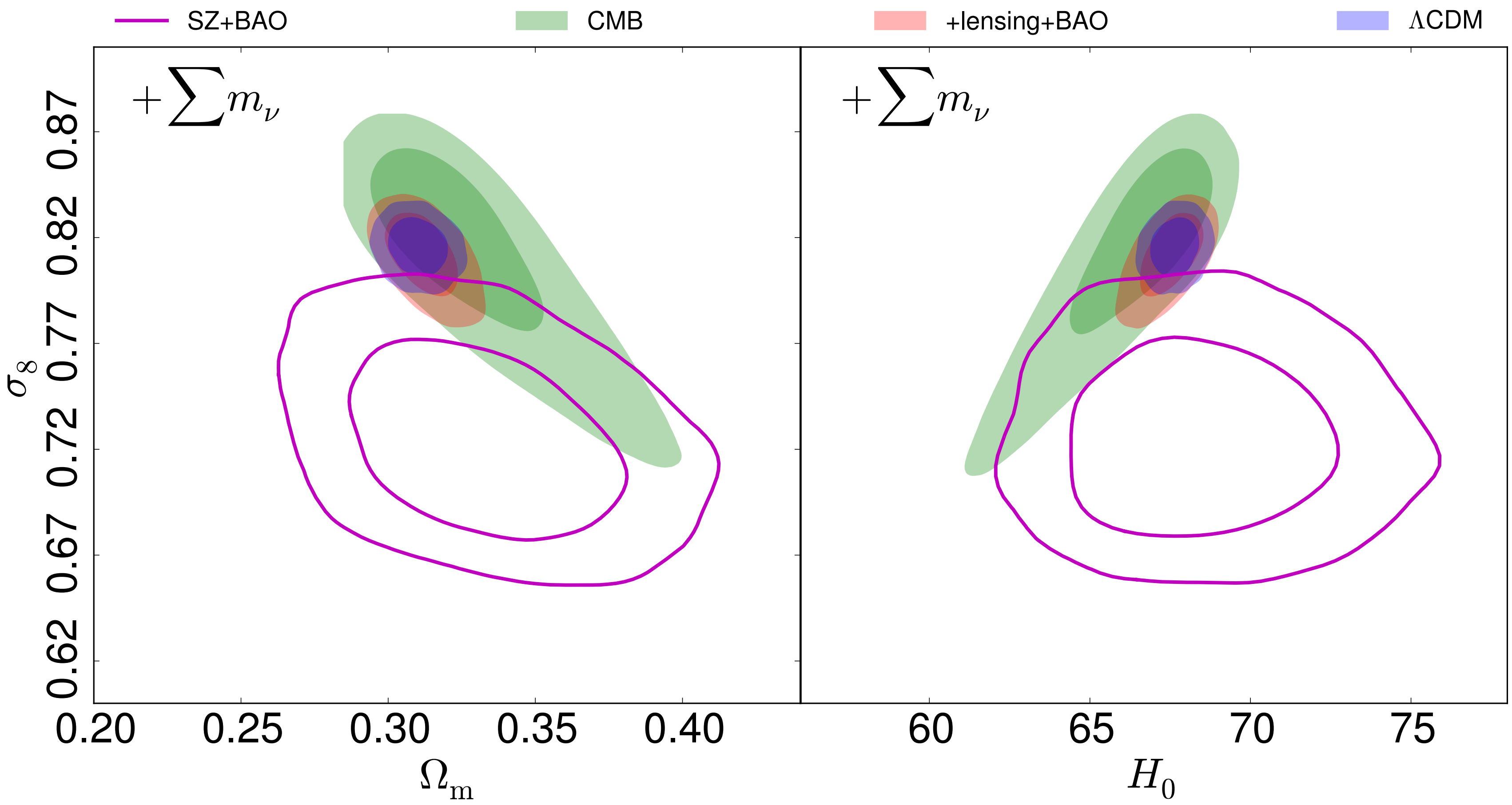


The primary CMB is sensitive to the global amplitude of the primordial spectrum A_s
σ_8 is a derived parameter

Planck CMB+SZ and the neutrino masses



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



How to reconcile Planck CMB and SZ counts ?

- Leave 1-b free

1-b=0.58 ± 0.04

“Revolution” in cluster physics ?! ⟶ 40% mass bias

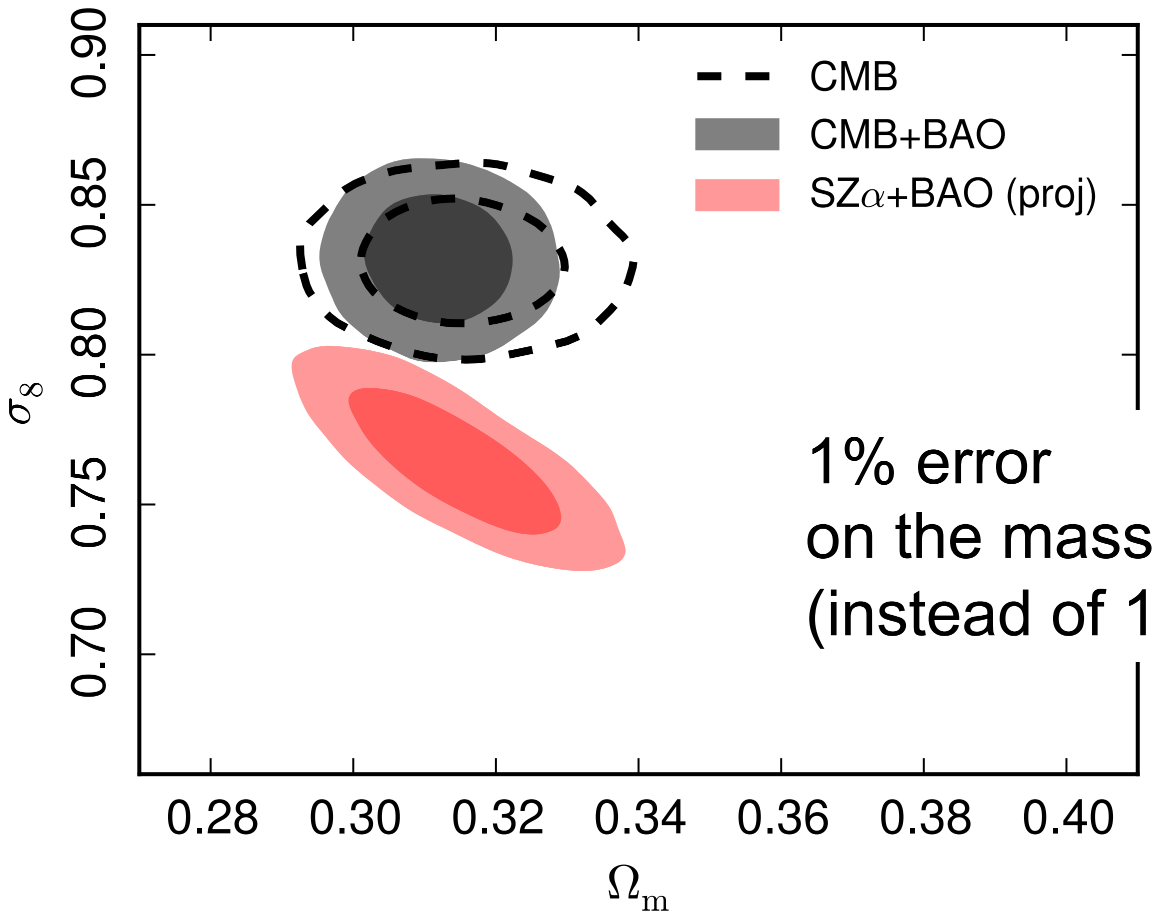
- Extend the minimal 6 parameter ΛCDM model

⟶ neutrino masses

Impact on fundamental physics !? ⟶ $\Sigma m_\nu > 0.06$ eV

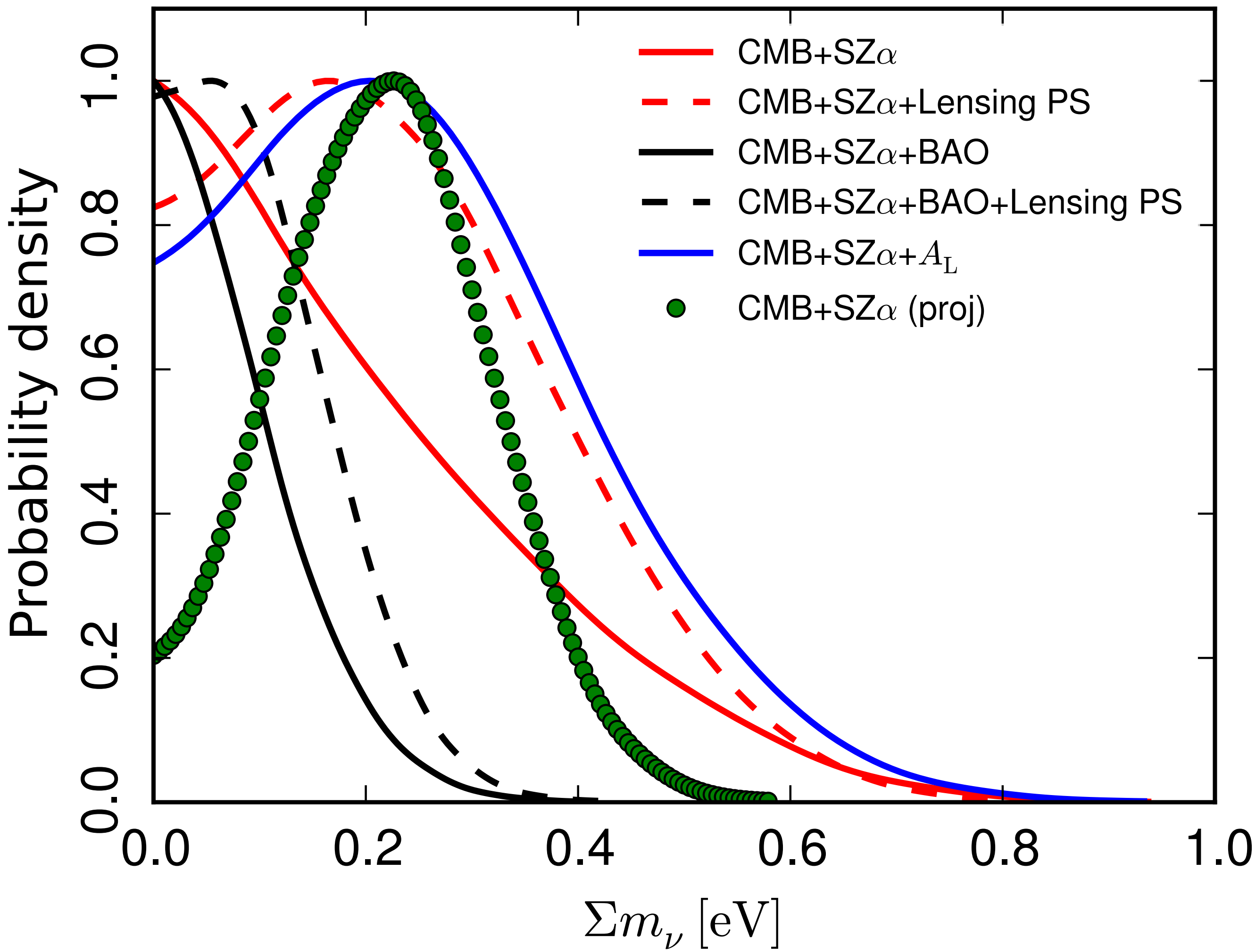
but tension with BAO !

Future ?
Planck SZ alone vs. primary CMB



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

Planck CMB+SZ and the neutrino masses



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.