From curiosity to agreement and back: Do clusters and CMB agree?

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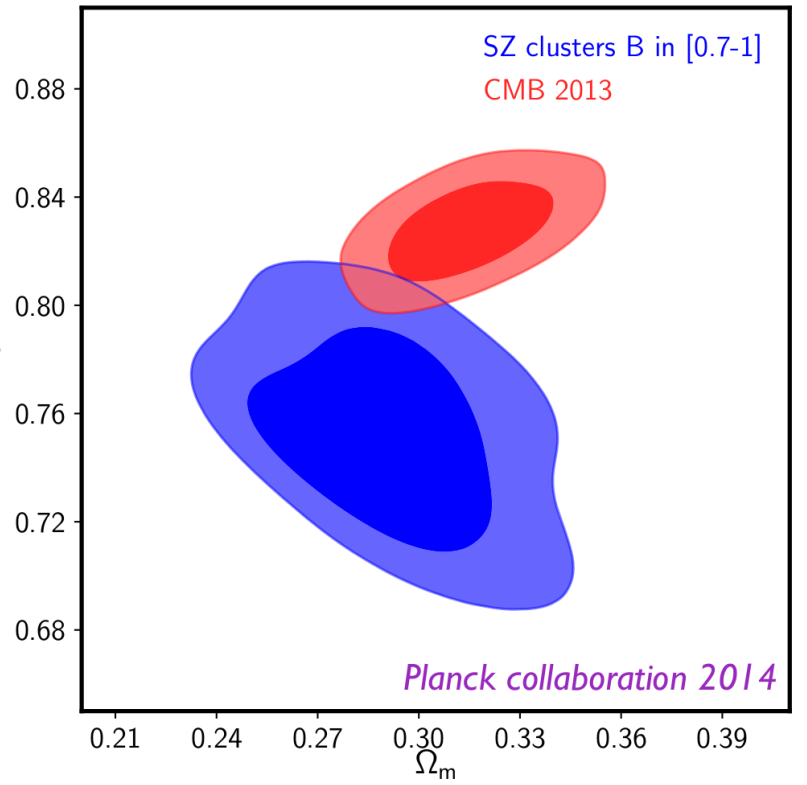
With **Laura Salvati** and Marian Douspis
and the Planck Collaboration

Starting point: March 2013

After the Early release in 2011: **Planck first cosmology results**

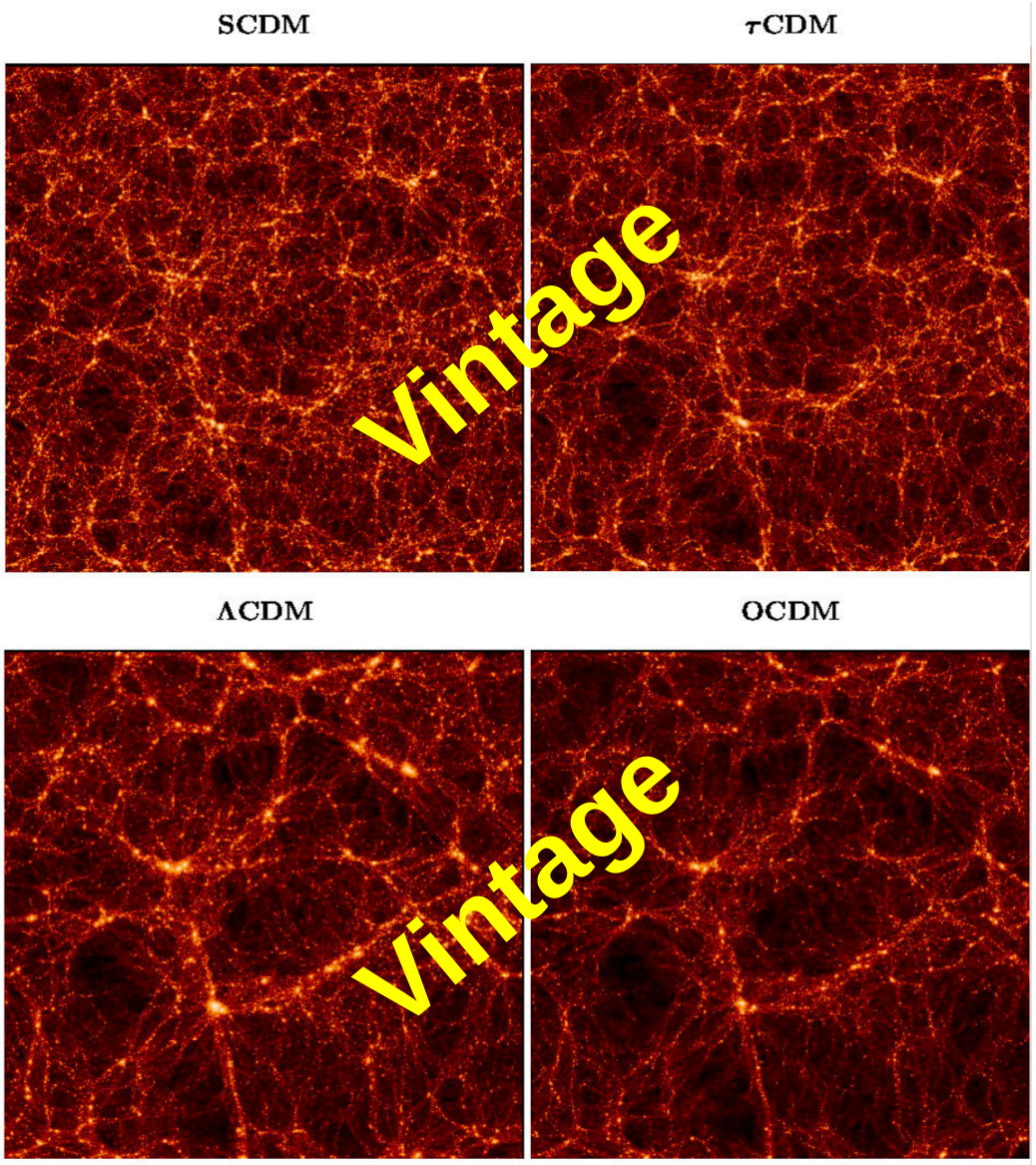
→ Cosmological parameters with Planck CMB and with SZ cluster counts show a 2.5σ tension on σ_8-Ω_m



Presentation content:

- How did we get there?
- What are the updates?
- Tension or curiosity: Yes, No, …. Maybe

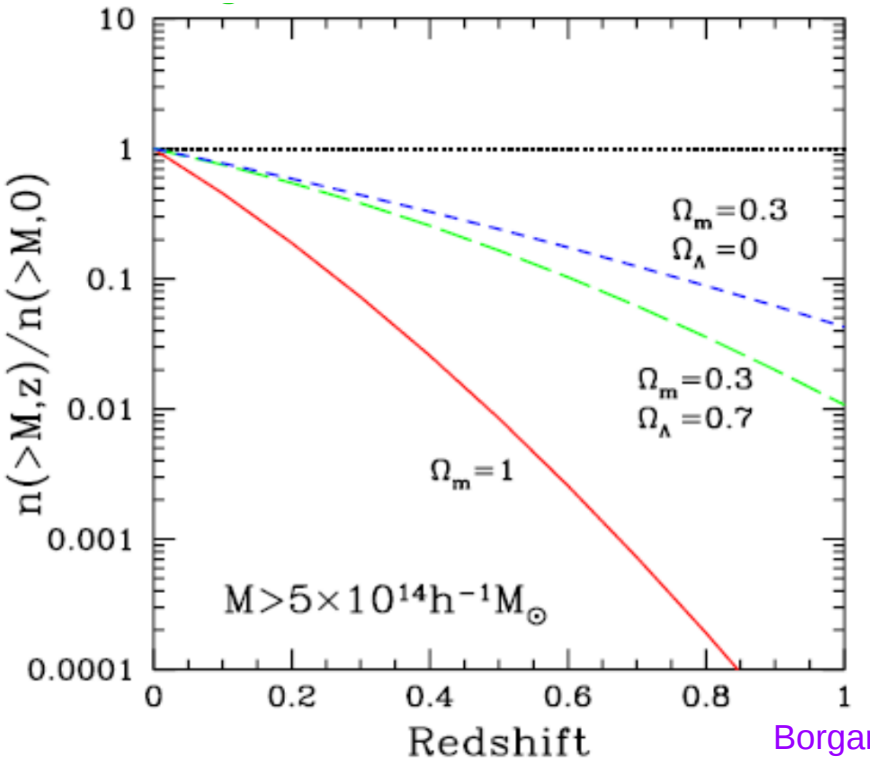
Cosmological parameters with cluster counts



Credits: Virgo consortium

Volume element & growth rate changed with cosmology → number of peaks vary

Evolution of Cluster counts → constrain cosmological parameters: σ_8, DM, DE, … Since ~1990



Borgani '06

Cosmological parameters with cluster counts

Compare the probability of observed cluster number counts with predictions from theory/model

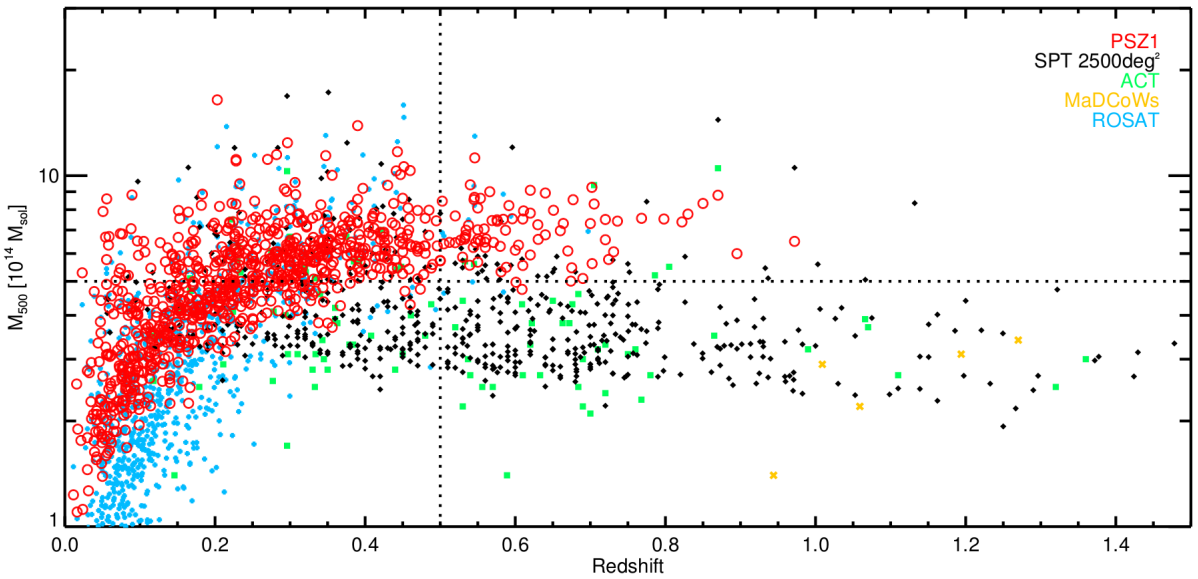
$$\frac{dN}{dz} = \int d\Omega \int dM_{500} \hat{\chi}(z, M_{500}, l, b) \frac{dN}{dz\, dM_{500}\, d\Omega}$$

Theoretical mass function: number of DM halos from simulations
Scaling relation: relating observable (SZ, X-ray, richness) to DM halo mass

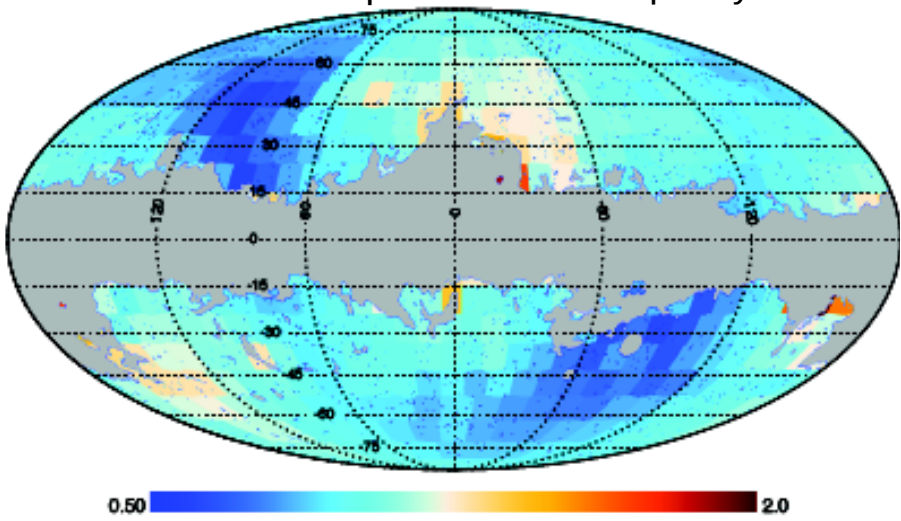
Cosmological sample: constructed from the obervations
Selection function: survey characteristics (noise, depth, …)

Selection of the cosmological sample

Planck collab. ‘15



Noise map in units of Compton y



Planck collab. ‘14

X-ray selection → redshift dimming & over-representation of cool-core clusters
SZ selection → no redshift dimming, quasi mass-selected
Planck & SPT/ACT: complementary → high mass intermediate z & higher-z lower mass

Inhomogeneous and scale-dependent noise
→ Completeness depends on cluster detection-filter size and position on the sky

Cosmological sample: Compromise between large number of clusters (with z) and high purity

Scaling relation

Derive cluster mass from global observed quantities
Use low scatter & unbiased mass proxies
→Complex physics but simplified assumptions for mass determination:

- Hydrostatic equilibrium
- No pressure from relativistic particles, no magnetic fields, etc
- No multi-temperature structure

Mass

$\propto M_{gas}$
$\propto T^{3/2}$
$\propto L_X^{3/4}$
From X-rays

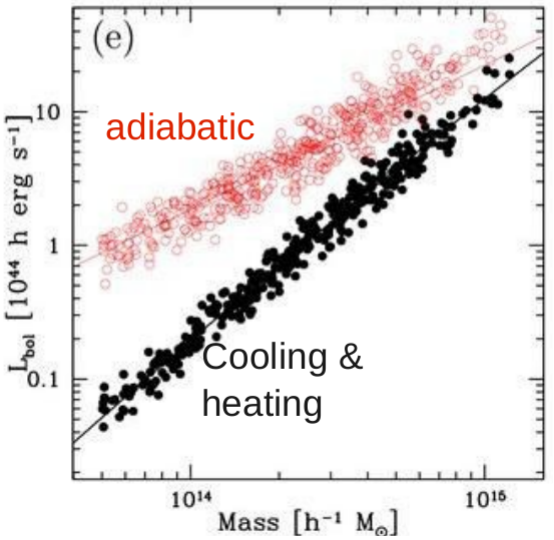
$\propto L_{optical}$
$\propto \sigma^2_{v,gal}$
From optical

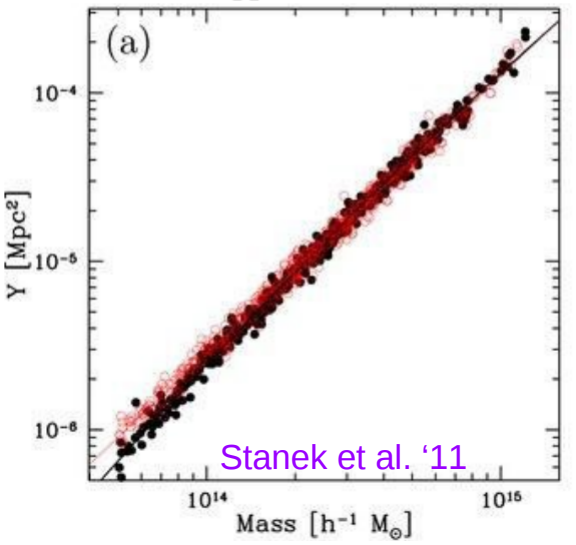
$\propto Y^{3/5}_{SZE}$
From SZ

$$E_X \propto \int_V n_e^2 \Lambda(T) dV \qquad F_\nu \propto \int_\Omega (P = n_e T) d\Omega$$

- **X-rays:** Strong dependence on non-gravitational physics
→High scatter L_X-M relation & bias, M_X is a better proxy

- **SZ:** Weaker dependence
→Low scatter Y_{SZ}-M relation
~unbiased selection

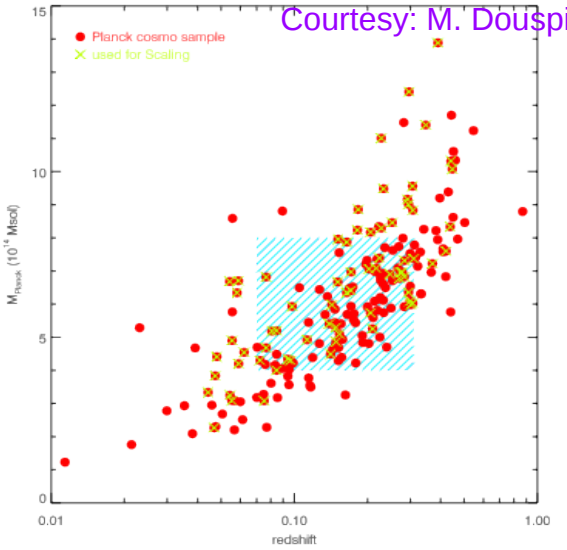




Scaling relation

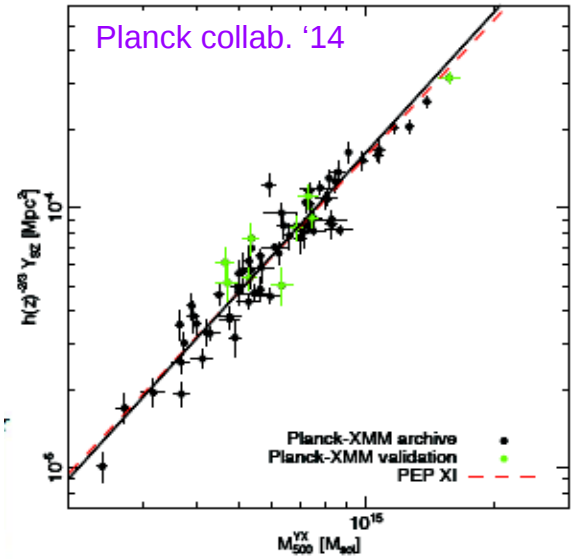
Subsample for scaling

Courtesy: M. Douspis



SZ – X scaling relation

Planck collab. ‘14



Scaling with 71 clusters from cosmo sample with XMM-Newton data **rescaled with simulations**

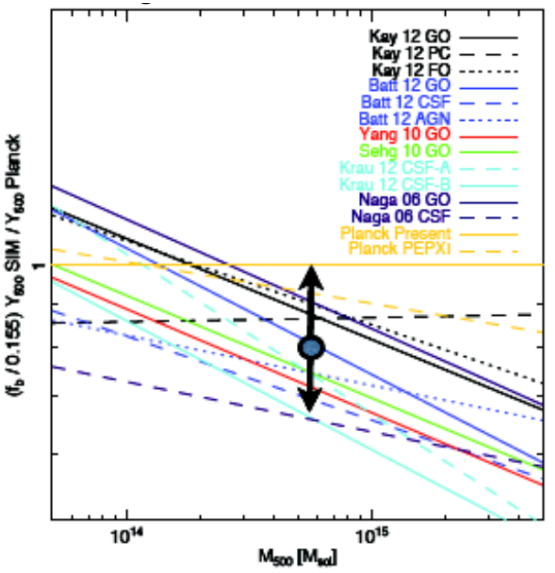
Y_{sz} measured in Planck & Y_X measured from X-ray data

$[Y_X \rightarrow M_X$ and $Y_X \rightarrow Y_{SZ}] \rightarrow$ **Y_{sz} - M_x**

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

$(1-b) = 0.8\ in\ [0.7-1.0]$ Mass bias: ratio hydro to true mass from sims

Planck collab. ‘14



Scaling relation

Weak lensing and Y_X-based mass estimates comparison, Y_X from X-ray Chandra data (Vikhlinin et al. '09)

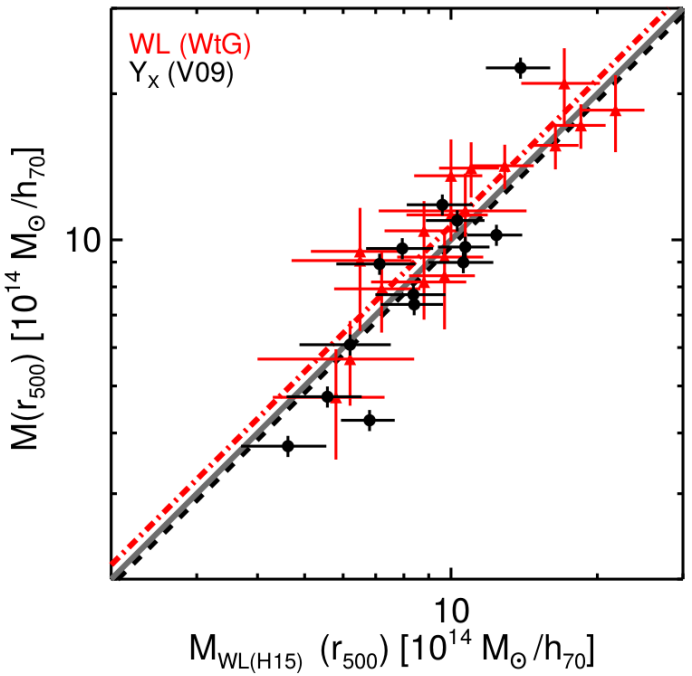
[$Y_X \rightarrow M_X$ and $Y_X \rightarrow Y_{SZ}$] → **$Y_{SZ} - M_X$**

Rescaled to WL

$$Y_{SZ} \propto M^{YX} = (1-b) M_{WL}$$ Mass bias: ratio hydro to true mass

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

de Haan et al. '16



Lensing-based scaling relation

- WtG → (1-b)~0.68 (von der Linden et al. '14)
- PSZ2LenS → (1-b)~0.76 (Sereno et al. '17)
- CCCP → (1-b)~0.78 (Hoekstra et al. '15)
- CMB lensing → (1-b)~1 (Planck collab. '16), (1-b)~0.7 (Zubeldia & Challinor '19)

& many others

Sample	N_{Cl}	z	σ_z	M_{500}	$\sigma_{M_{500}}$	b_{SZ}
PSZ2LenS	32	0.20	0.15	4.8	3.4	-0.27 ± 0.11
PSZ2LenS Cosmo	15	0.13	0.09	6.4	4.1	-0.40 ± 0.14
LC^2-single	135	0.24	0.14	7.8	4.8	-0.25 ± 0.04
CCCP	35	0.23	0.07	8.5	3.8	-0.22 ± 0.07
CLASH	13	0.37	0.13	11.3	3.3	-0.39 ± 0.08
LoCuSS	38	0.23	0.04	7.5	2.8	-0.18 ± 0.05
WtG	37	0.36	0.13	11.5	5.2	-0.43 ± 0.06

Sereno et al. '17

Planck 2013 Curiosity: Clusters vs CMB

189 clusters (@S/N≥7) using scaling to X-rays

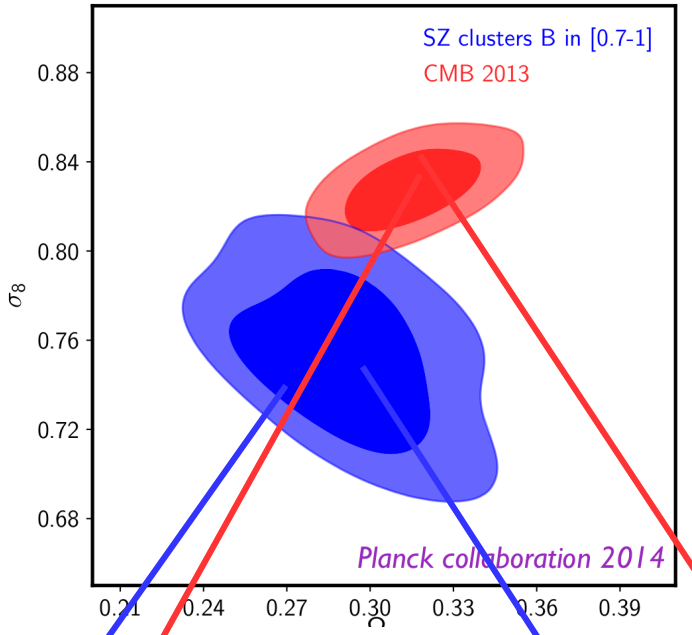
n_s, Ω_b, Y*, α, S marginalised over

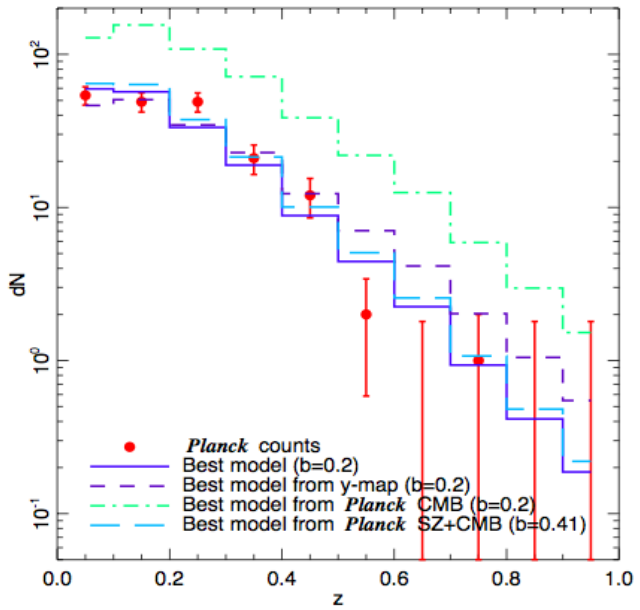
(1-*b*) in [0.7-1] with mean 0.8

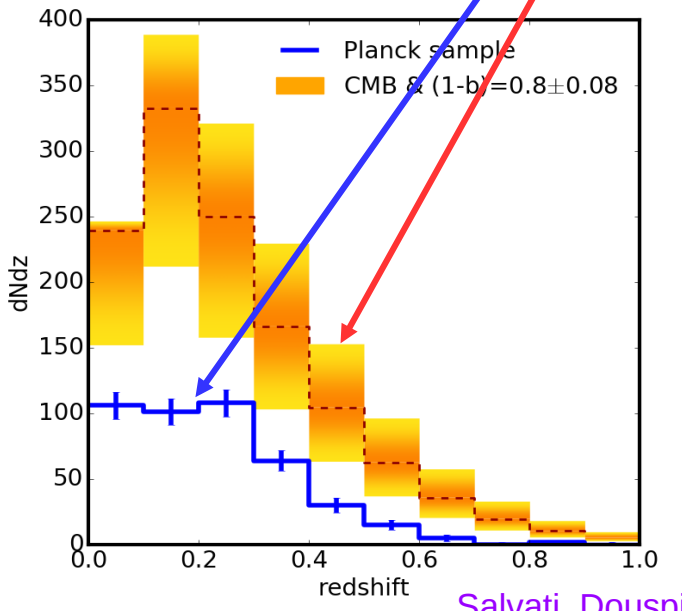
→ Higher values of Ω_m,σ_8 from CMB

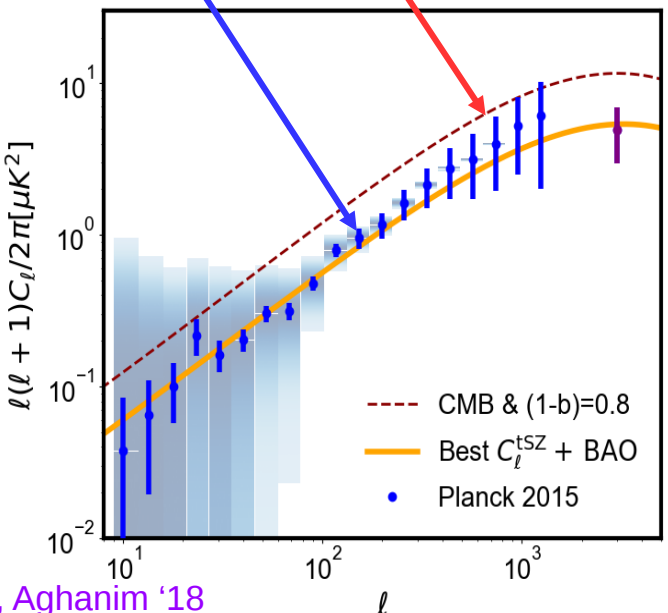
~2.5σ tension between CMB and SZ counts

Half the massive clusters are not in the cosmological sample





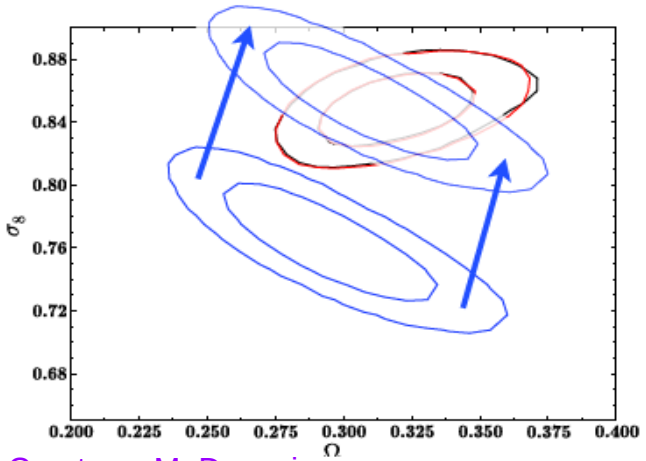




Salvati, Douspis, Aghanim '18

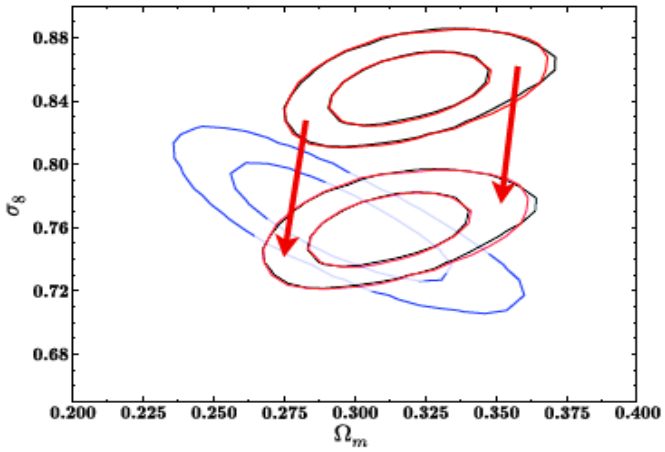
How to reconcile clusters & CMB?

Increase σ_8 from clusters



Courtesy: M. Douspis

Decrease σ_8 from CMB



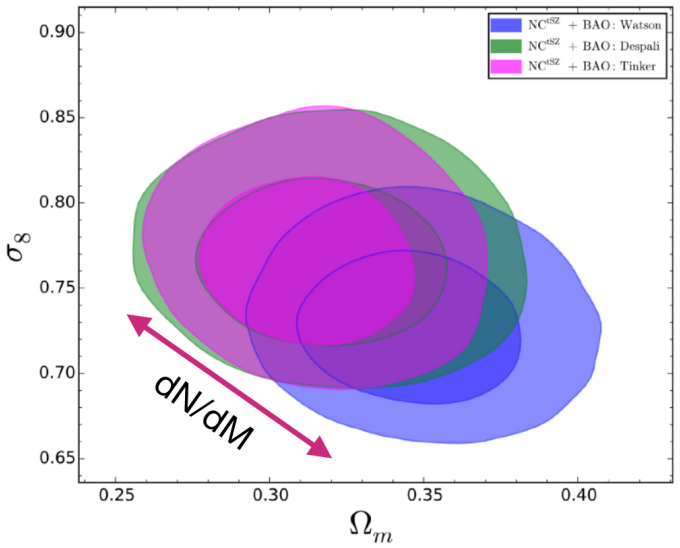
Possible solutions are to change e.g.:

- Number of clusters (missing half massive low z clusters): increase cosmological sample
- Theoretical model: change mass function? Change scaling relation?
- Initial spectrum
- Change transfer function: include massive neutrinos

Planck 2015: Exploring the ingredients

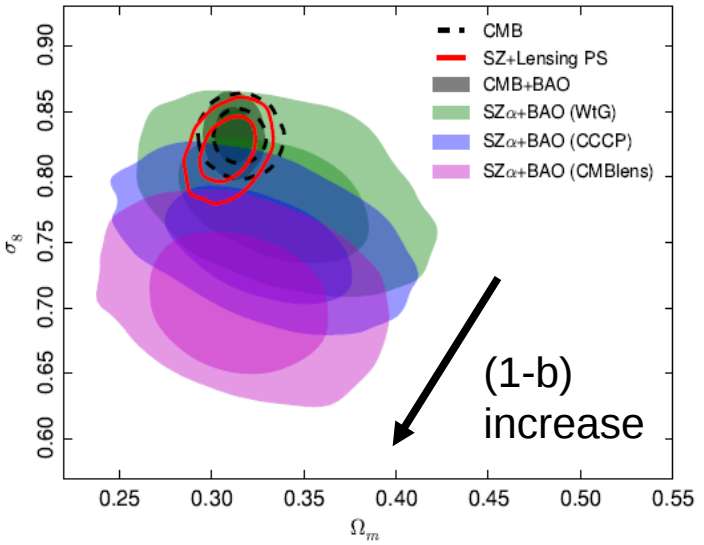
Mass function

Ritz, Salvati, Douspis



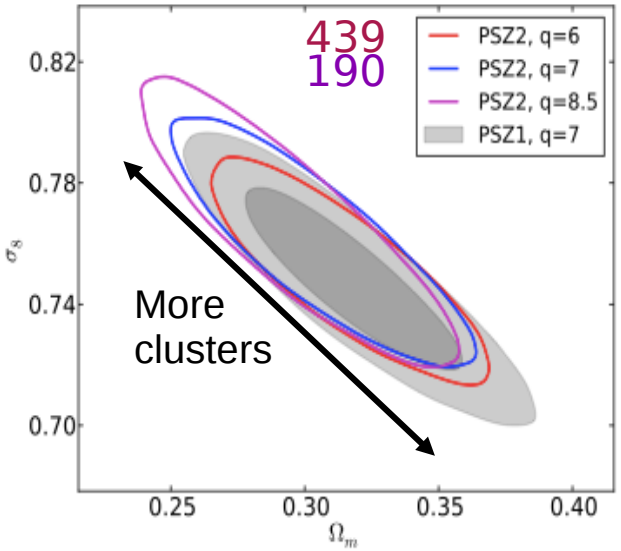
Mass bias parameter

Planck collab. ‘16



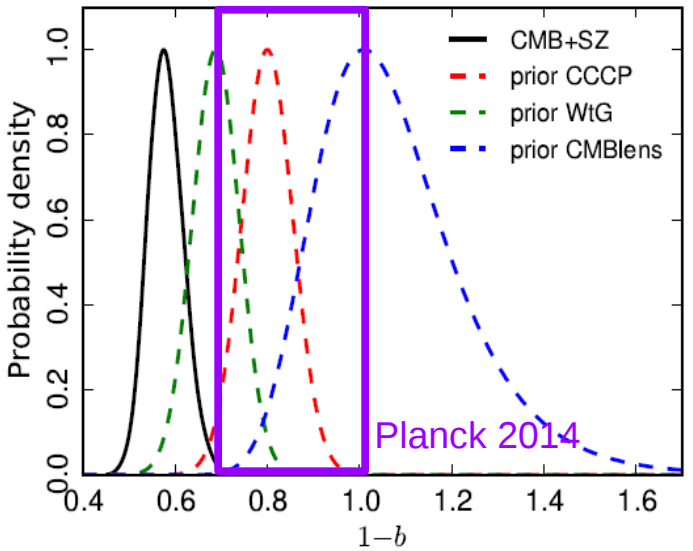
Cosmological sample

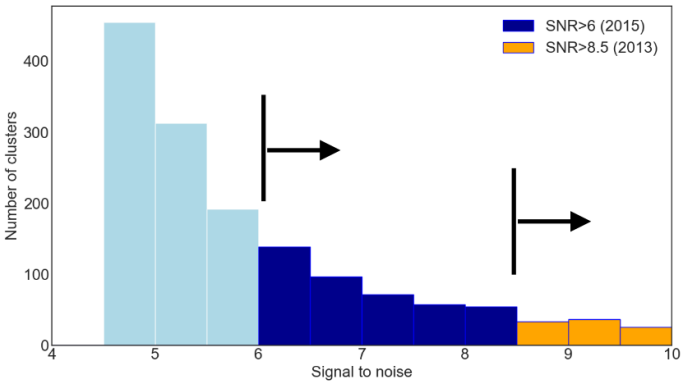
Planck collab. ‘16



Same “tension”

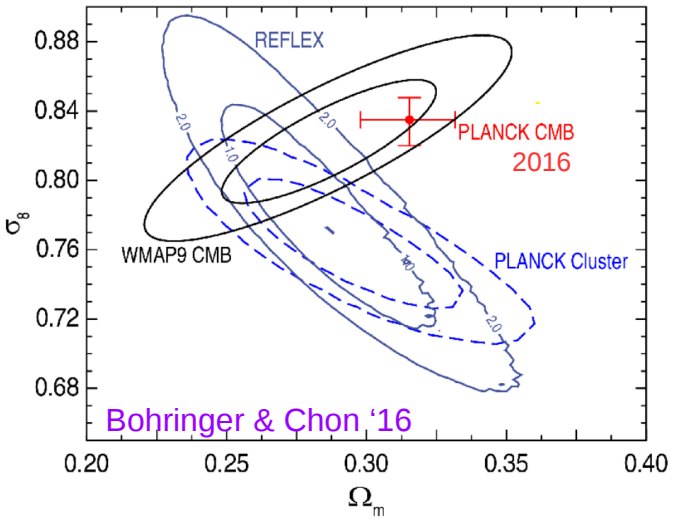
Reduced only if mass bias is low: close to the CMB preferred value



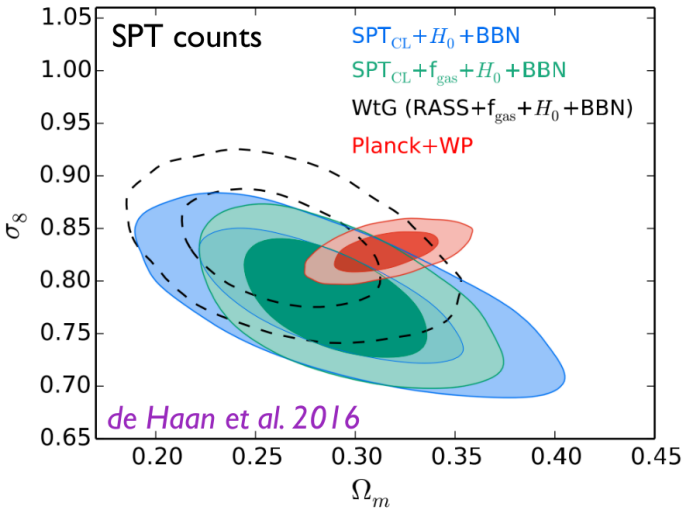


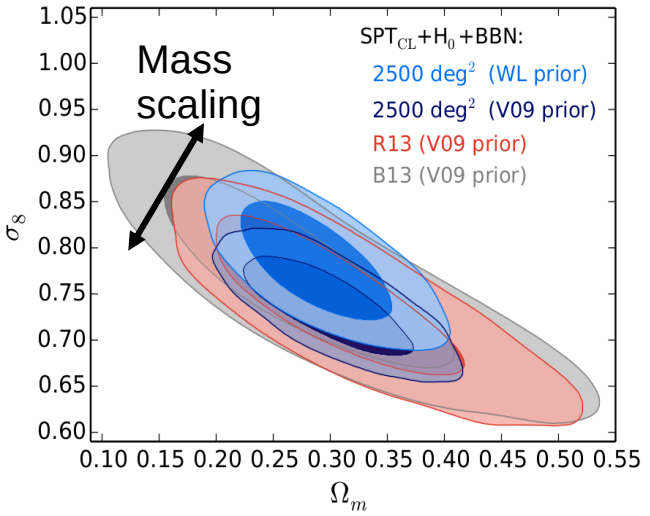
What about other cluster samples?

X-rays



SZ from SPT





σ_8-Ω_m from X-ray luminosity function of REFLEX-II
Very different sample & selection function
→ Agreement with Planck SZ cluster results (Planck Collab. '16)

σ_8-Ω_m from 377 SPT clusters
Lensing-priors from WtG on the scaling relation

σ_8-Ω_m from SPT analyses:

- 18 clusters (14 with Chandra), Benson et al. '13
- 100 clusters, Reichard et al. '13
- 377 candidates (82 with Chandra) & lensing-prior on X-ray scaling, de Haan et al. '16

→ σ_8-Ω_m central value changed by 10%

Updates & changes

Planck CMB 2013
- polarisation from WMAP

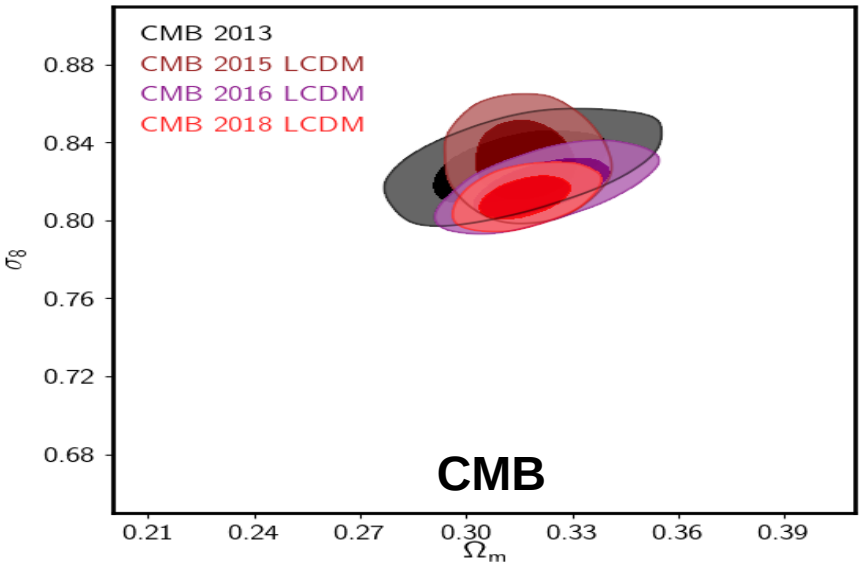
Planck CMB 2015
- Polarisation from LFI

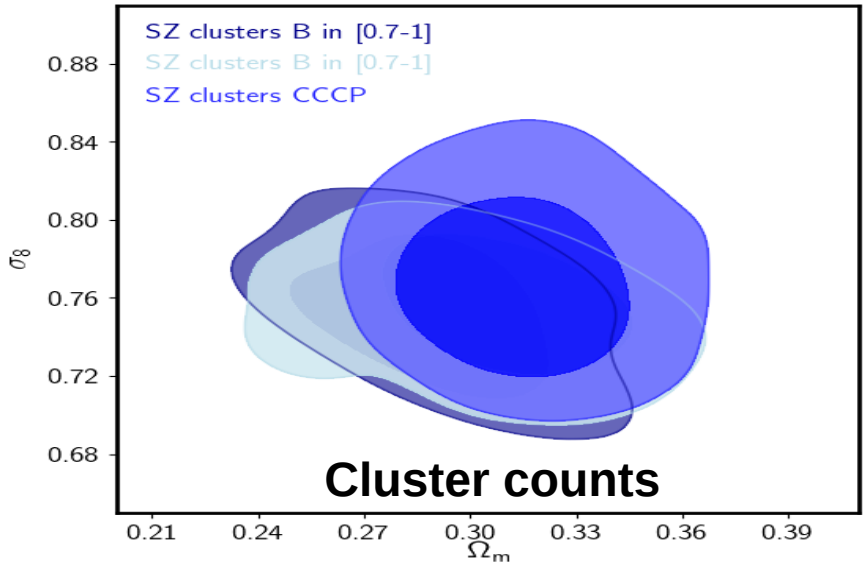
Planck CMB 2016 & 2018
- Polarisation from HFI (inc. low l)

→ better estimate of τ: **low reionisation optical depth** from τ = 0.89 to **τ ~ 0.05**

Planck SZ Clusters 2013
- 189 clusters
- slope Y-M from 71 clusters & amplitude from <12 sims>
- Mass bias (1-b) in [0.7-1], mean 0.8

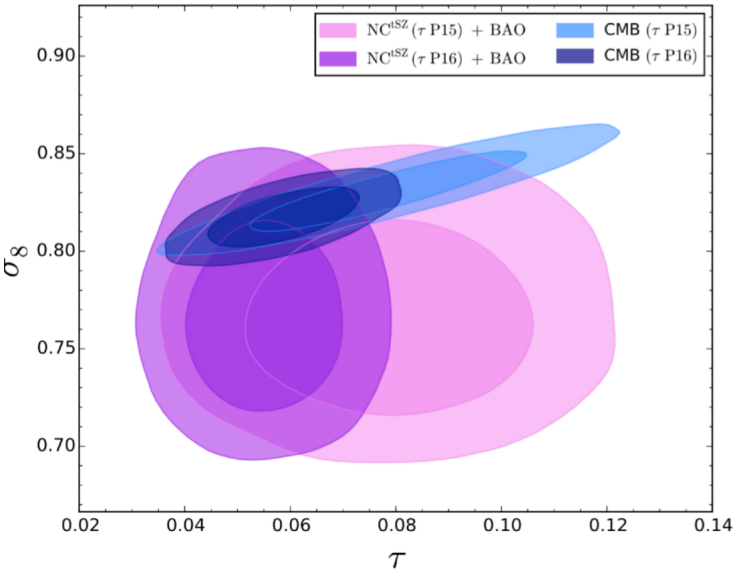
Planck SZ Clusters 2015
- 439 clusters, dN(z,S/N)
- slope Y-M from 71 clusters & amplitude from lensing estimates
- Mass bias CCCP (1-b)~ 0.78±0.1





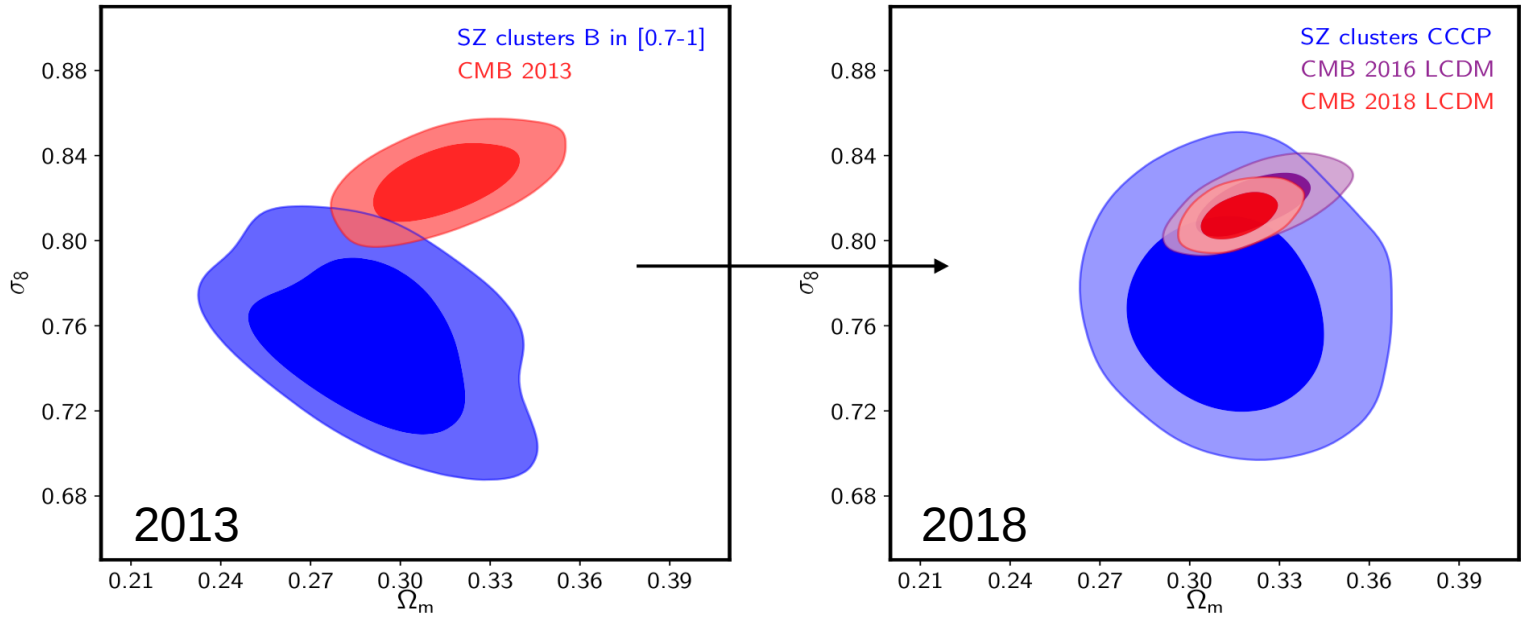
Revisited analysis: from curiosity to agreement?

Same SZ counts as Planck ‘16
Same prior on mass bias [CCCP lensing (1-b)=0.78]
Sampling cosmology & scaling-relation parameters
→ SZ constraints unchanged
From WMAP prior on τ to Planck-HFI low-l polarisation
→ reduced σ_8



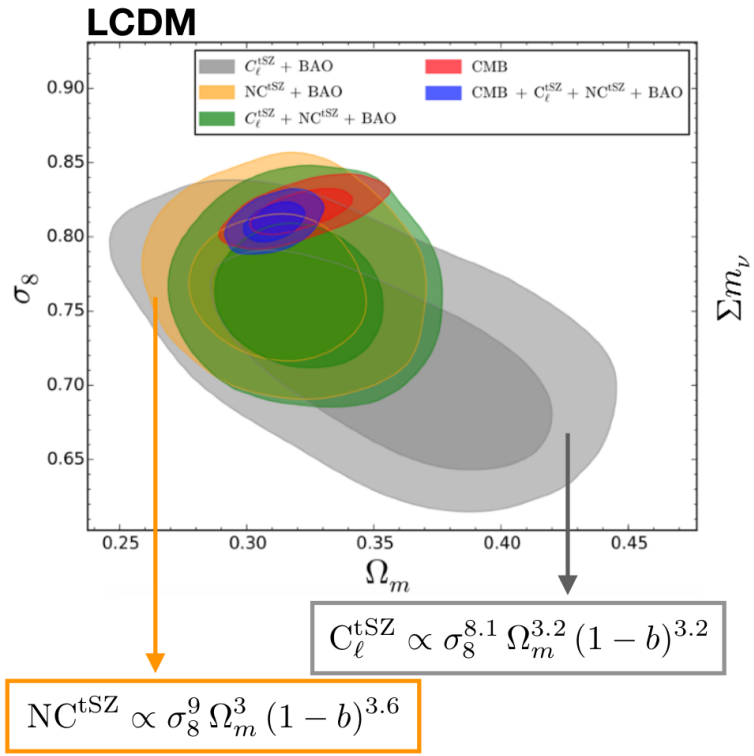
Planck CMB & SZ-count tension on σ_8-Ω_m reduced from ~2.5 σ to <1.5 σ

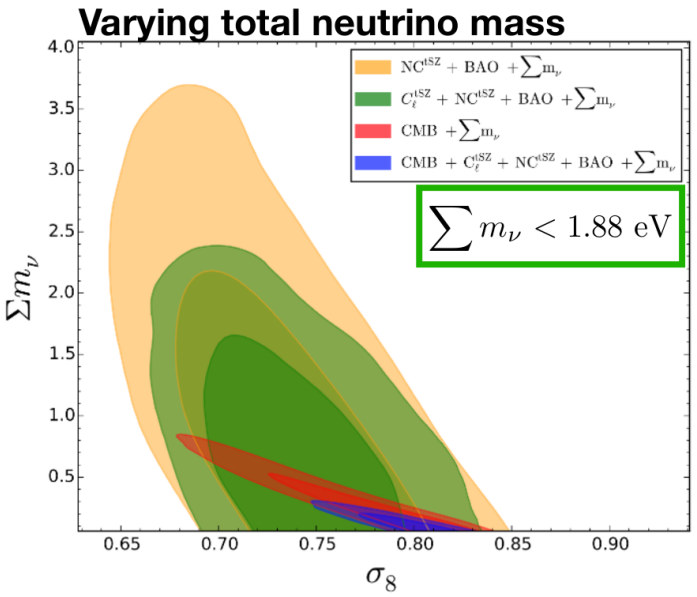
Salvati, Douspis, Aghanim ‘18

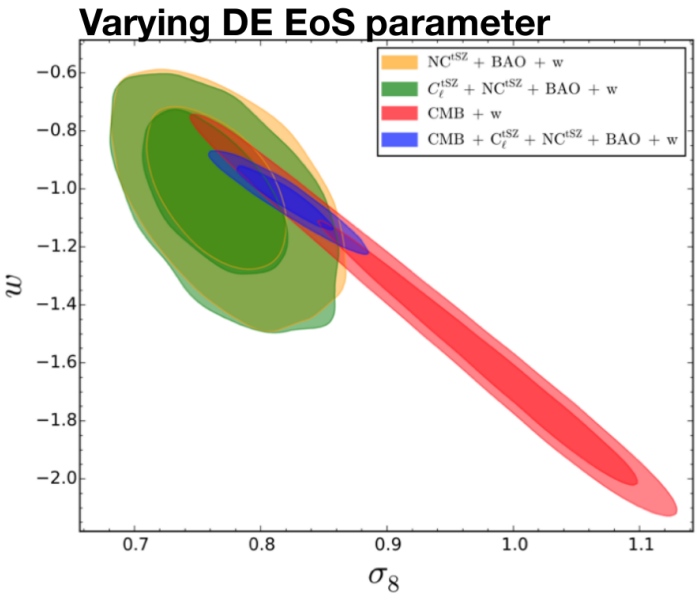


Revisited analysis: from curiosity to agreement?

Salvati, Douspis, Aghanim ‘18







Extensions to LCDM (especially neutrinos) reduce slightly more the difference between CMB and cluster counts on σ_8-Ω_m to below ~**1.2σ**

No more tension but ...

Revisited analysis: from agreement back to curiosity?

Degeneracy between mass bias and σ_8

→ CMB & SZ are reconciled if (1-b) is low (~0.6) and σ_8 is high

$\sigma_8 (\Omega_m/0.3)^{1/3} \sim 0.78 \pm 0.03$ SZ (Clusters+CI)+BAO

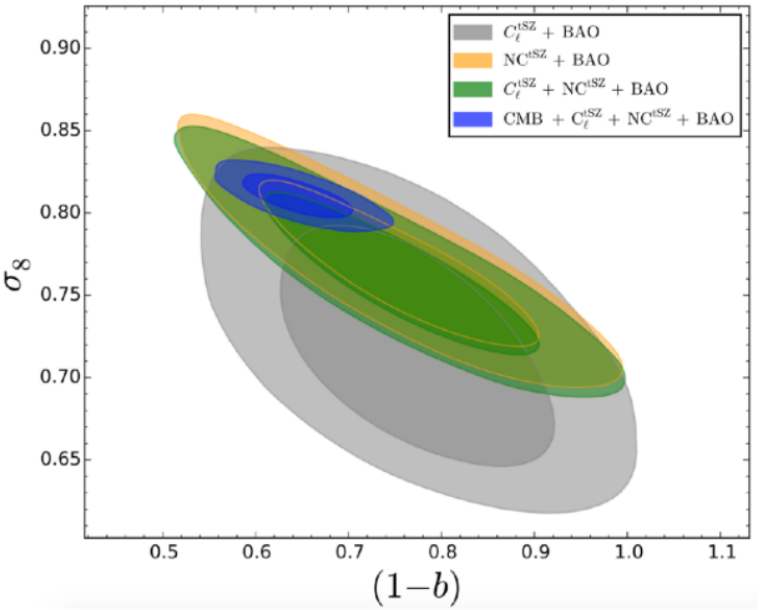
$\sigma_8 (\Omega_m/0.3)^{1/3} \sim 0.84 \pm 0.02$ CMB+tSZ

CMB prefers low mass bias values

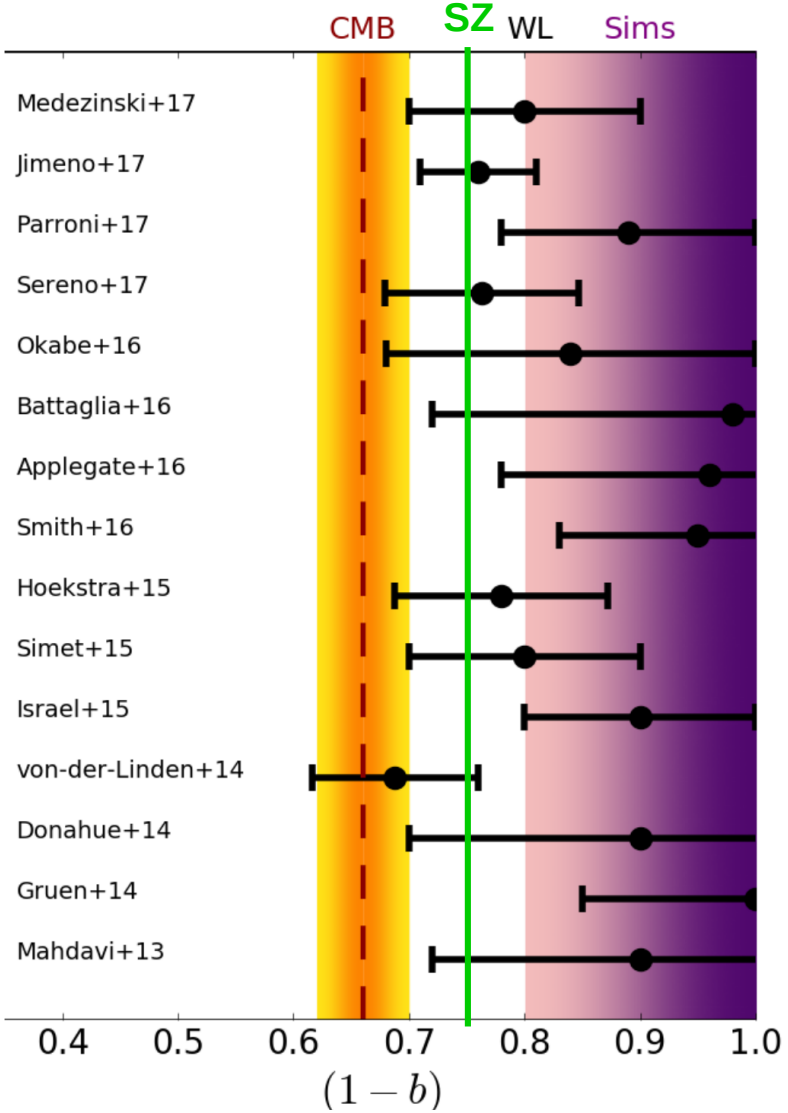
(1 - b) = **0.58** ± 0.04 → Planck '15
(1 - b) = 0.65 ± 0.04 LCDM → Salvati '18
(1 - b) = 0.63 ± 0.04 DE → Salvati '18
(1 - b) = 0.67 ± 0.04 Neutrinos → Salvati '18
(1 - b) = **0.62** ± 0.03 → Planck '18

While SZ prefers higher values
(1 - b) = 0.75±0.10

Salvati, Douspis, Aghanim '18



From curiosity to tension?

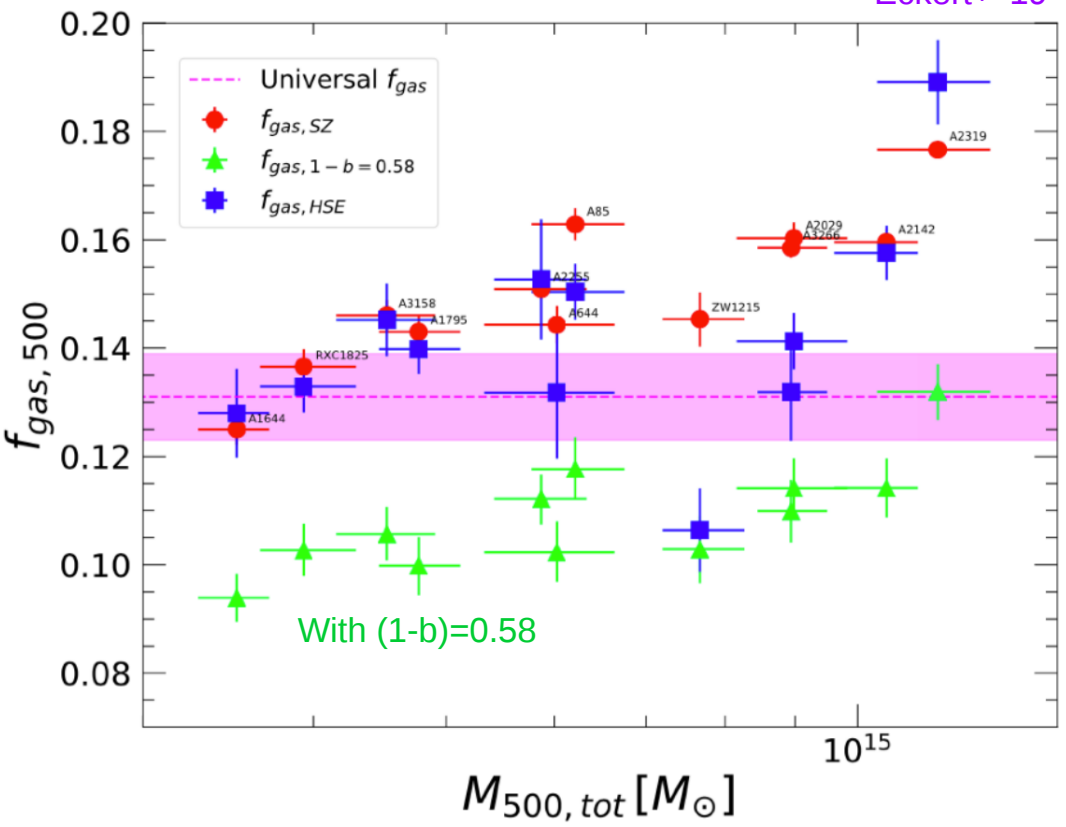


Mass bias of CMB vs estimates from WL and simulations

… (1 – b) ~ 0.6 too low!

Low value of (1-b) implies low gas fraction in clusters → **rejected at ~4.4σ**

Eckert+ ‘19



How to reconcile (bis): Is mass bias unique & constant?

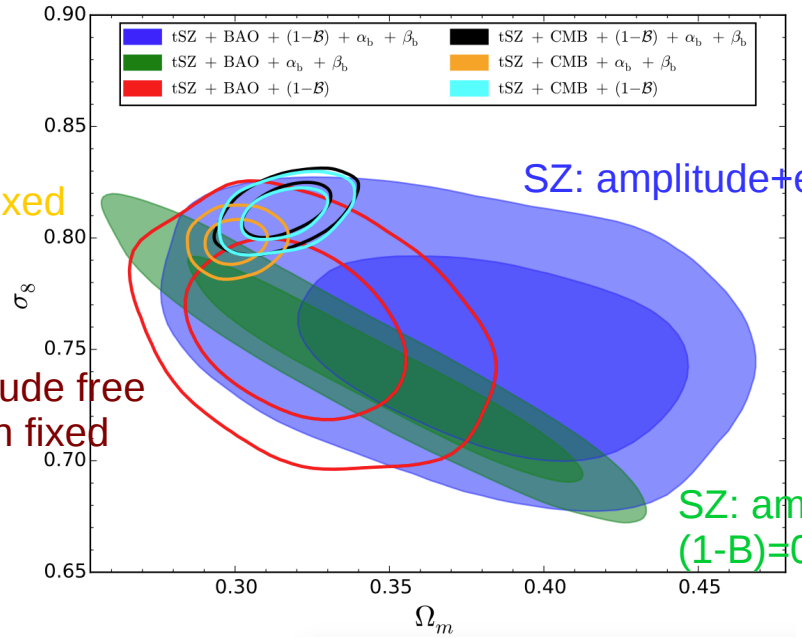
Systematic study exploring: parametrisation in bins, proior on mass bias, selected sample, etc.

$$(1-b)_{\rm var} = (1-\mathcal{B}) \cdot \left(\frac{M}{M_*}\right)^{\alpha_b} \cdot \left(\frac{1+z}{1+z_*}\right)^{\beta_b}$$

$4.82 \cdot 10^{14} M_\odot$ mean mass of PSZ2 catalog

0.22 median redshift of PSZ2 catalog

Salvati+ ‘19



CMB+SZ: amplitude fixed + evolution free

SZ: amplitude+evolution free

SZ: amplitude free + evolution fixed

SZ: amplitude fixed+evolution free (1-B)=0.8

Do variations of mass bias improve more cosmological agreement? → **Not really**

Do data suggest any bias variation? →mild redshift evolution depending on sample

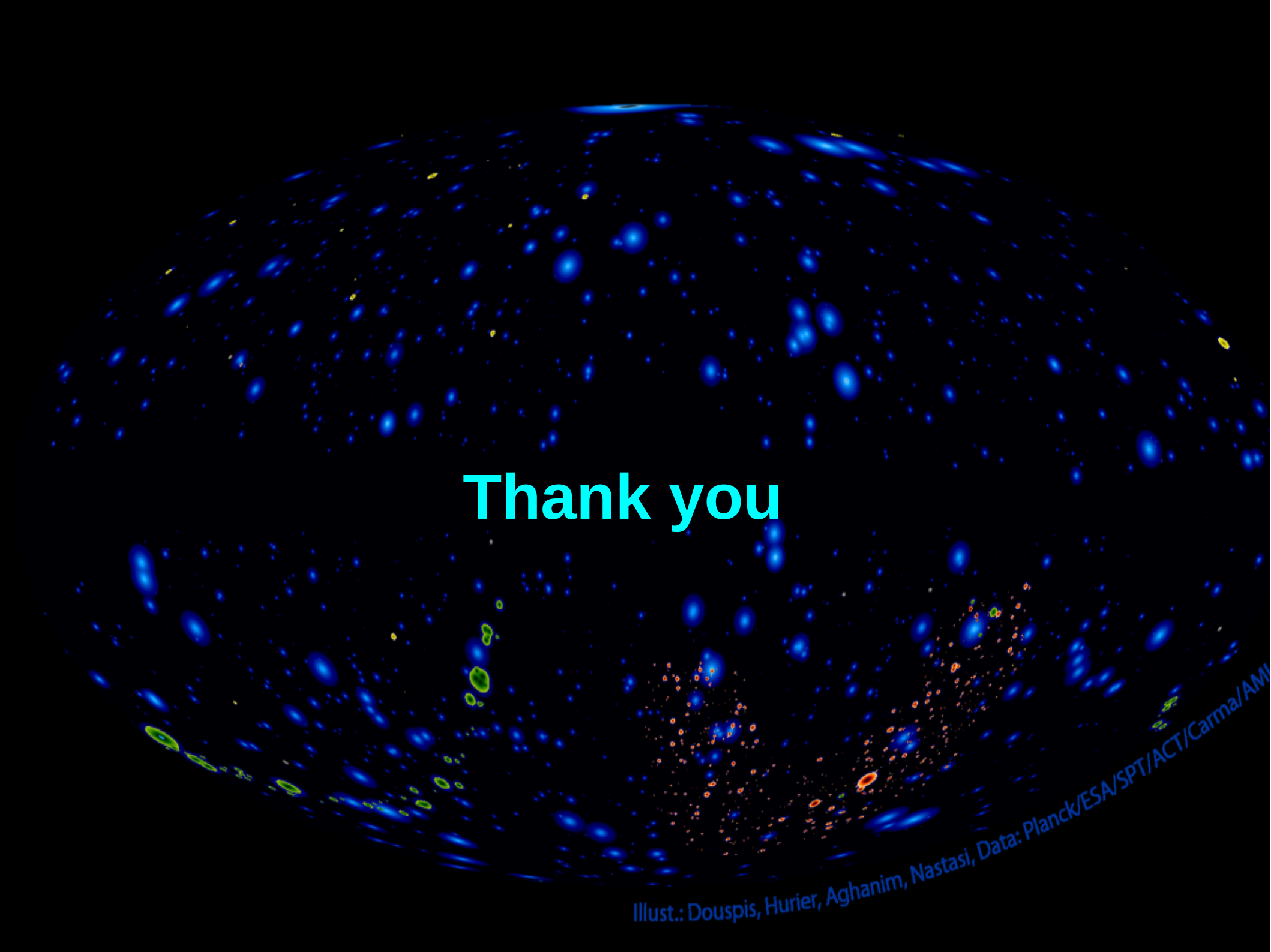
Conclusions

- Cosmology from a few hundreds of SZ clusters with reduced τ :
  - → **No tension on σ_8-Ω_m between CMB and SZ counts** (difference <2σ with C_l^{SZ})
  - → Cluster constraints agree with lambda (w=-1.06) & set limit on neutrino mass to 0.18eV
  - → Analysis not limited by statistical errors but by systematics mostly mass bias calibration: @present (1-b) in [0.7, 1] to be reduced to a few %

- CMB prefers mass bias (1-b) in [0.6, 0.65]
  - → Curiosity compared to simulations & most of WL mass estimates & SZ

- Comparison with universal gas fraction implies that the most massive local clusters would be missing about a third of their baryons
  - → (1-b)~0.6 from CMB **rejected at~4.4σ**

- Higher resolution SZ map, CMB lensing, and high quality X-ray data should increase constraining power of C_l^{SZ} & improve mass estimates of large cluster samples


Thank you
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