Dissecting Cluster Cosmology:
toward a roadmap for forthcoming cluster surveys

tSZ cluster cosmology

Planck, SPT and beyond …

Laura Salvati

In collaboration with: Marian Douspis, Nabila Aghanim, Adelie Gorce, Alex Saro, Raphael Wicker, Gaspard Aymerich, Stefano Gallo, Gabriel Pratt and many others …

Outline

Credit: 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. 2018

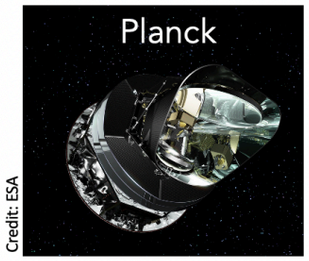
4195 optically confirmed clusters (13,211 deg^2)
Hilton et al. 2021

Credit: SPT, K. Vanderlinde

677 SPT-SZ sources with S/N>4.5 (2,500 deg^2)
Bleem et al. 2015

470 SPT-ECS sources with S/N>4 (2,770 deg^2)
Bleem et al. 2019

89 SPTpol sources with S/N>4.6 (100 deg^2)
Huang et al. 2020



Credit: ESA

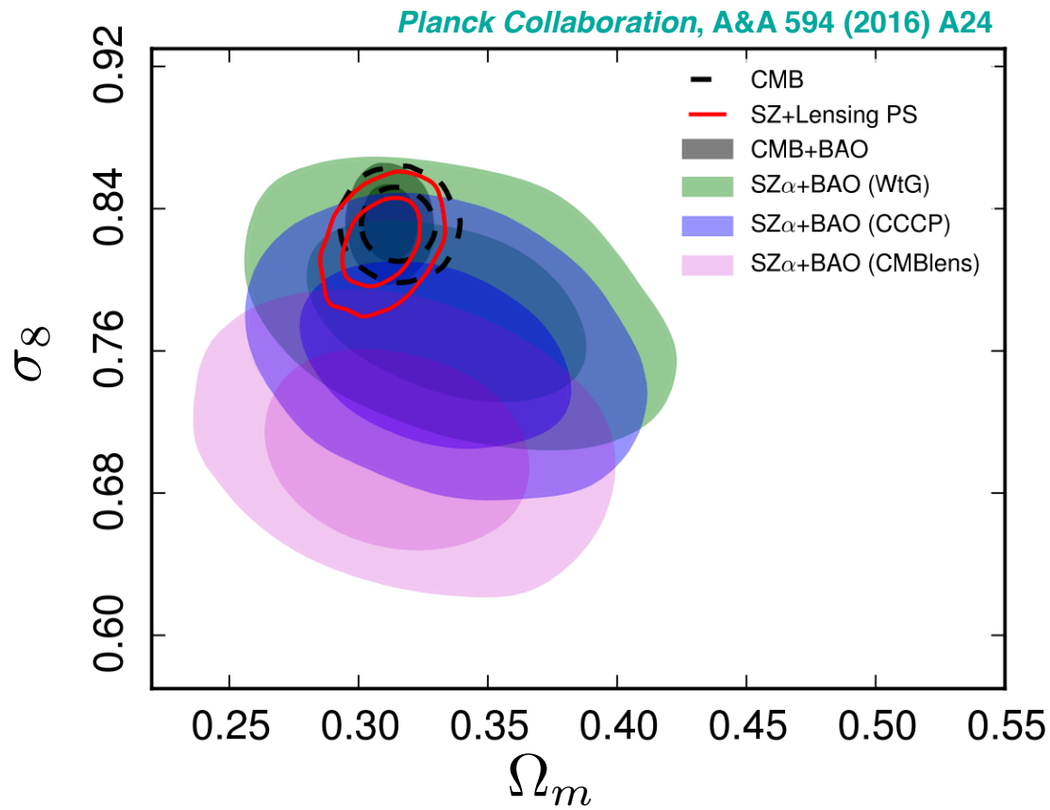
1653 SZ sources with S/N>4.5 (35,000 deg^2)
Planck Collaboration XXVII 2015

16

Slide from Jean-Baptiste On monday

- Planck tSZ observations
  - Still room for improvement
  - tSZ power spectrum
  - Combination with other experiments
    - Planck + SPT
- Impact of HMF calibration

Planck cluster cosmology



Scaling Relations

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

$\alpha,\ Y_*$ → from X-ray observations

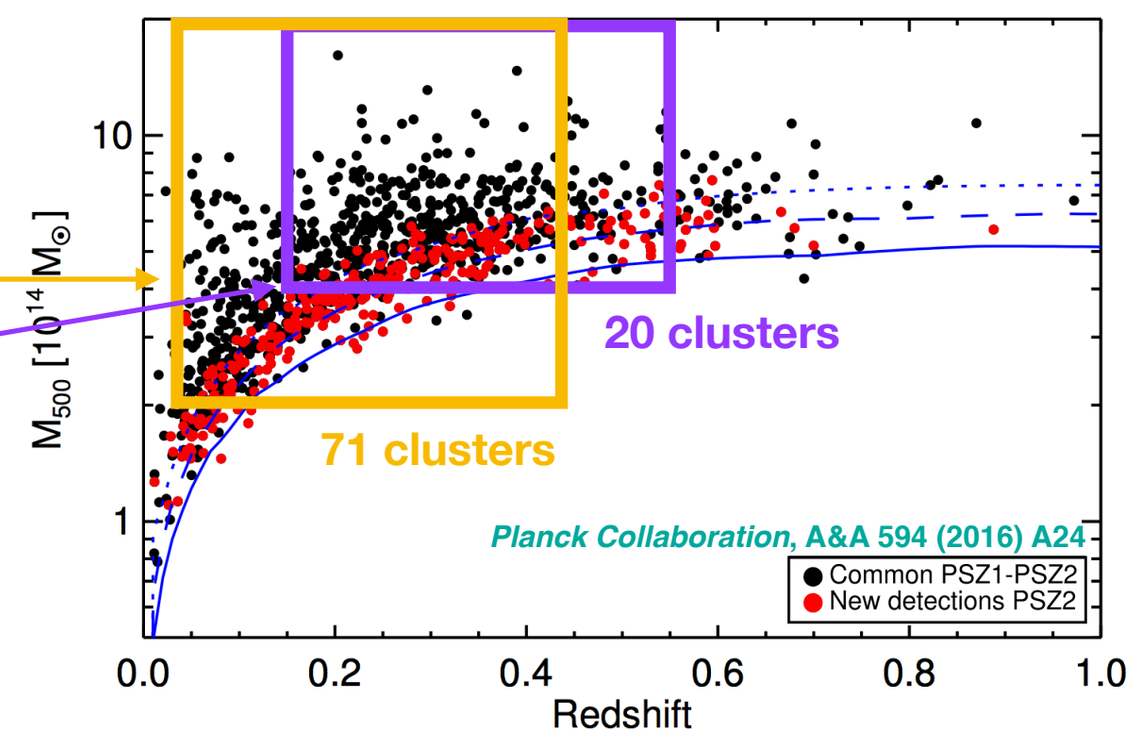
$(1-b)$ → from WL mass evaluations

$\beta = 2/3$ → from self-similarity

Planck Collaboration, A&A 594 (2016) A24

$$(1-b) = \frac{M_{\mathrm{SZ}}}{M_{500}}$$

Cosmological cluster sample: 439 clusters



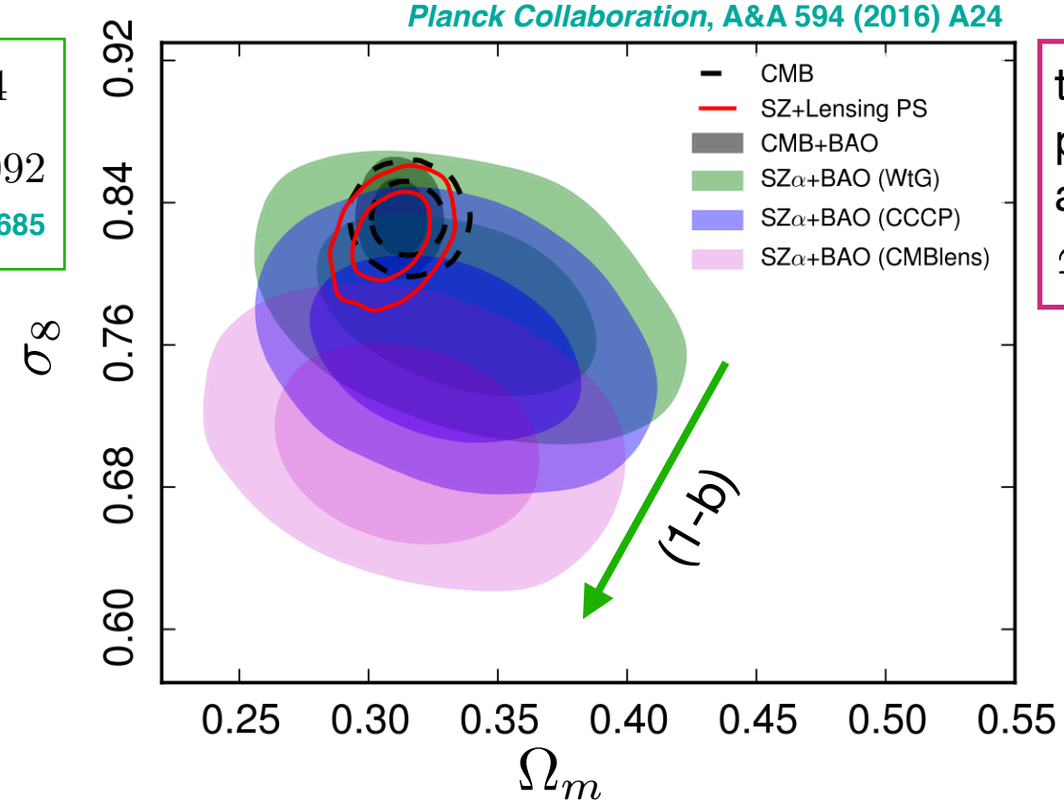
Planck cluster cosmology

$$\mathrm{CMB} + \mathrm{NC}^{\mathrm{tSZ}} : (1-b) = 0.58 \pm 0.04$$

$$\mathrm{CCCP}: (1-b) = 0.780 \pm 0.092$$

Hoekstra et al., MNRAS 449 (2015) no.1, 685

Planck Collaboration, A&A 594 (2016) A24



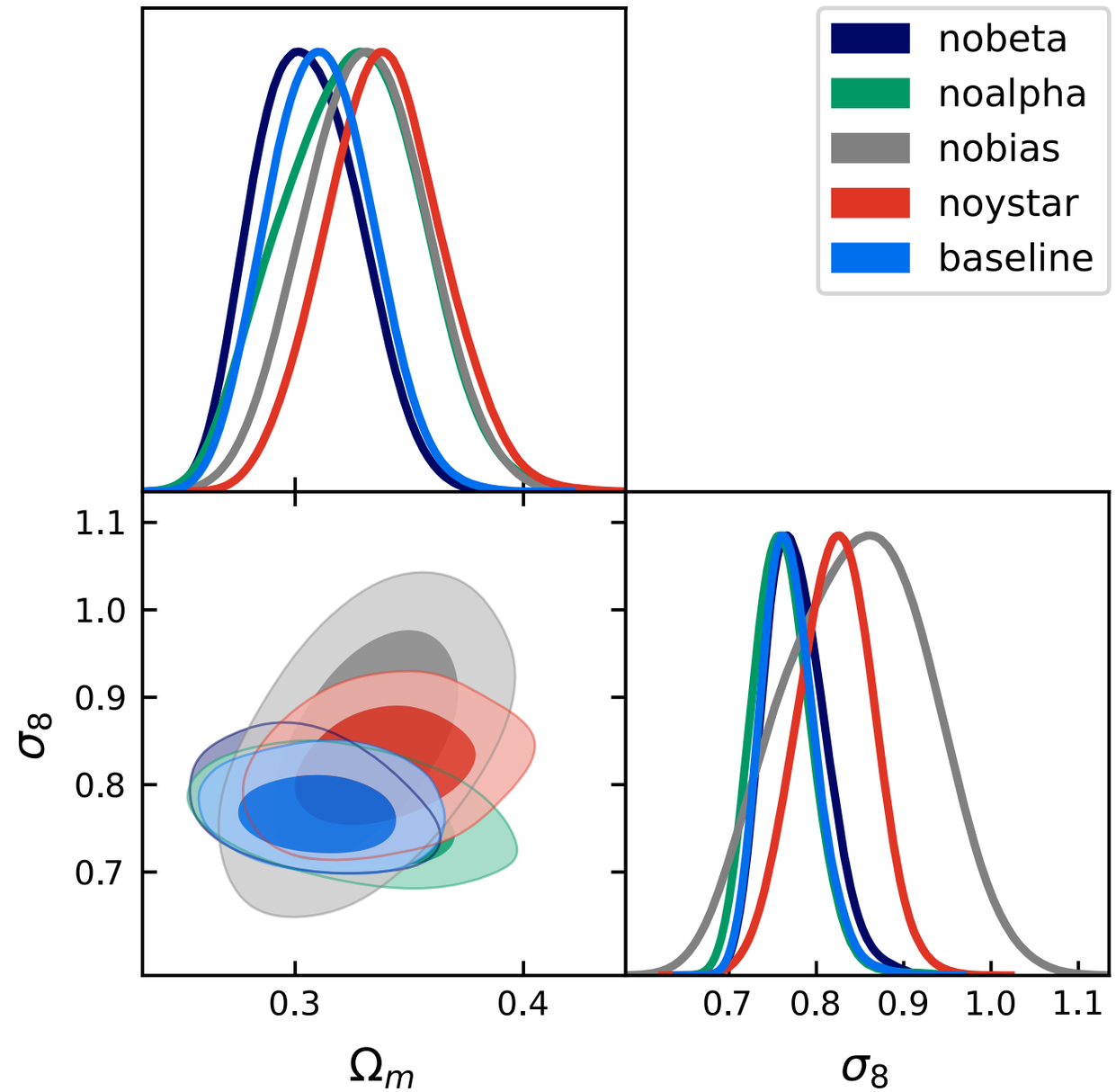
tension between CMB primary anisotropies and Galaxy Clusters: $\simeq 2.4\,\sigma$ on σ_8

Zubeldia & Challinor, MNRAS 489, 401–419 (2019)

Data set	$1 - b_{\mathrm{SZ}}$
WtG	0.688 ± 0.072
CCCP	0.780 ± 0.092
Sereno et al. (2017)[a]	0.66 ± 0.10
Penna-Lima et al. (2017)	0.73 ± 0.10
Medezinski et al. (2018)	0.80 ± 0.14
Hurier & Lacasa (2017)	0.71 ± 0.07
Planck 2015 CMB lensing[b]	$1.01^{+0.24}_{-0.16}$
Planck 2015 SZ + *Planck* 2018 CMB	0.62 ± 0.04
This work	0.71 ± 0.10

Planck cluster cosmology

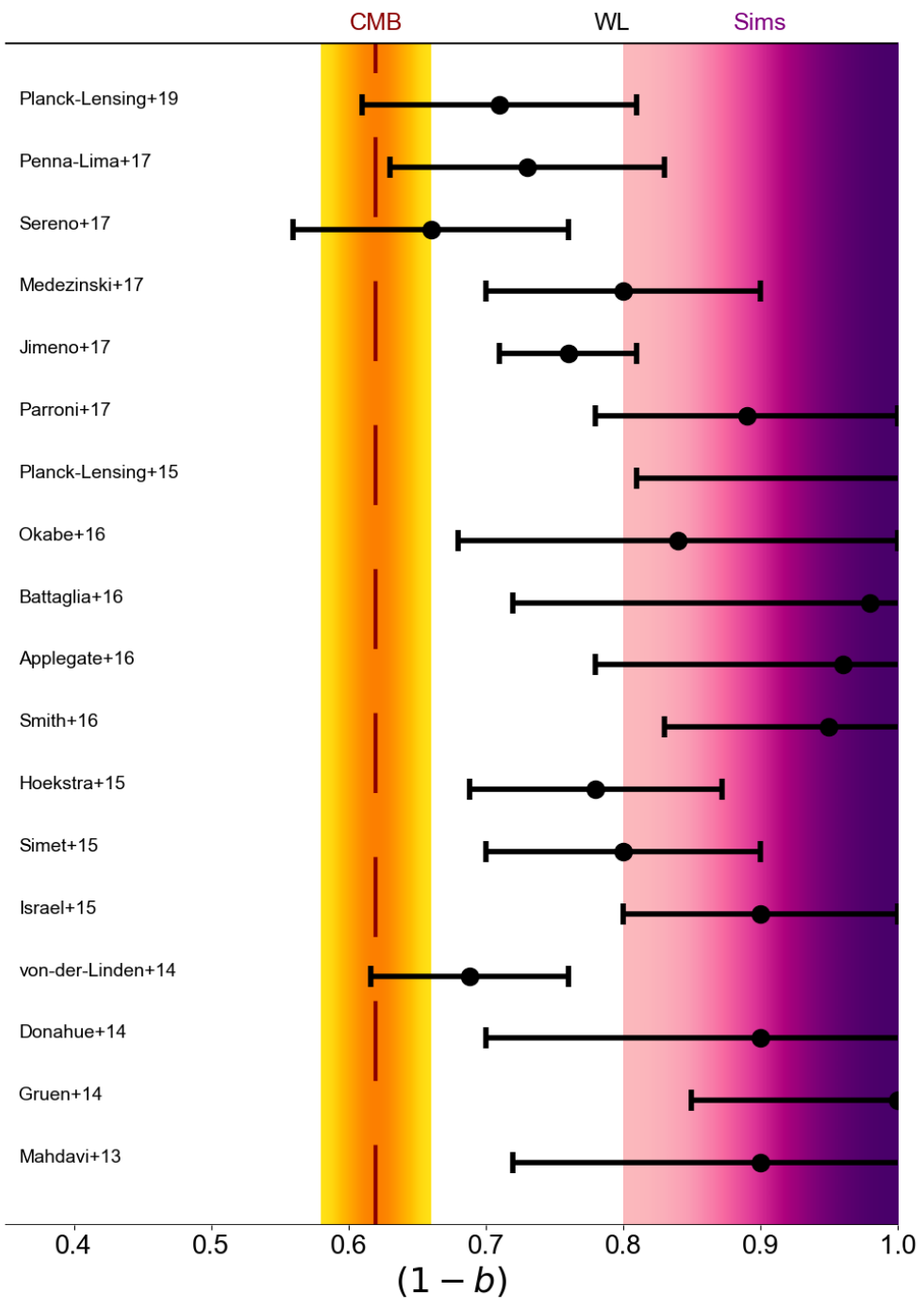
$$E^{-\beta}(z)\left[\frac{D_A^2(z)\,Y_{500}}{10^{-4}\,\mathrm{Mpc}^2}\right] = Y_*\left[\frac{h}{0.7}\right]^{-2+\alpha}\left[\frac{(1-b)\,M_{500}}{6\cdot 10^{14}M_\odot}\right]^{\alpha}$$



Mass bias

$(1-b) \simeq 0.6$ too low!

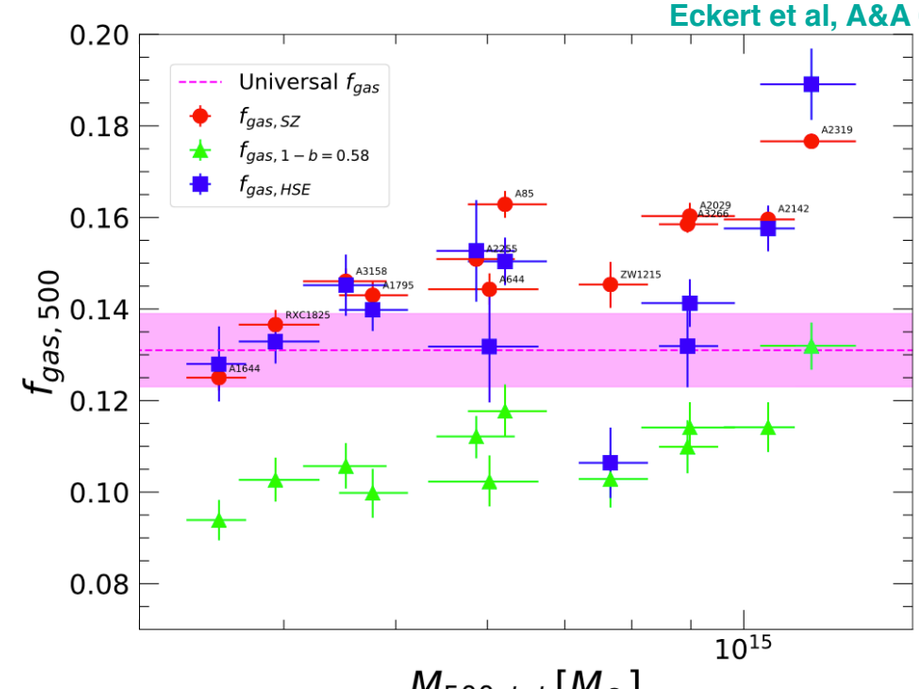
Salvati et al, A&A 614 (2018) A13

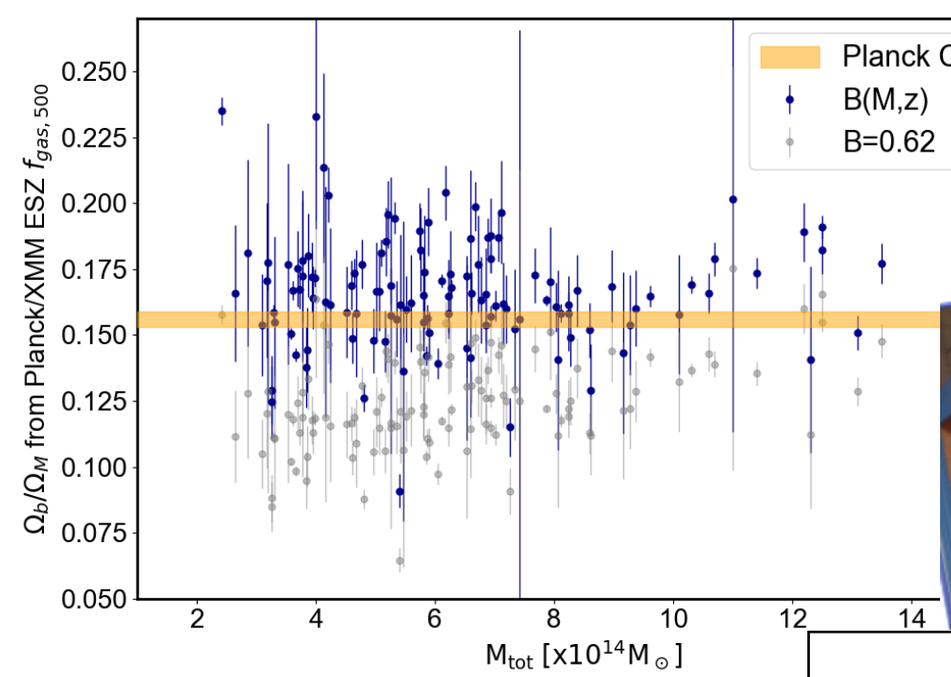


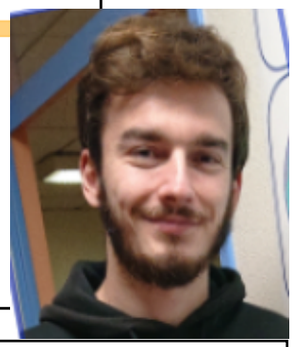
see also results in
Gianfagna et al, MNRAS 502 (2021) no.4, 5115-5133

Gas fraction

Eckert et al, A&A 621, A40 (2019)



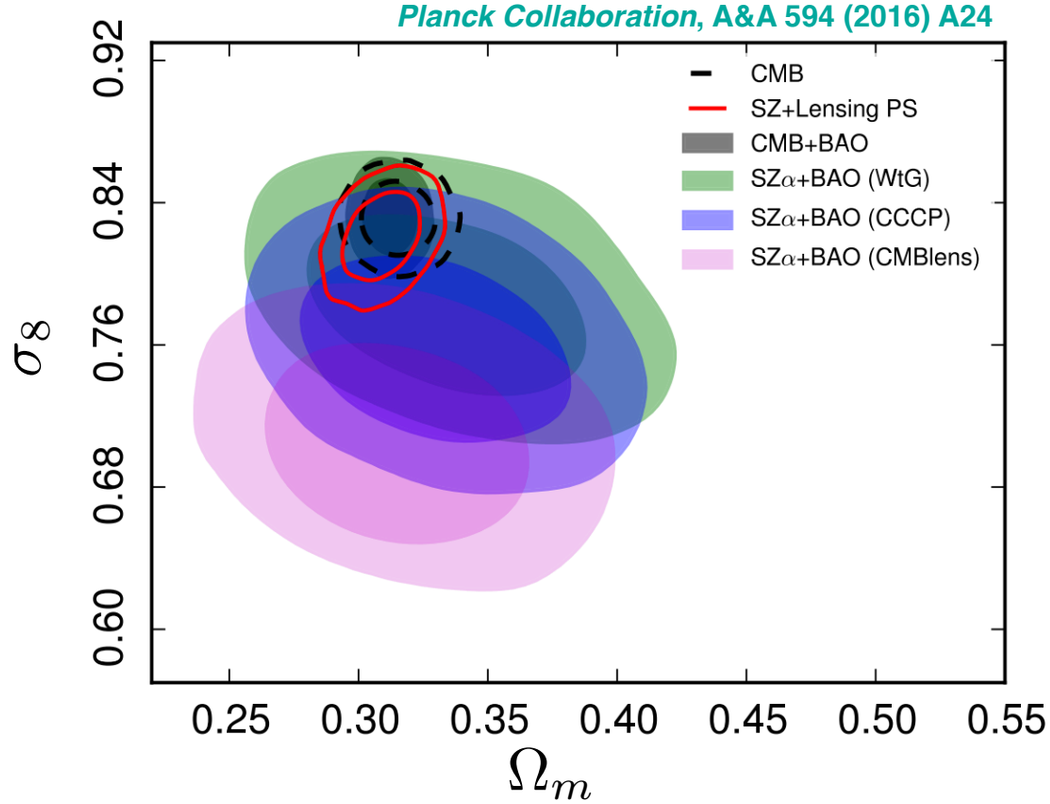




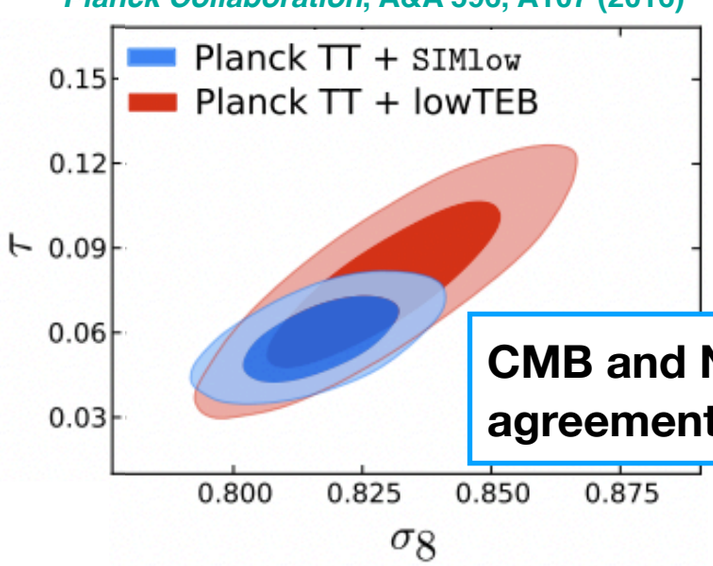
Wicker et al.,
A&A 674 (2023) A48

Tension or mass calibration?

Planck Collaboration, A&A 594 (2016) A24



Planck Collaboration, A&A 596, A107 (2016)



CMB and NCtSZ: agreement at $1.5\,\sigma$ on σ_8

CMB + NCtSZ

$(1-b) = 0.58 \pm 0.04$	P15
$(1-b) = 0.65 \pm 0.04$	LCDM
$(1-b) = 0.67 \pm 0.04$	Neutrinos
$(1-b) = 0.63 \pm 0.04$	DE
$(1-b) = 0.62 \pm 0.03$	P18

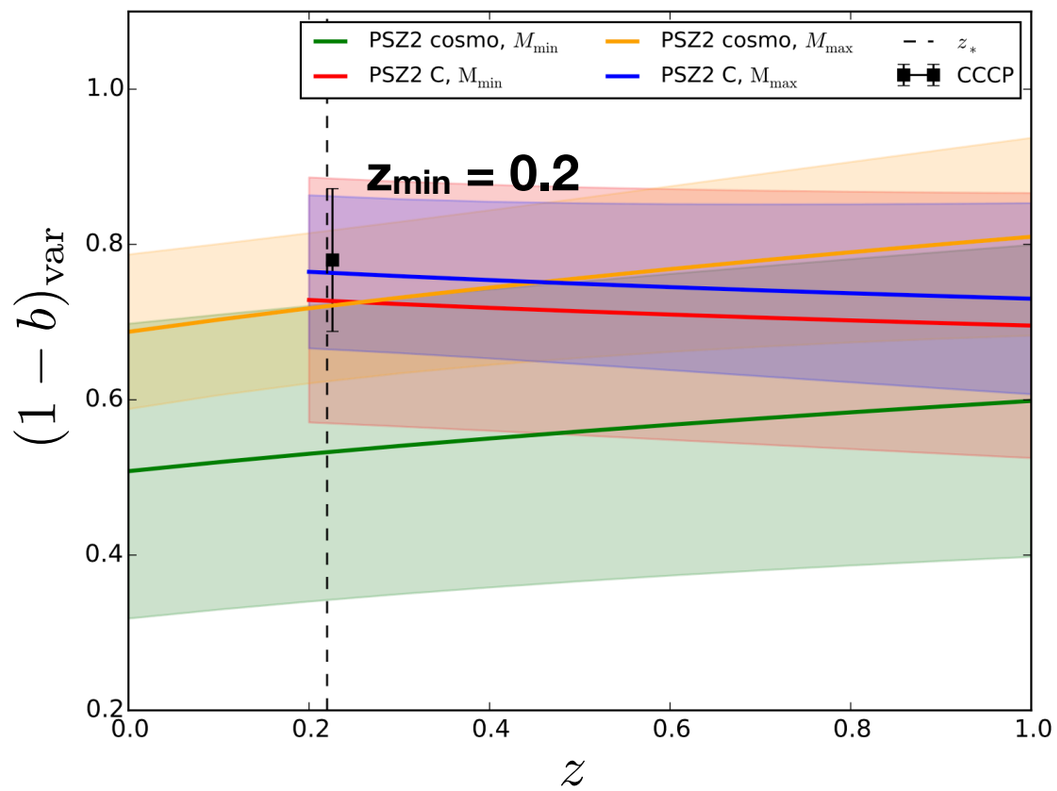
Salvati et al., A&A 614, A13 (2018)

Mass bias: (M,z) dependence

Mass-redshift Parametrisation

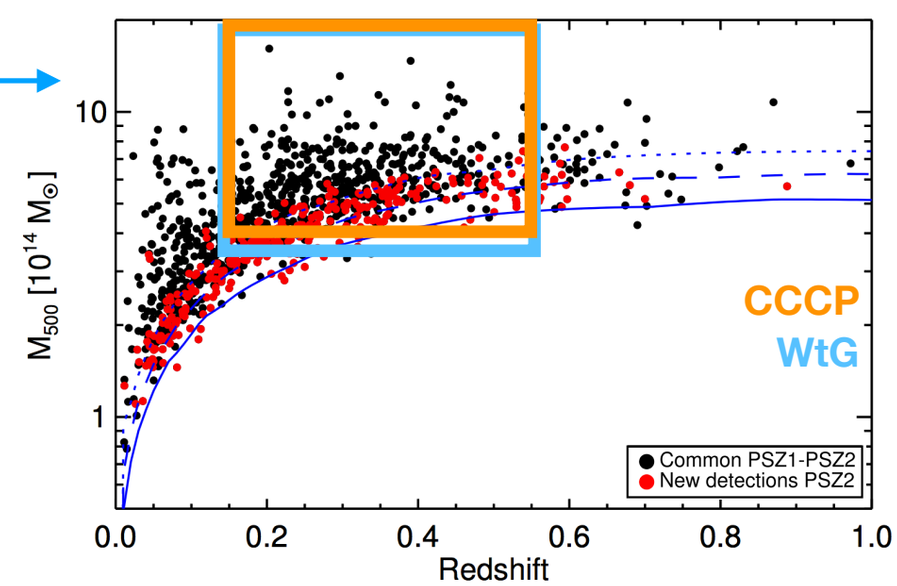
Salvati et al., A&A 626, A27 (2019)

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



Results from other analyses

- WtG (22 clusters) and CCCP (18 clusters) mass dependence: decreasing trend
- CoMaLit analysis Sereno&Ettori, MNRAS 468 (2017) no.3, 3322 redshift dependence: decreasing trend (135 clusters)
- X-COP analysis Eckert et al, A&A 621, A40 (2019) mass dependence: decreasing trend (12 clusters)

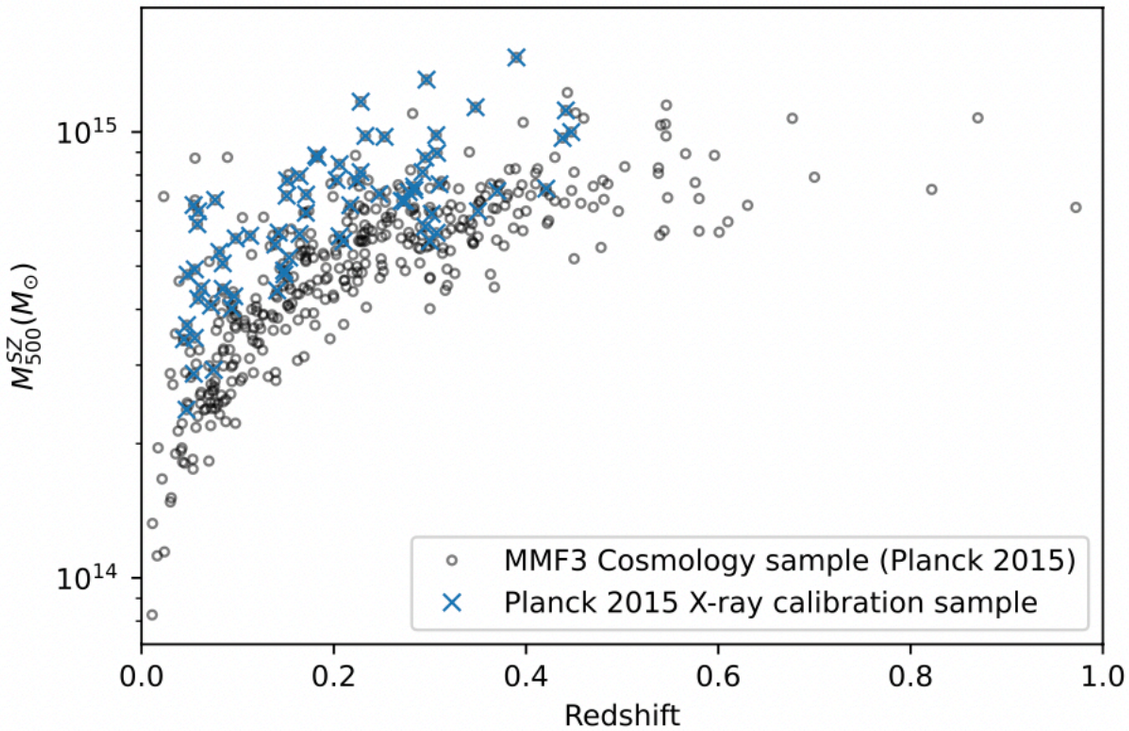


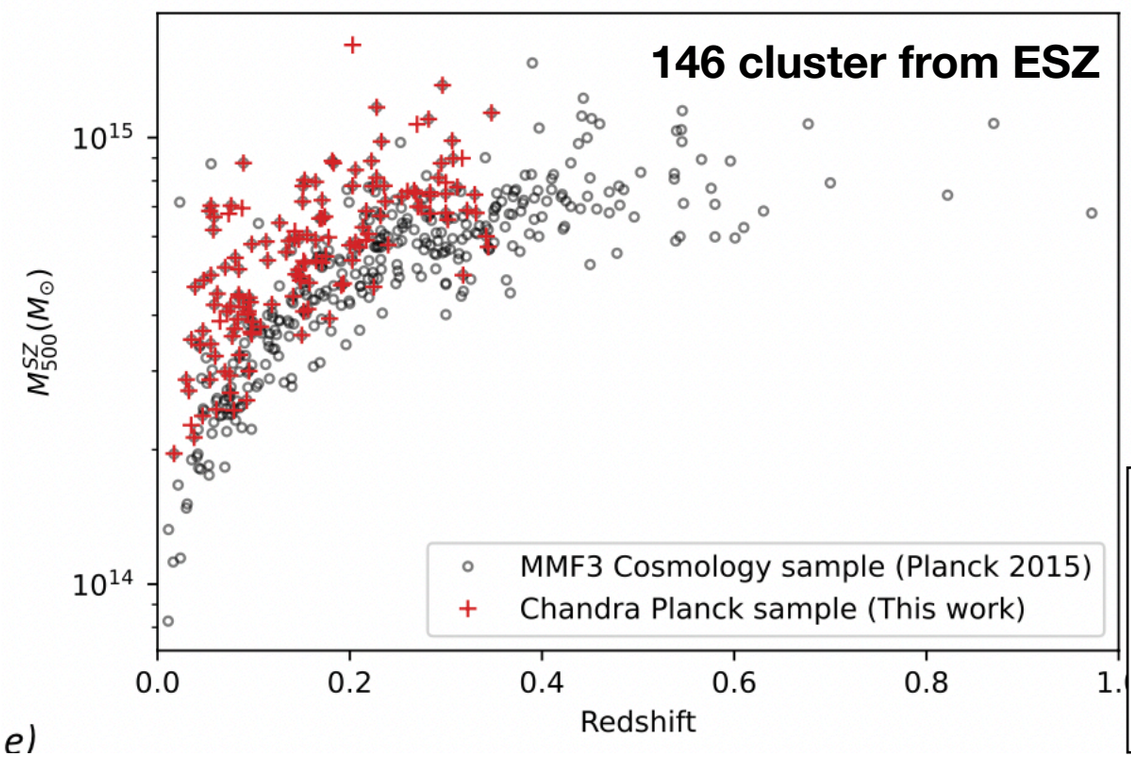
New scaling relation calibration

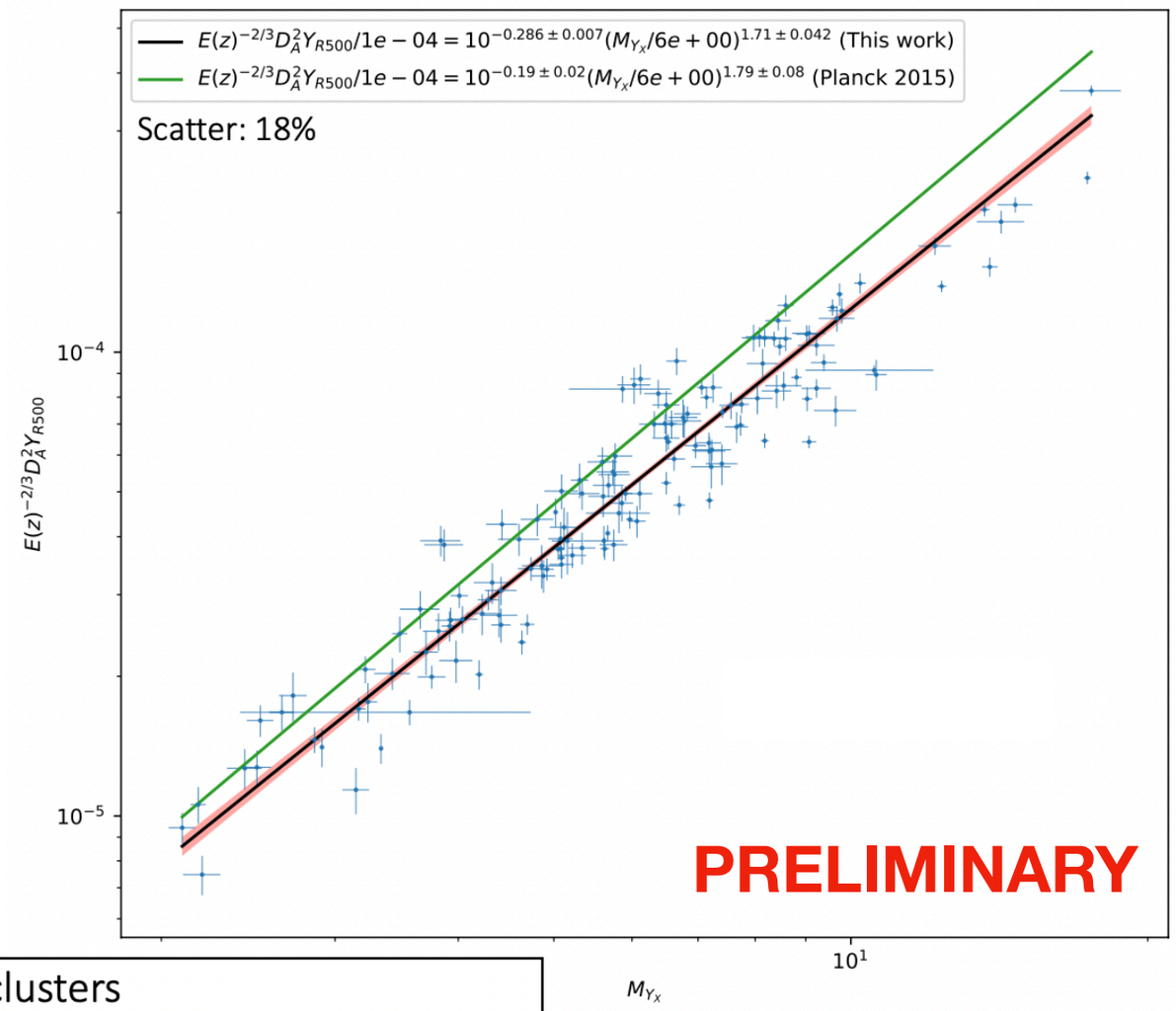
Aymerich et al., in prep.

Chandra-Planck
Legacy Program for Massive Clusters of Galaxies

Santos et al., ApJ 914 (2021) 1, 58







More clusters
Better low-mass leverage
Similar high-mass leverage
Better low-redshift leverage
Slightly worse high-redshift leverage

New scaling relation calibration

Aymerich et al., in prep.

Chandra-Planck
Legacy Program for Massive Clusters of Galaxies

Santos et al., ApJ 914 (2021) 1, 58

PRELIMINARY scaling relation:

$$E^{-2/3}(z)\frac{D_A^2\,Y_{500}}{10^{-4}\mathrm{Mpc}^2} = 10^{-0.29\pm0.01}\left(\frac{(1-b)M_{500}}{6\cdot10^{14}M_\odot}\right)^{1.71\pm0.1}$$

Scatter: 20%

Planck collab. 2015 Cosmology from SZ number counts scaling relation :

$$E^{-2/3}(z)\left[\frac{D_A^2\,Y_{500}}{10^{-4}\,\mathrm{Mpc}^2}\right] = 10^{-0.19\pm0.02}\left(\frac{(1-b)\,M_{500}}{6\times10^{14}\,M_\odot}\right)^{1.79\pm0.08}$$

Scatter: 18%

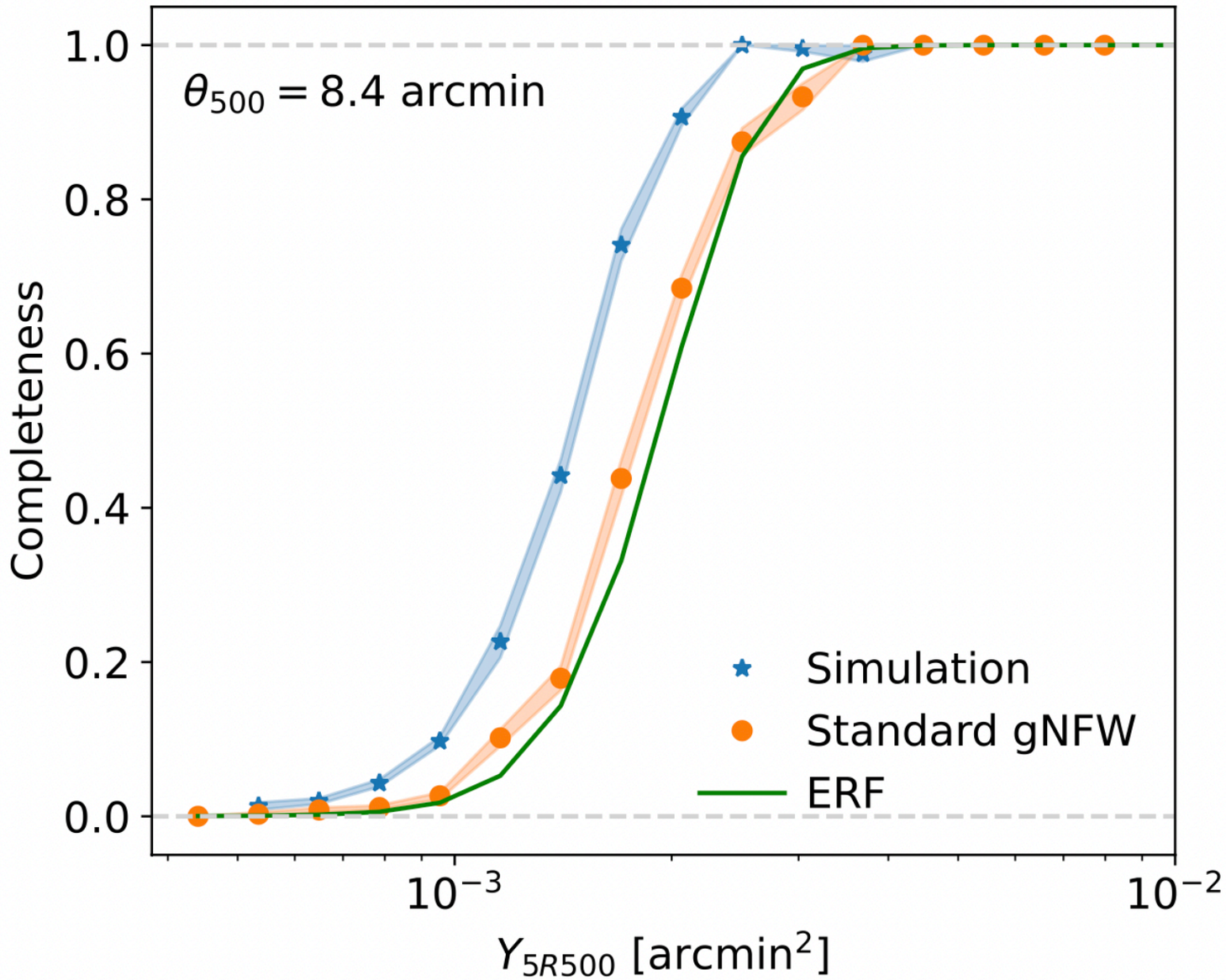
The new scaling relation has:
Lower normalization: Chandra and XMM temperature calibration don't match, Chandra measures hotter and thus heavier cluster. The **difference is coherent with predictions from Schellenberger et al. 2015** (20% difference)

Shallower slope: The new scaling relation is closer to self-similar (slope of 5/3)

Comparable uncertainties: Lower uncertainties on Y_{SZ}-M_{Y_X} (larger sample) but higher uncertainties on Y_X-M_{Y_X} compensates the difference

Modelling of Selection function

Gallo et al., in prep.



Completeness of spherical images ~ analytical ERF estimation

BUT

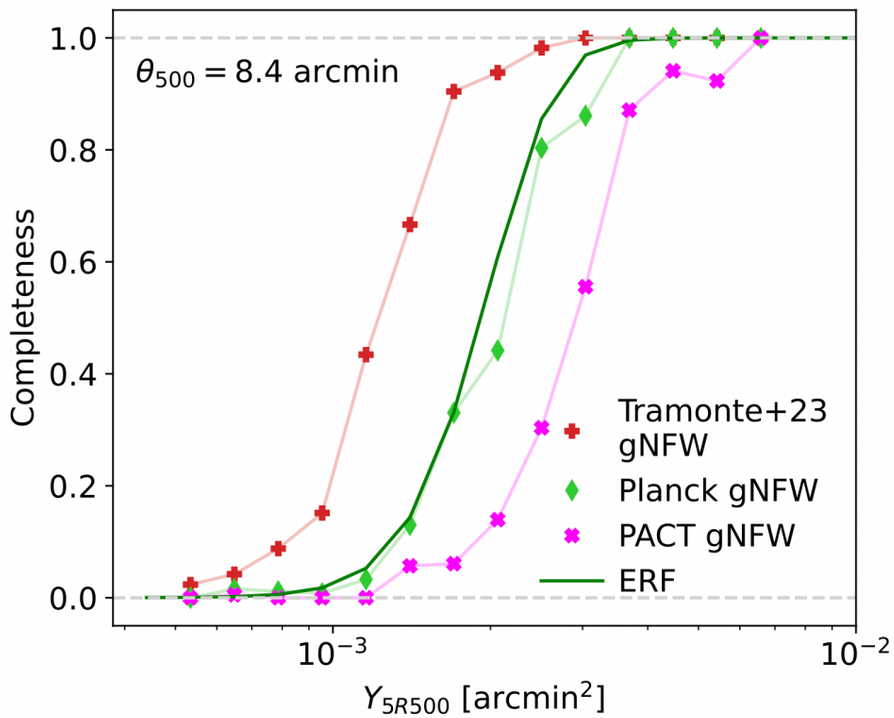
Simulation images show higher completeness than spherical ones

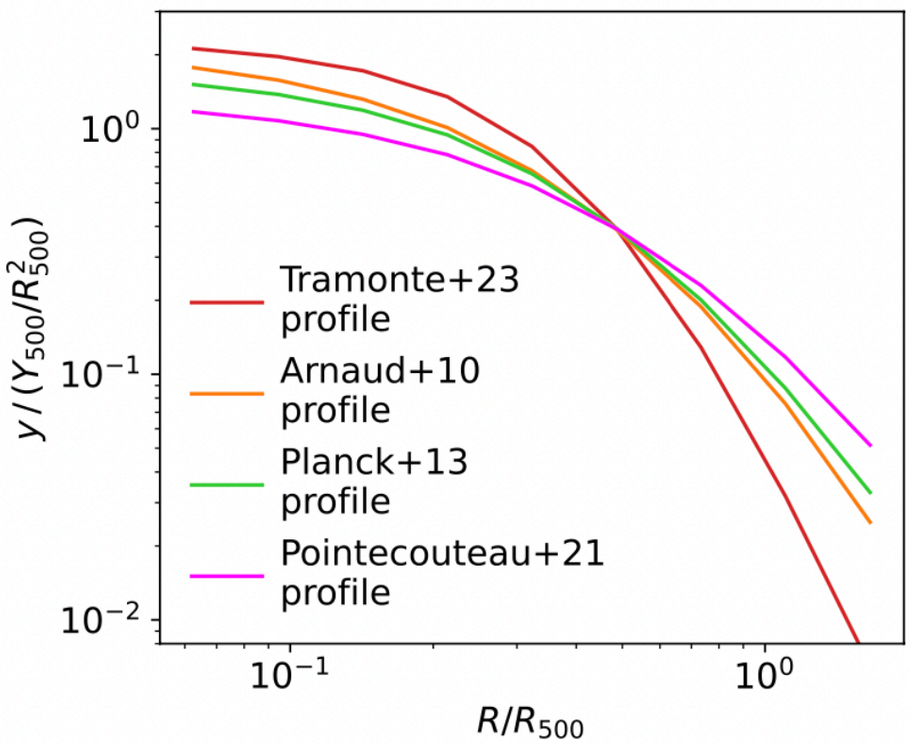
- IllustrisTNG-300 hydrodynamical simulation
- $M_{500} \gtrsim 1 - 2 \times 10^{14} M_\odot$
- $0.05 < z < 0.3$
- 6 projections per cluster ⟶ almost 9000 images

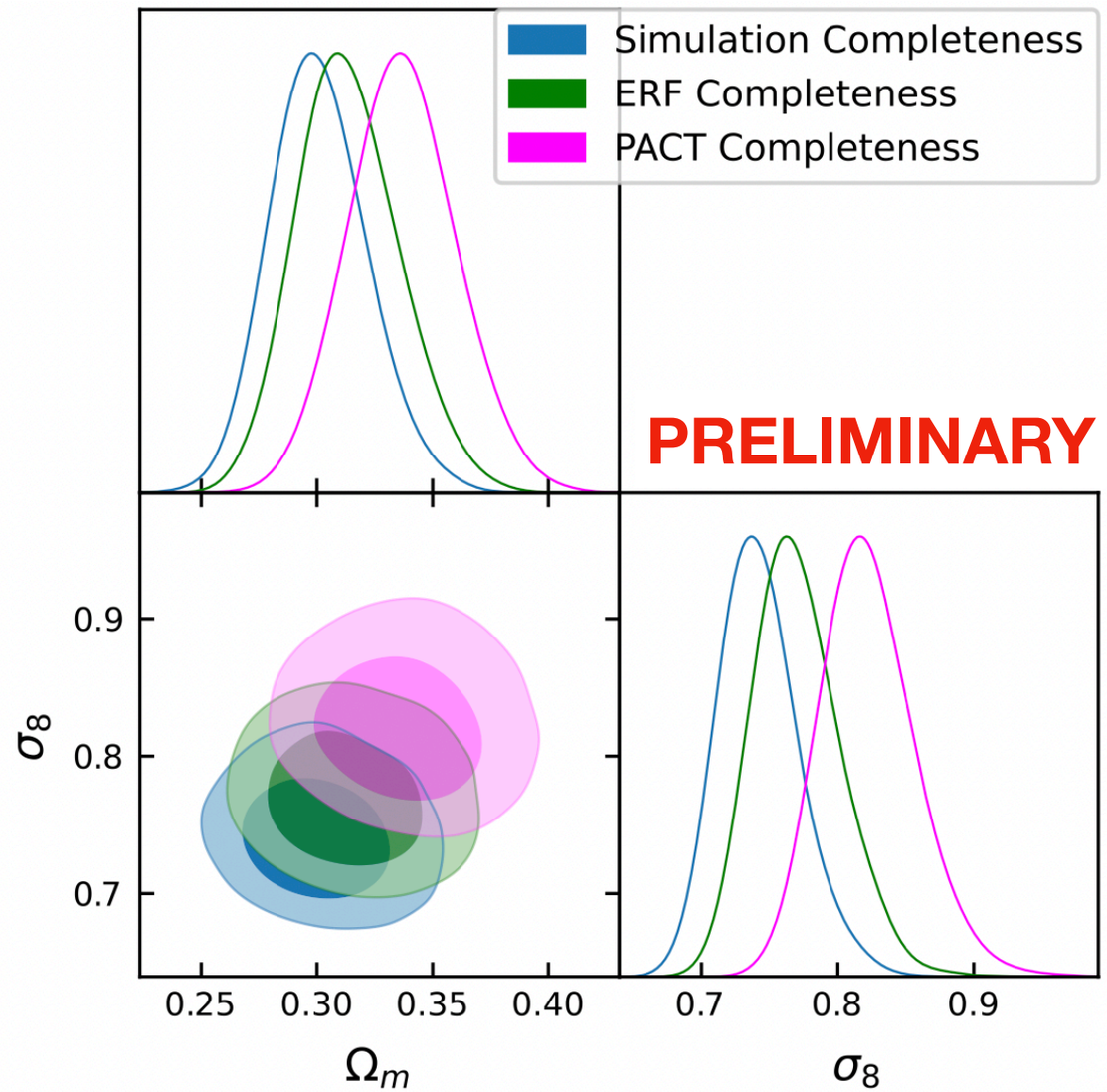
Slide from Stefano Gallo
mmUniverse conference

Modelling of Selection function

Gallo et al., in prep.



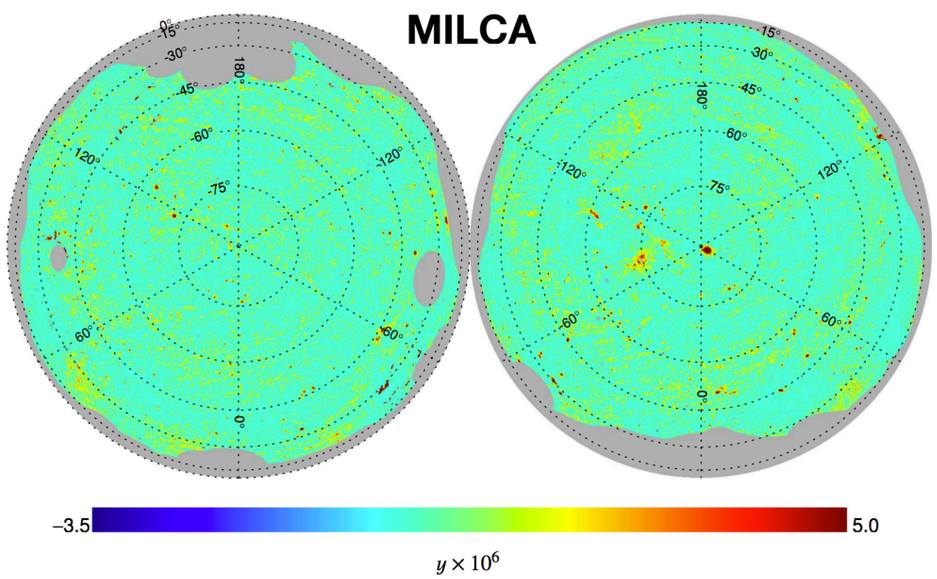




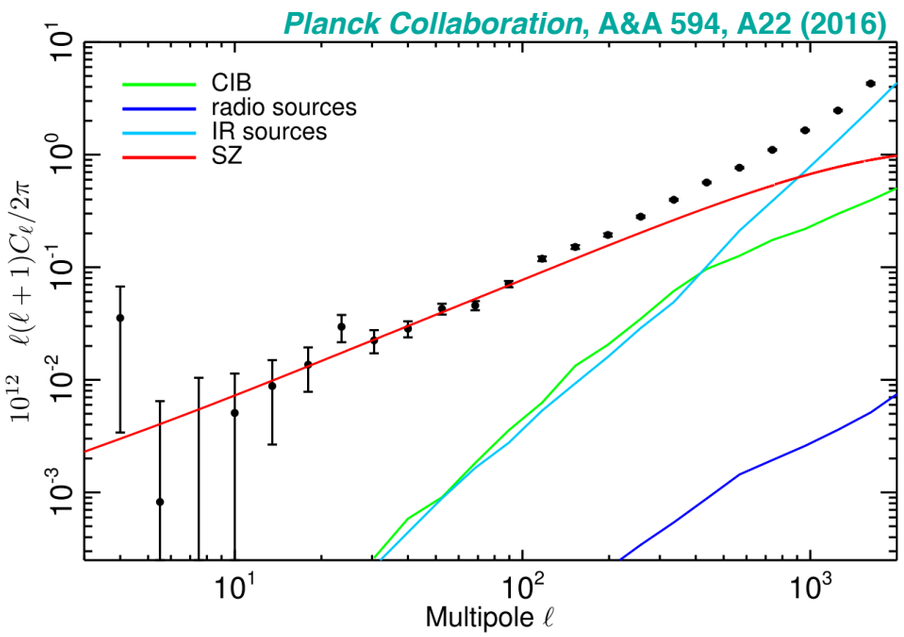
tSZ power spectrum

Salvati+
A&A 614 (2018) A13

Total diffuse signal



Hurier et al., A&A 558, A118 (2013)

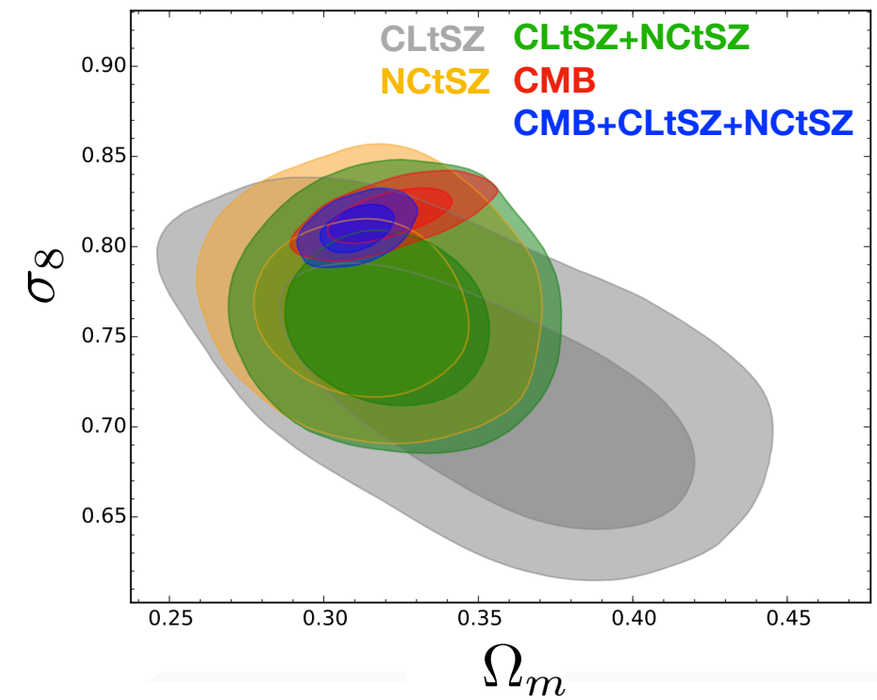


Planck Collaboration, A&A 594, A22 (2016)

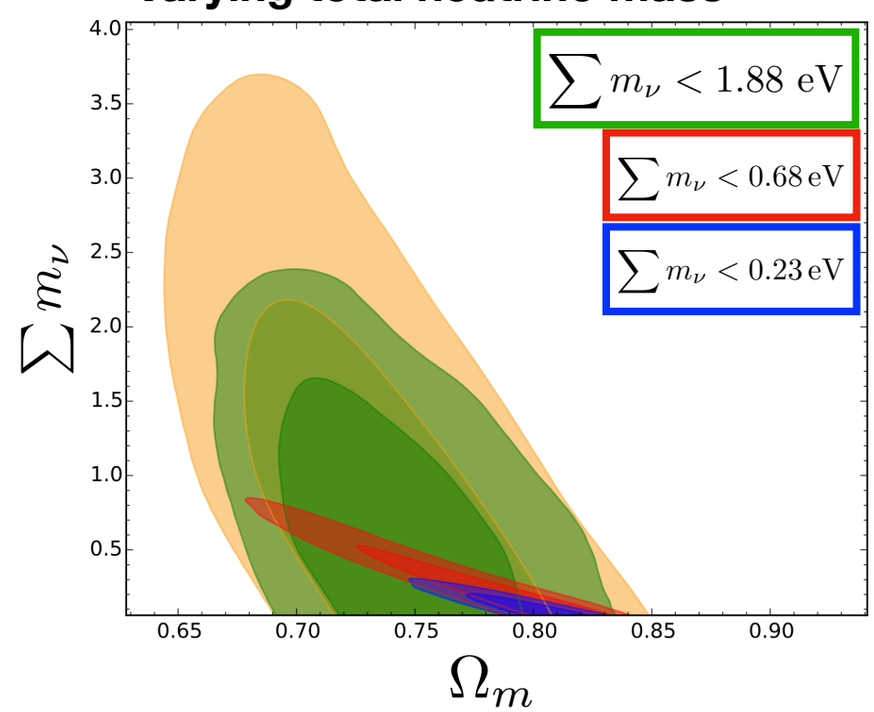
$$C_\ell^{\rm tSZ} \propto \sigma_8^{8.1}\,\Omega_m^{3.2}\,(1-b)^{3.2}$$

$$NC^{\rm tSZ} \propto \sigma_8^{9}\,\Omega_m^{3}\,(1-b)^{3.6}$$

LCDM



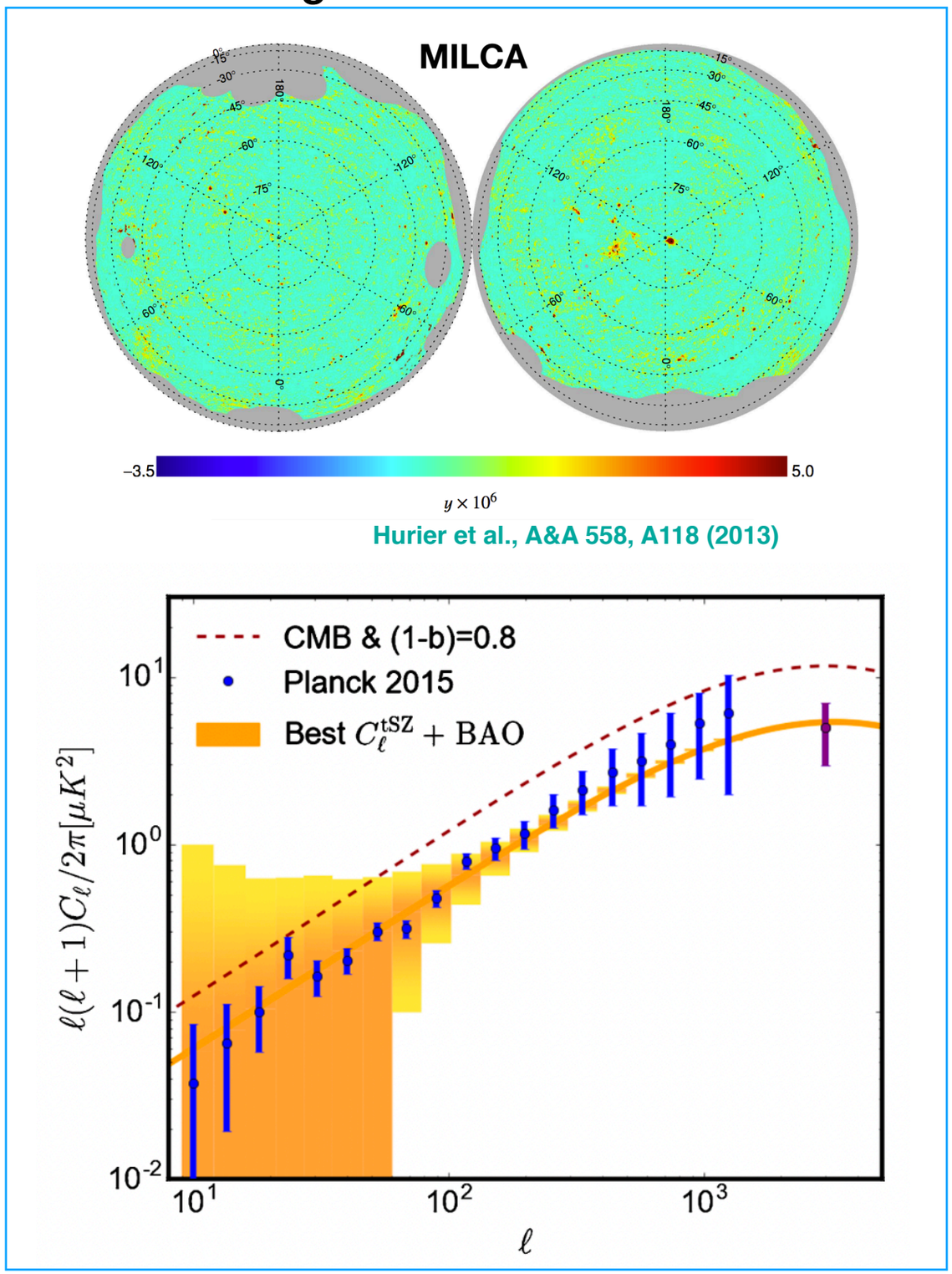
Varying total neutrino mass



tSZ power spectrum

Salvati+
A&A 614 (2018) A13

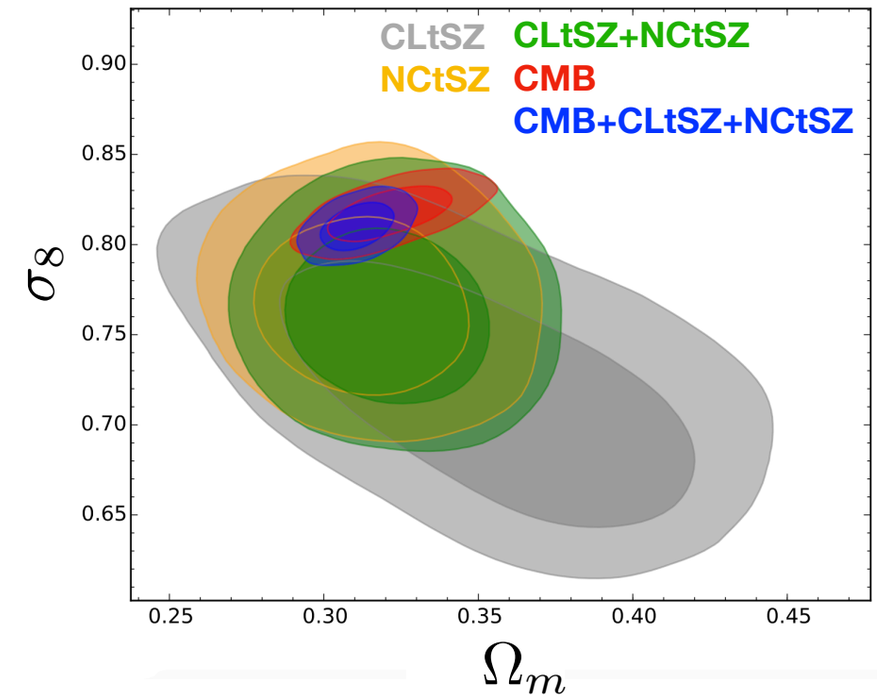
Total diffuse signal



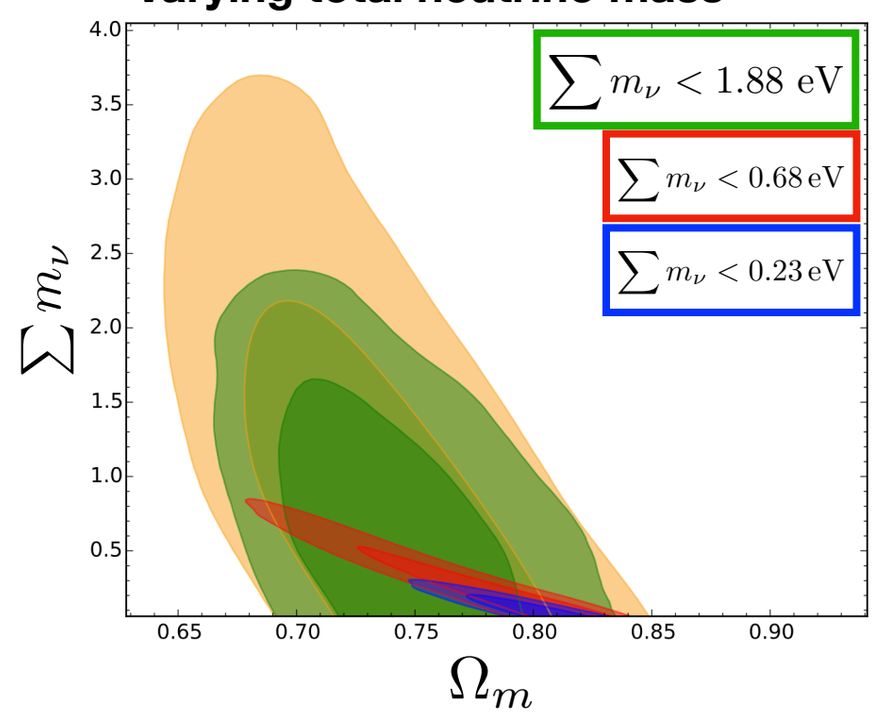
$$C_\ell^{\rm tSZ} \propto \sigma_8^{8.1}\,\Omega_m^{3.2}\,(1-b)^{3.2}$$

$$NC^{\rm tSZ} \propto \sigma_8^{9}\,\Omega_m^{3}\,(1-b)^{3.6}$$

LCDM



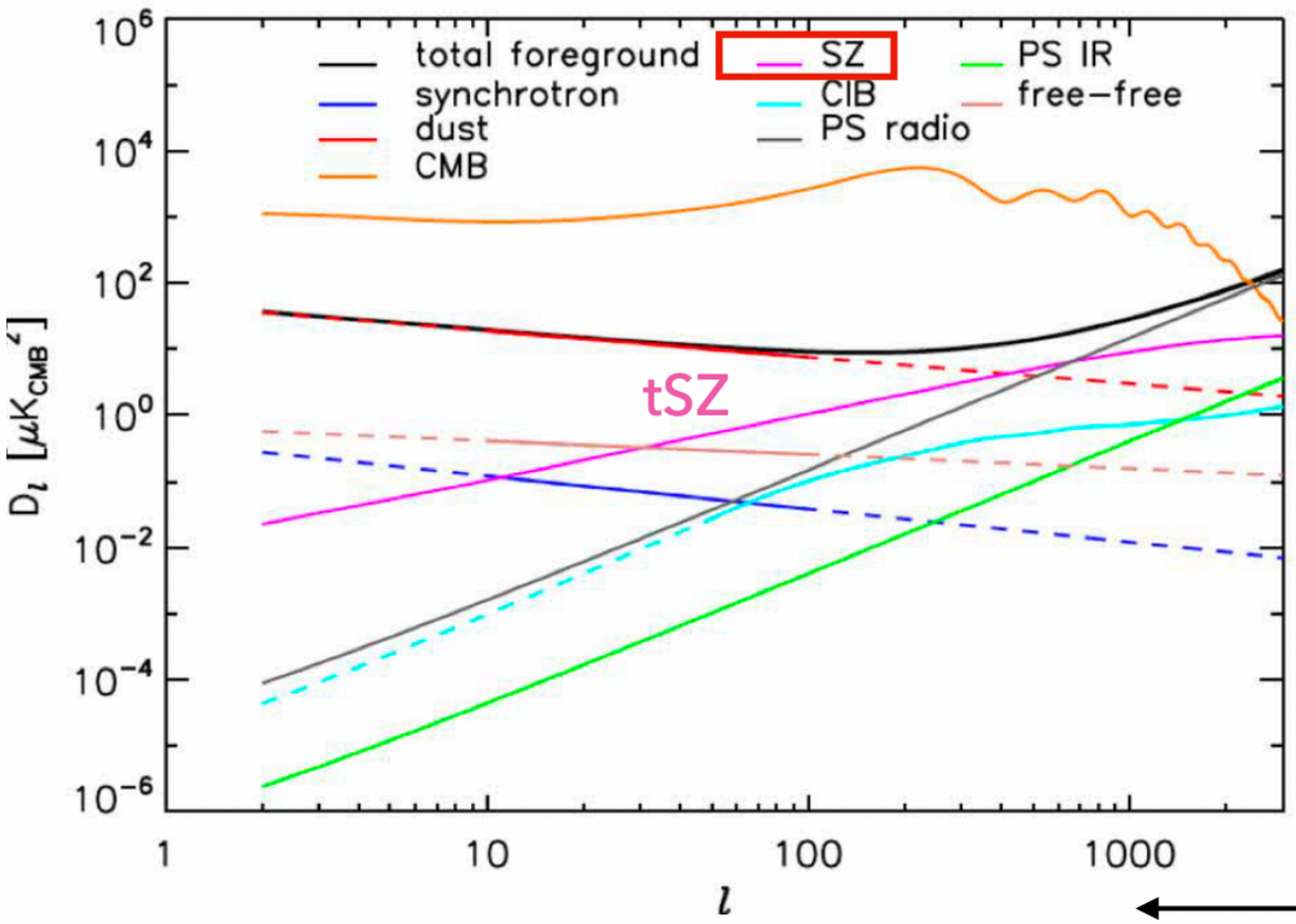
Varying total neutrino mass



tSZ power spectrum

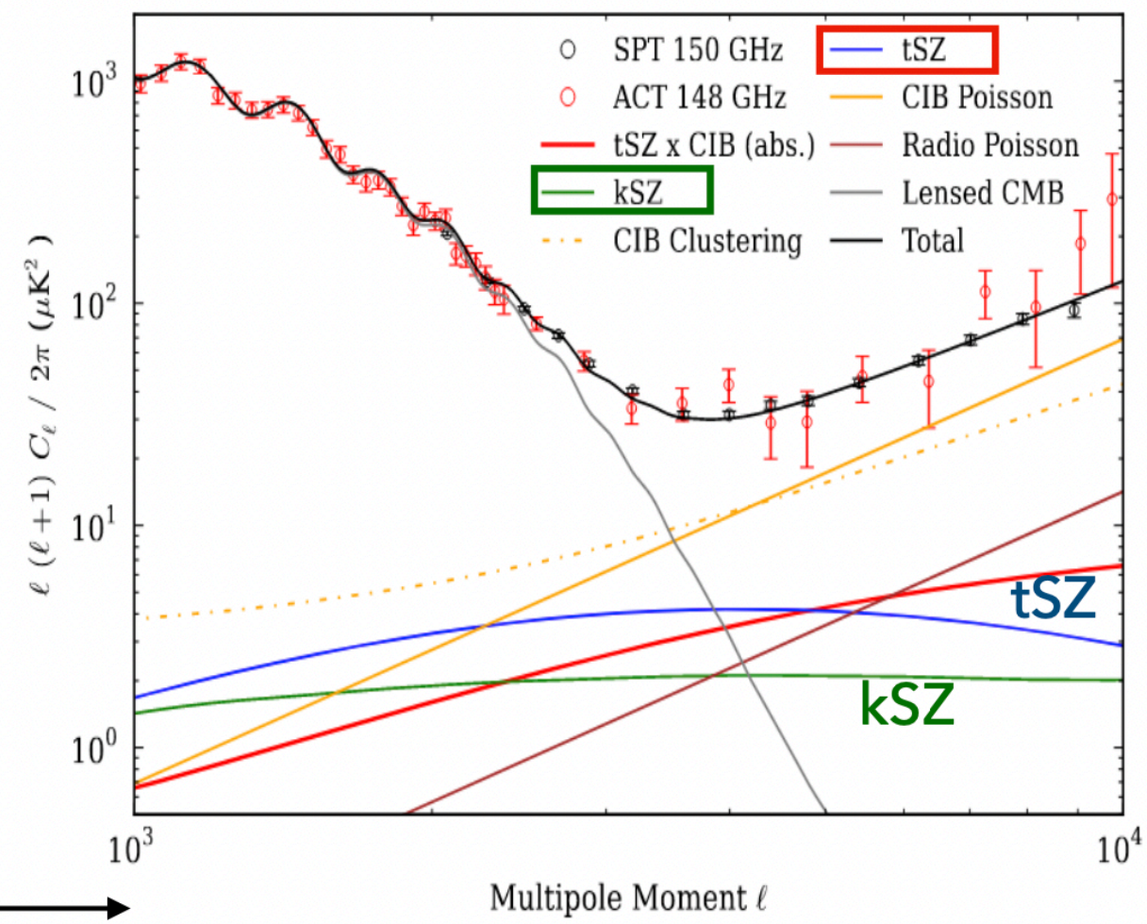
- tSZ/kSZ is hidden among many other signals
- tSZ/kSZ not negligible at small scales as Primordial CMB damped

Planck/Large scales



Planck coll. 2013

SPT/small scales



Addison et al. 2012

Slide from Marian Douspis mmUniverse conference

tSZ power spectrum

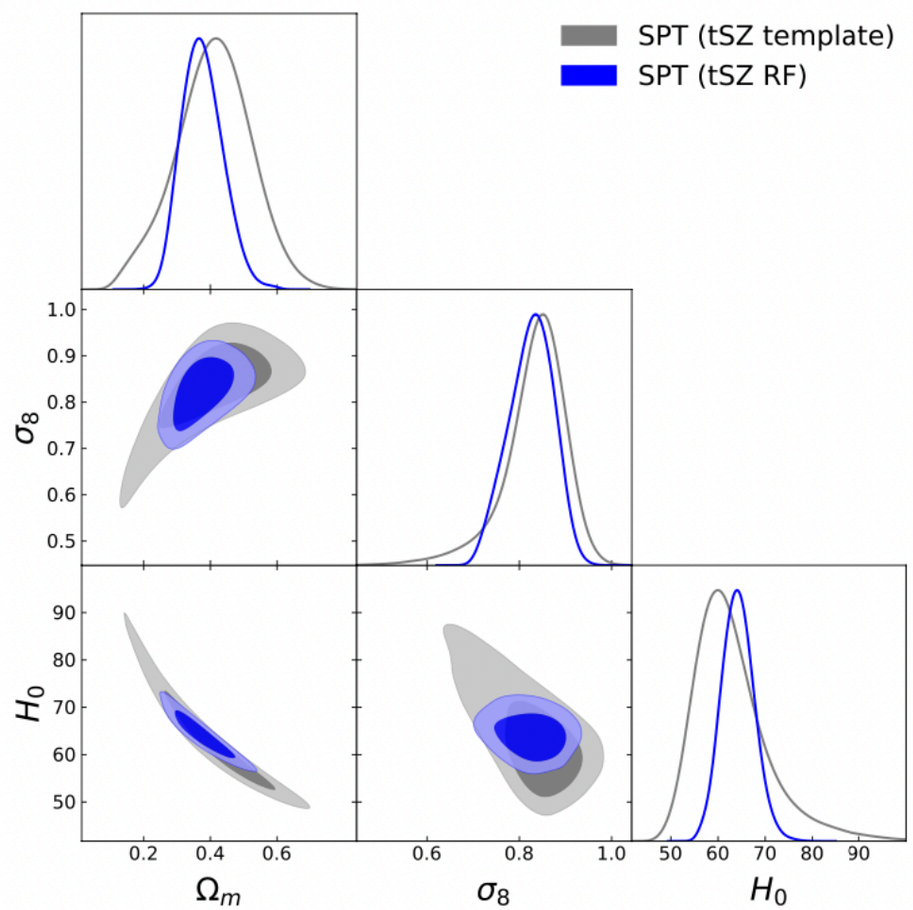
From halo model: $Cls[\Theta] \equiv \iiint dMdz\ dV\ \chi(obs)\ S(obs - M)\ \frac{dN}{dMdz}\ p(M, z)$

Random Forest emulator for tSZ power spectrum Douspis, Salvati et al., A&A 659 (2022) A99

Effect of cosmological information of tSZ

Ω_M
Ω_b
H_0
n_s
σ_8
A_{tSZ}
$Y*$
α
$(1-b)$

+ 6 foreg
+ 4 instrum
prior on $\Omega_b h^2$
prior on n_s
prior on α
prior on $Y*$



Compatibility of results

Better χ^2 with free cosmological parameters:

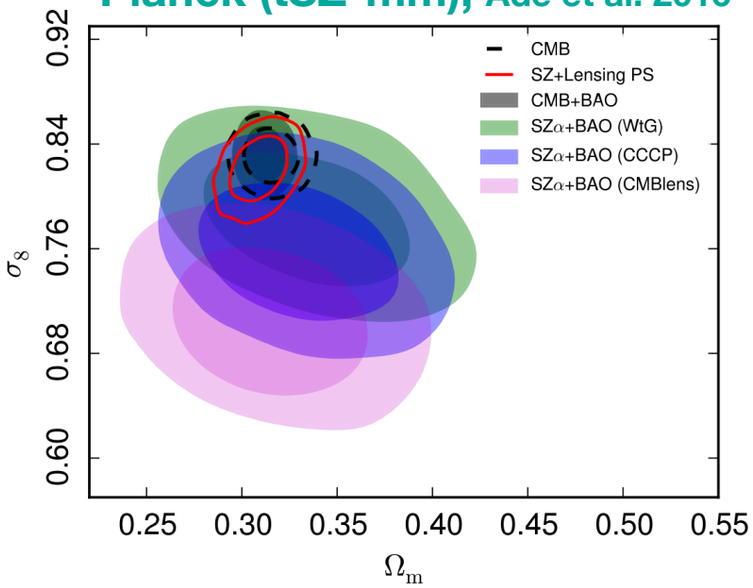
Fixed Cosmo Template	Free Cosmo Template	Free Cosmo RF(Θ)
236	216	215
dof	~dof-3	~dof-3

Stronger constraints on $(\Omega_M,\ \sigma_8)$

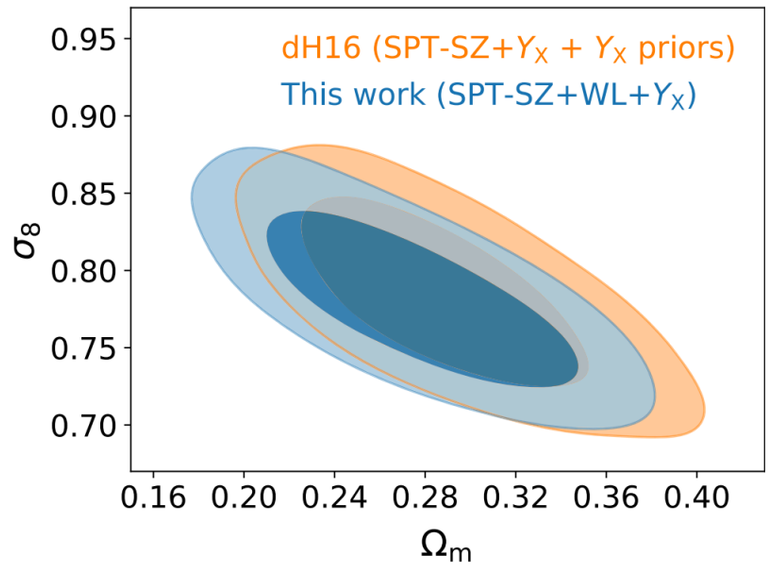
Slide from Marian Douspis
mmUniverse conference

Cluster cosmology

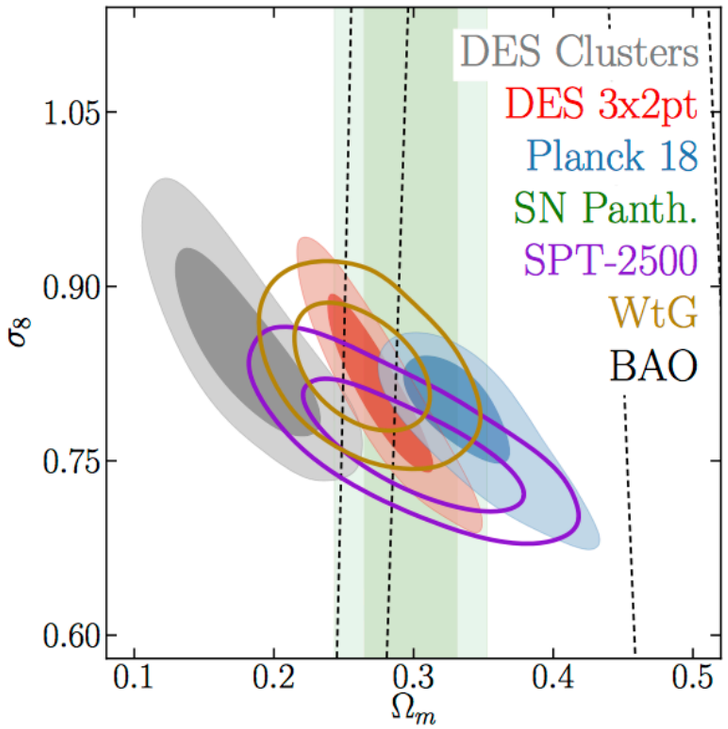
Planck (tSZ-mm), Ade et al. 2016



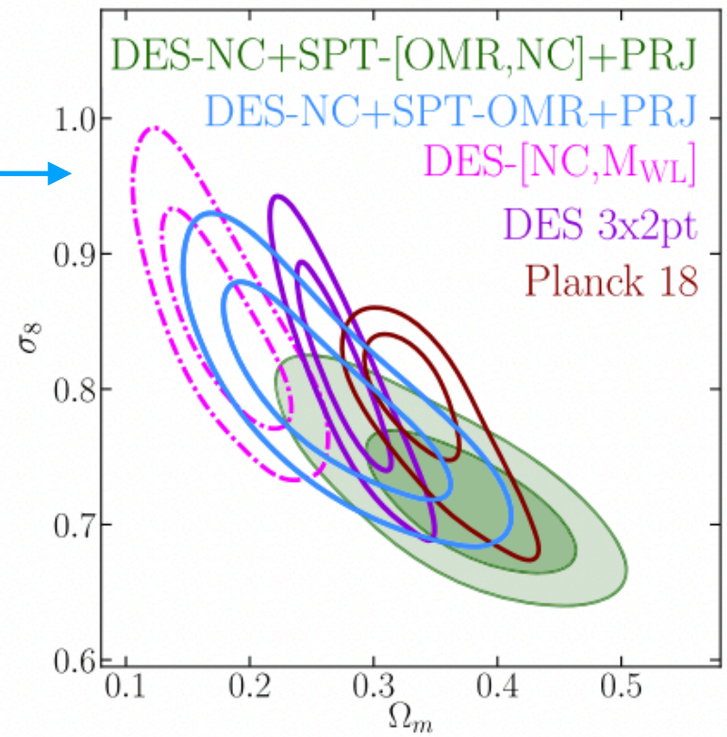
SPT (tSZ-mm), Bocquet et al. 2019



DES (optical), Abbott et al. 2020

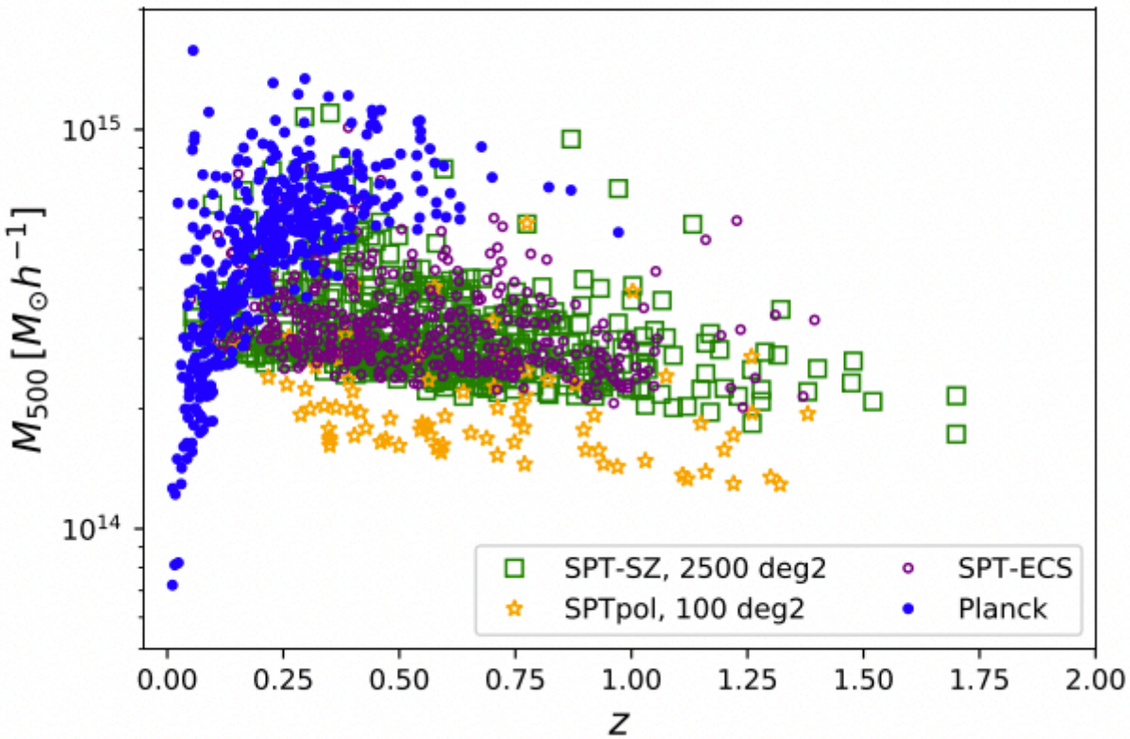


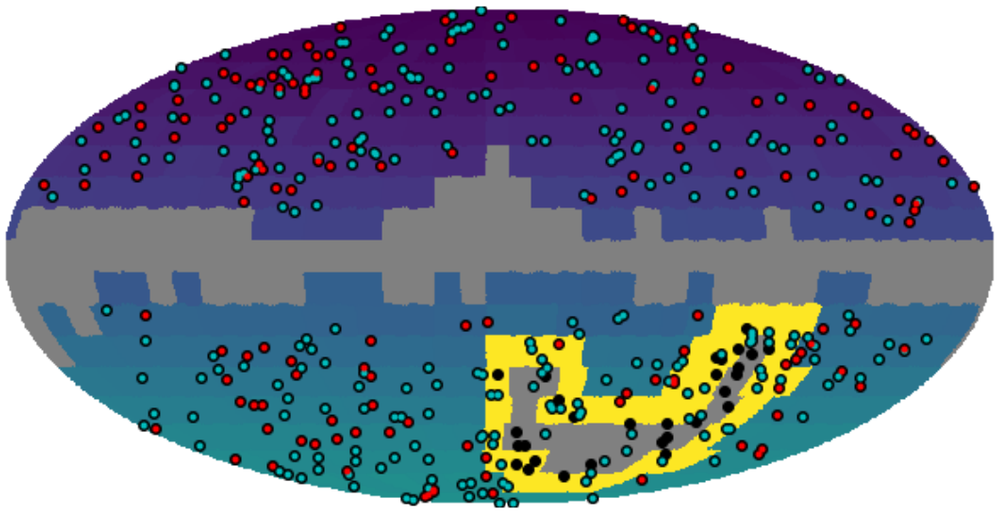
SPT+DES, Costanzi et al. 2021



Planck + SPT

Salvati, Saro + SPT collab.
ApJ 934, no.2, 129 (2022)



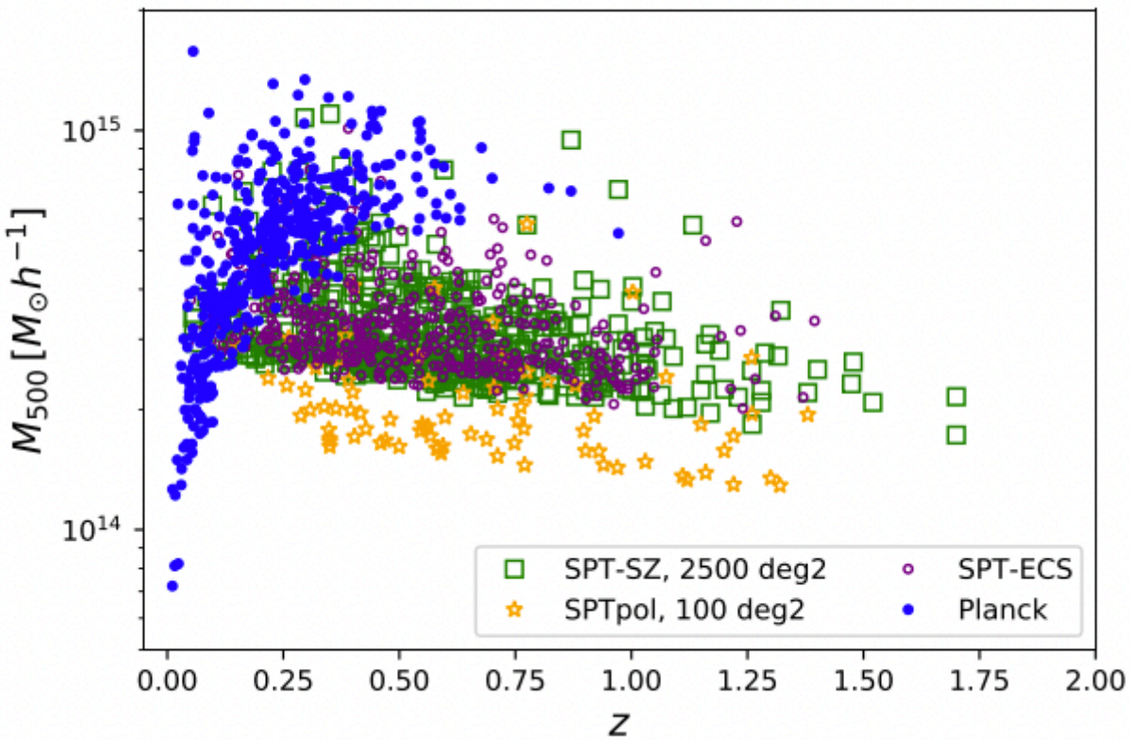


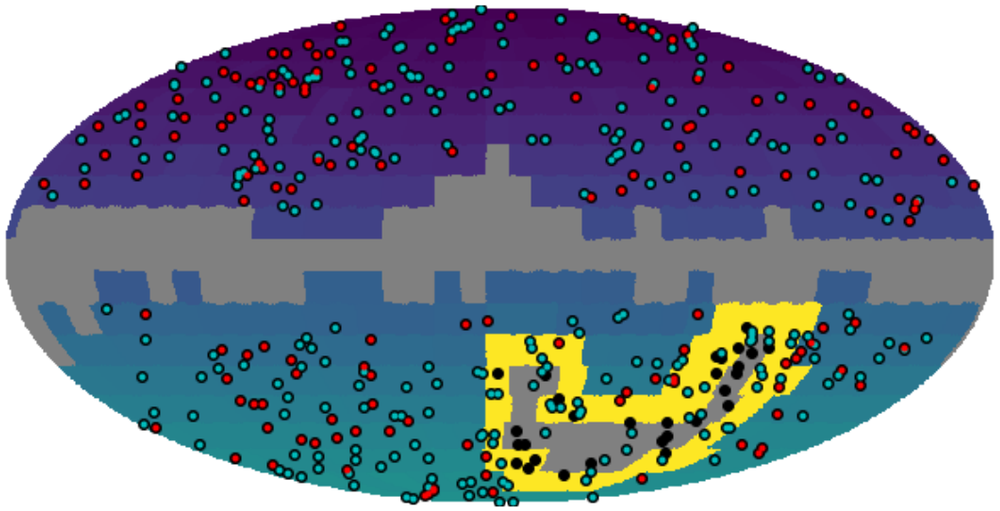
Paper I. Combining Planck and SPT Cluster Catalogs:
Cosmological Analysis and Impact on the Planck Scaling Relation Calibration

- First combined cosmological analysis of Planck and SPT-SZ cluster catalogs
- Independent calibration of Planck scaling relations, exploiting cosmological constraining power of SPT-SZ sample

Planck + SPT

Salvati, Saro + SPT collab.
ApJ 934, no.2, 129 (2022)





Planck

Planck 2015. A&A 594, A24 (2016)
Planck 2015. A&A 594, A27 (2016)

- Survey characteristics:
  - 65% of the sky (~26815 deg2)
  - Frequencies: 100, 143, 217, 353, 545, and 857 GHz (HFI instrument)
  - Resolution: [5',10']
- Cosmological Catalog
  - 439 clusters
  - z = [0,1]
- Cluster extraction: Matched Multi-filters approach
  - Arnaud profile
- EXTERNAL Mass calibration
  - X-ray and WL observations

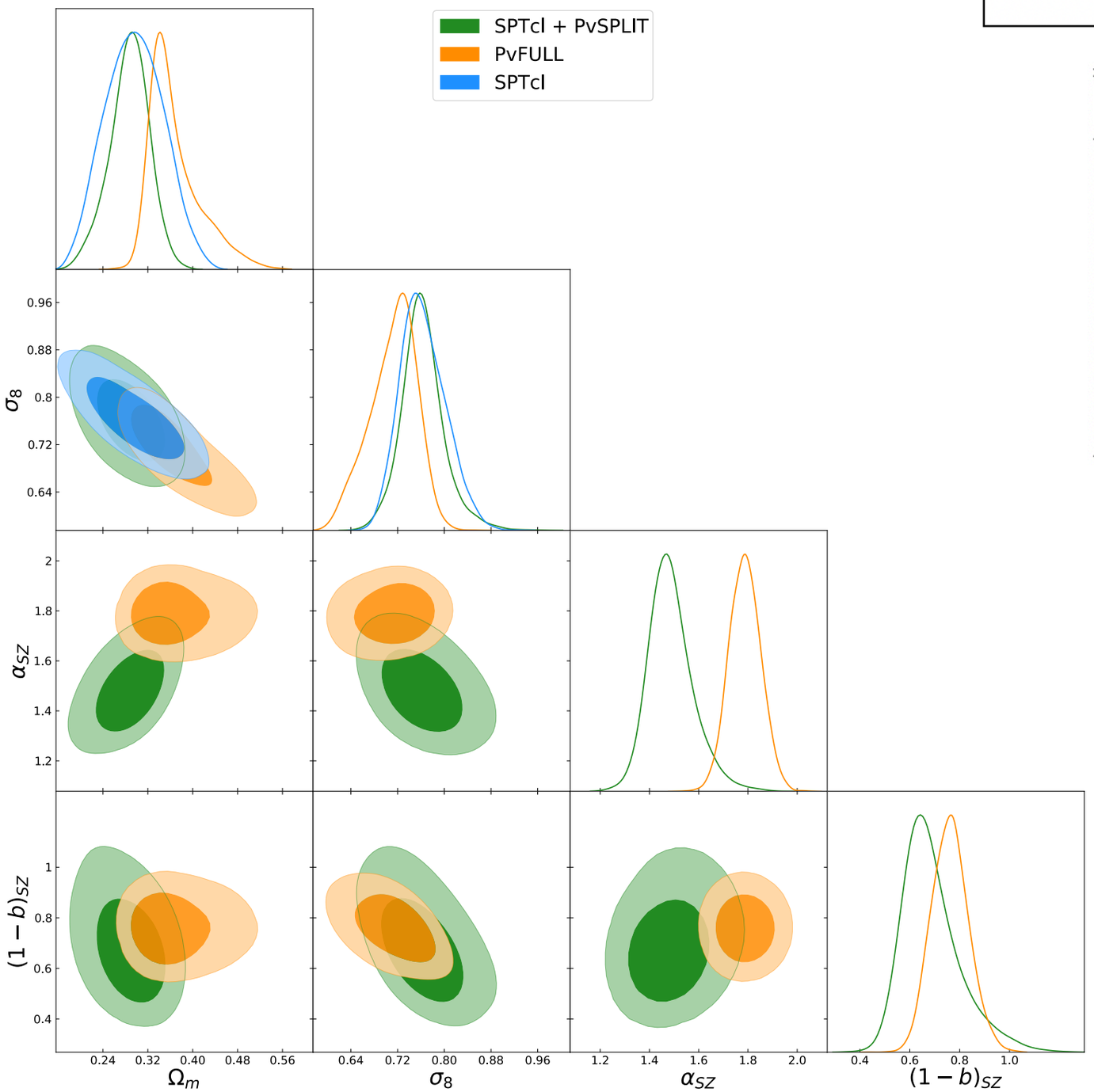
SPT-SZ

SPT. Bleem at al., APJ Suppl. 216 (2015) no.2, 27
SPT. Bocquet et al., APJ 878 (2019) no.1, 55

- Survey characteristics:
  - 2500 deg2 area
  - Frequencies: 95, 150 GHz
  - Resolution: ~ 1'
- Cosmological catalog
  - 365 clusters
  - z = [0.25,1.7]
- Cluster extraction: Matched Multi-filters approach
  - Beta profile
- INTERNAL Mass calibration
  - X-ray and WL observations
  - empirical, multi-observable approach

Planck + SPT

Salvati, Saro + SPT collab.
ApJ 934, no.2, 129 (2022)



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

$\nu\Lambda$CDM			
	SPTcl + PvSPLIT	PvFULL	SPTcl
Ω_m	$0.29^{+0.04}_{-0.03}$	$0.37^{+0.02}_{-0.06}$	0.30 ± 0.03
σ_8	$0.76^{+0.03}_{-0.04}$	$0.71^{+0.05}_{-0.03}$	$0.76^{+0.03}_{-0.04}$
$\alpha_{\rm SZ}$	$1.49^{+0.07}_{-0.10}$	1.79 ± 0.06	–
$(1-b)_{\rm SZ}$	$0.69^{+0.07}_{-0.14}$	$0.76^{+0.07}_{-0.08}$	–

Parameter	Value
$\log Y_{*,{\rm SZ}}$	-0.19 ± 0.02
$\alpha_{\rm SZ}$	1.79 ± 0.08
$\beta_{\rm SZ}$	0.66
$\sigma^a_{\ln Y_{\rm SZ}}$	0.173 ± 0.023
$(1-b)_{\rm SZ}$	0.780 ± 0.092

Parameter	Value
$\log Y_{*,{\rm SZ}}$	-0.19 ± 0.02
$\beta_{\rm SZ}$	0.66
$\sigma^a_{\ln Y_{\rm SZ}}$	0.173 ± 0.023

Planck + SPT

Salvati, Saro + SPT collab.
ApJ 934, no.2, 129 (2022)

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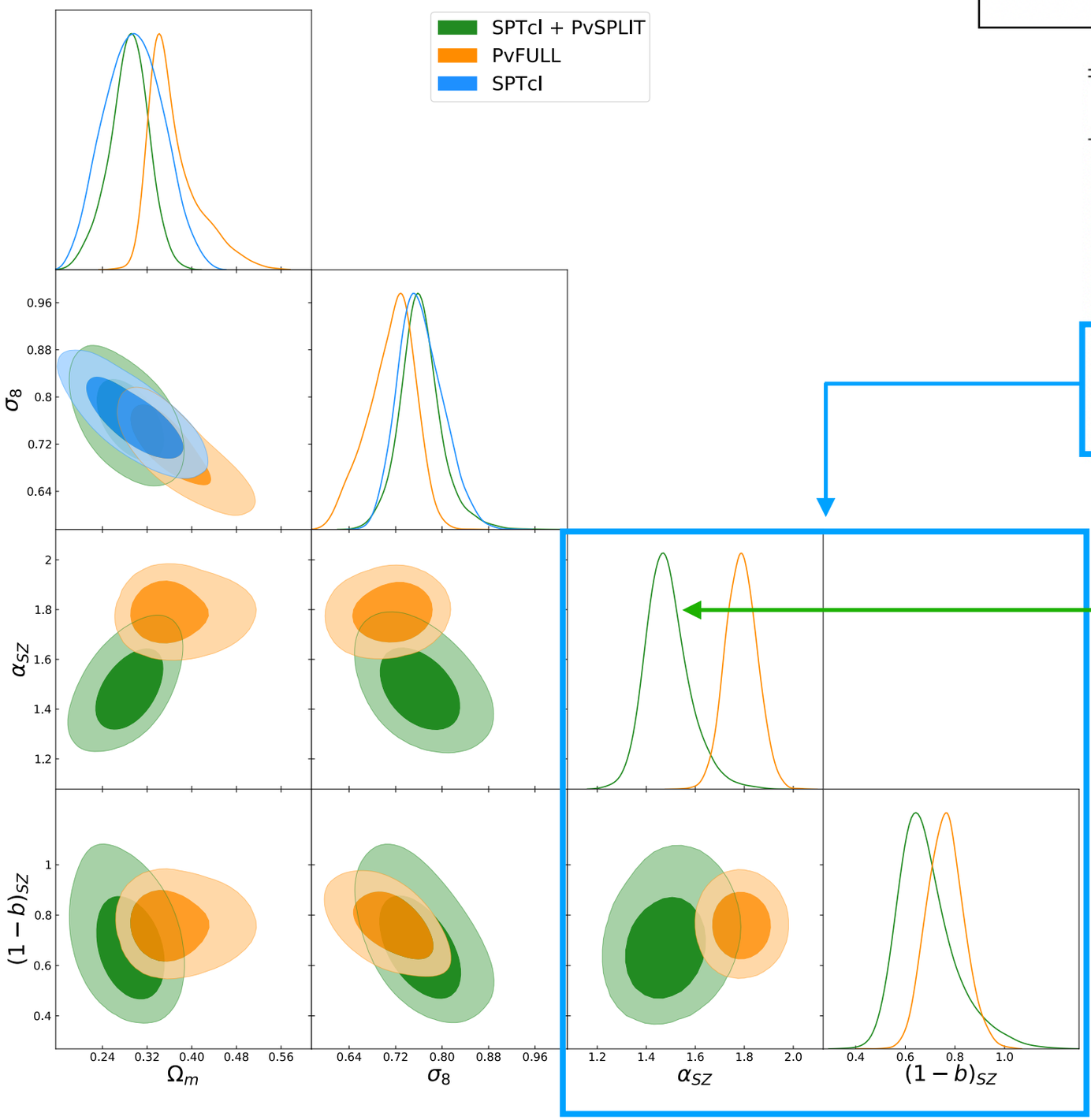

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lower value of Ω_m

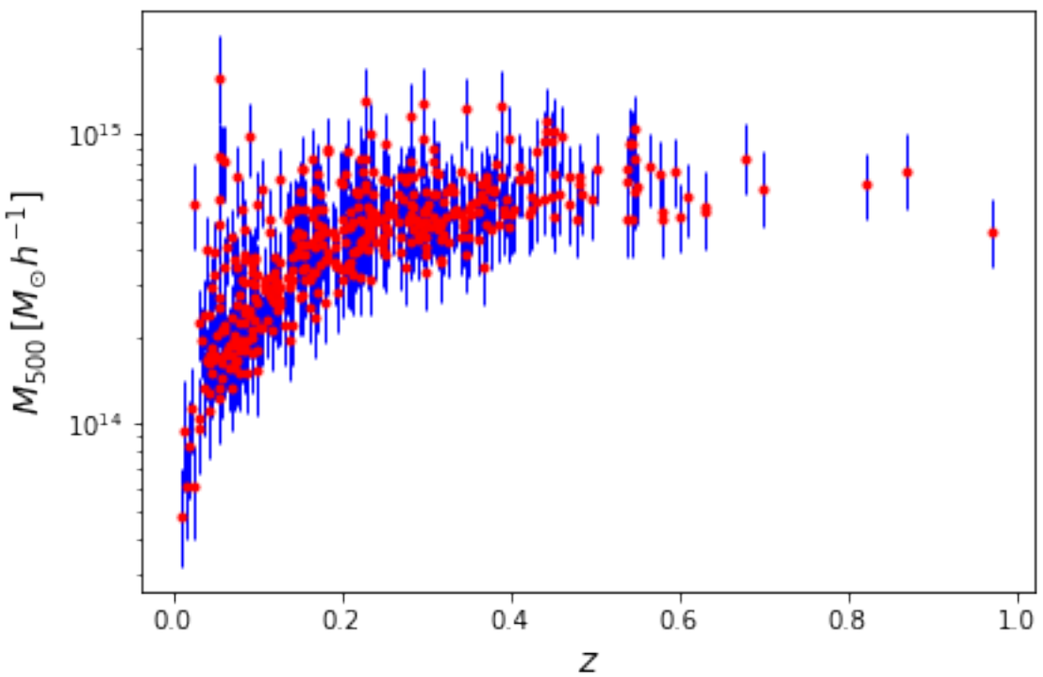
- tilt in the HMF (accounting for less objects at lowM)
- accomodate for this tilt (balancing highM - lowM)

Planck + SPT

Salvati, Saro + SPT collab.
ApJ 934, no.2, 129 (2022)

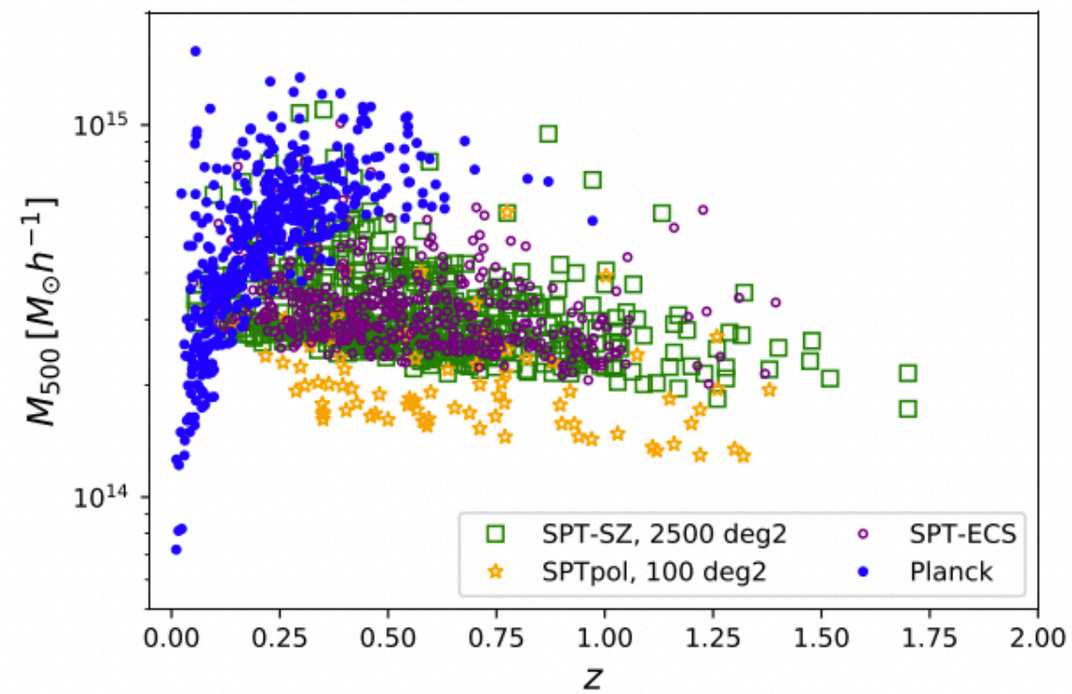
Released Catalogs

https://pole.uchicago.edu/public/data/sptplanck_cluster/



Cluster masses M_{500}

- marginalising over cosmological and scaling relation parameters



Cluster masses M_{500}

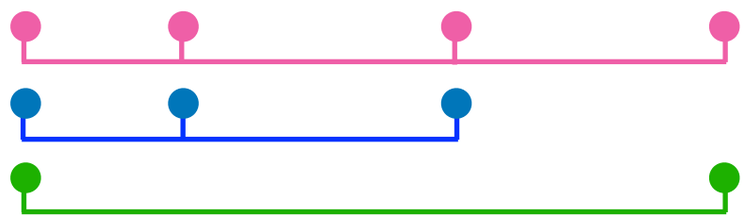
- fixed values of cosmological and scaling relation parameters

Planck + SPT

Salvati, Saro + SPT collab.
ApJ 934, no.2, 129 (2022)

$$(1-b)_M = \frac{M_{\rm SZ}}{M_{500}}$$

$$(1-b)_M = \mathrm{Amp} \cdot \left(\frac{M_{500}}{M_*}\right)^{\gamma_M} \cdot \left(\frac{1+z}{1+z_*}\right)^{\gamma_z} \cdot \left(\frac{\sigma_f(\theta)}{\bar{\sigma_f}(\theta)}\right)^{\gamma_n}$$



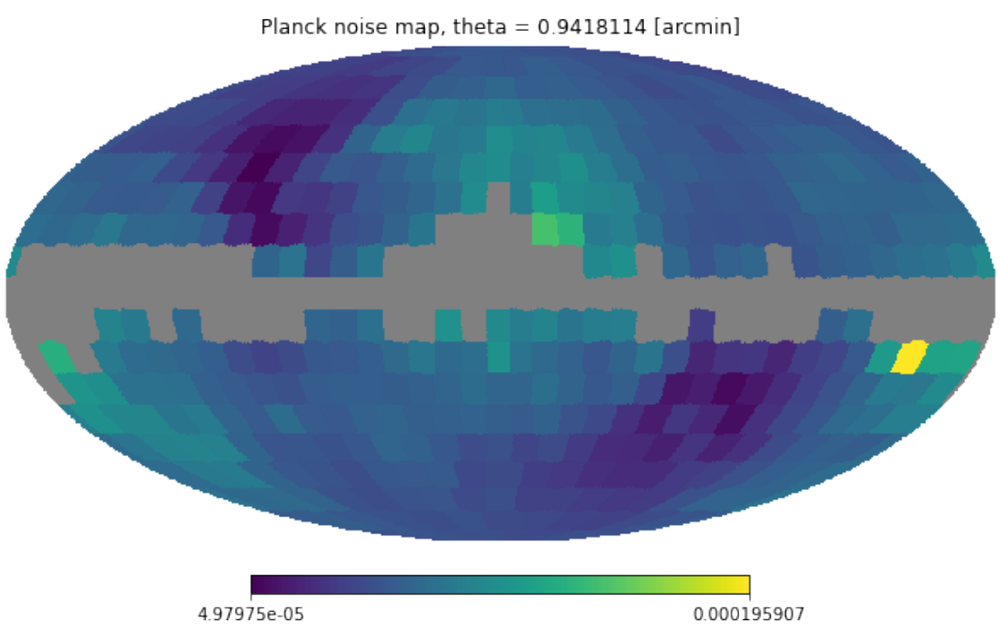
	bias(M,z)	bias(noise)	bias(M,z,noise)
Amp	$0.69^{+0.05}_{-0.10}$	$0.60^{+0.06}_{-0.14}$	$0.69^{+0.04}_{-0.09}$
γ_M	$-0.40^{+0.04}_{-0.06}$	-	$-0.41^{+0.04}_{-0.06}$
γ_z	0.74 ± 0.13	-	0.81 ± 0.13
γ_n	-	$-0.37^{+0.14}_{-0.12}$	$0.05^{+0.06}_{-0.08}$

Increasing trend for high-z and low-M

Increasing trend for high-z and low-M

Mass estimation in patches with higher noise are more biased (possibly due to a loss in tSZ signal)

Systematic related to cluster detection



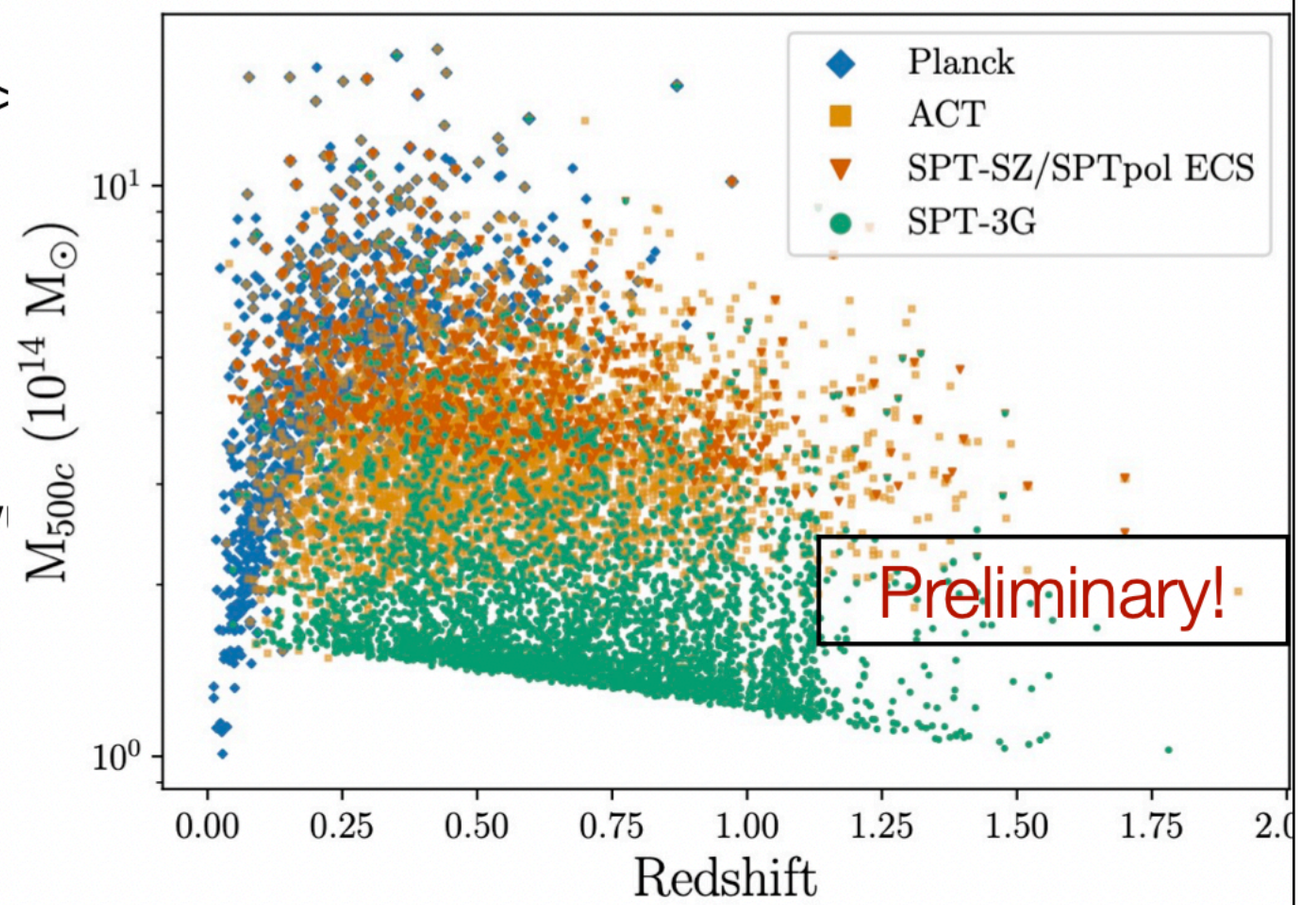
The SPT-3G SZ Catalog

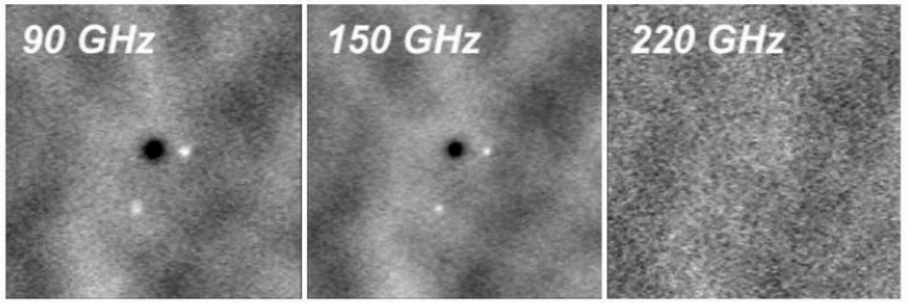
- First catalog being produced from 2019-2020 data

- Preliminary cluster run has produced a catalog with 2457 cluster candidates at xi> (>99% purity)

- 5891 candidates at 3.85 < xi < **130.2**(!)

- Candidates screened through DES, promising targets flagged for additional followup. A total of 12 nights of NIR follow with Magellan/FourStar of SPTpol 500d/ SPT-3G cluster candidates has resulted in 124 SPT-3G cluster candidates with NIR imaging [2 more nights coming this July!], analysis of these systems is ongoing





SPT-CL J2344-4243 (Phoenix Cluster, z=0.6) see in SPT-3G data at S/N>120

Slide from Lindsey Bleem mmUniverse conference

Forecasts: impact of HMF

Salvati+
A&A 643, A20 (2020)

Experiments

- **Euclid-like**
  survey area: 15000 deg2
  z = [0.1,1.9]
- **LSST-like**
  survey area: 18000 deg2
  z = [0.1,1.4]
- **WFIRST-like**
  survey area: 2400 deg2
  z = [0.1,2.0]

Scaling Relations

$$x(M_{200}^{\rm ob}) = \frac{\ln M_{200}^{\rm ob} - \ln M_{\rm bias} - \ln M_{200}}{\sqrt{2\sigma^2_{\ln M_{200}}}}$$

$$\ln M_{\rm bias}(z) = B_{M,0} + \alpha \ln(1+z)$$

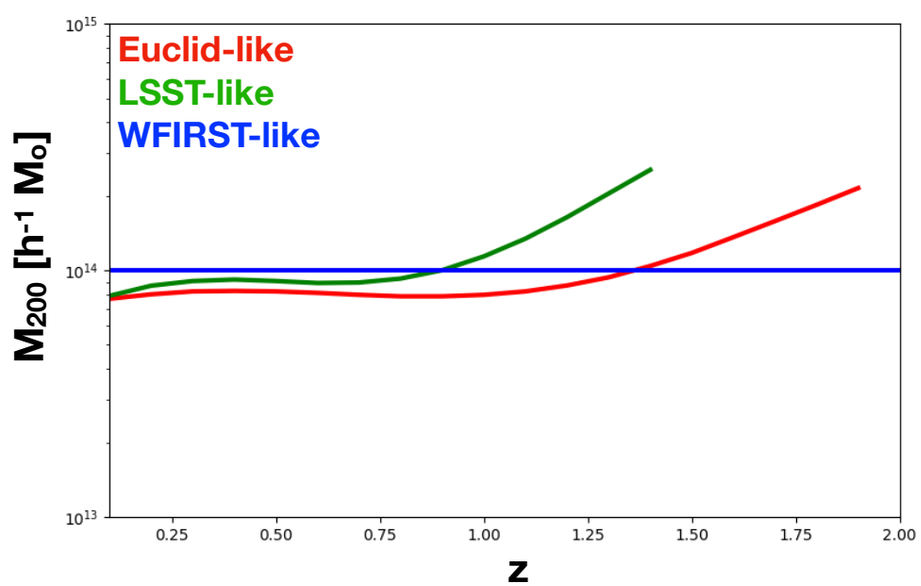
$$\sigma^2_{\ln M}(z) = \sigma^2_{\ln M,0} - 1 + (1+z)^{2\beta}$$

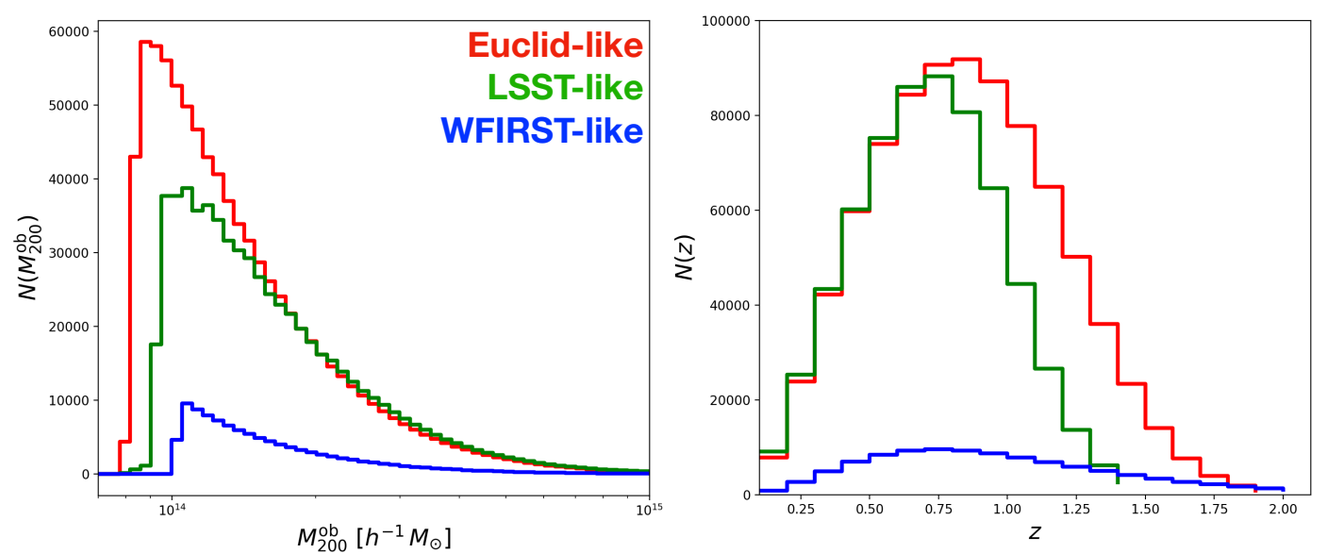
Mass Function

- **Tinker et al. 2008 (T08)**
- **Despali et al. 2016 (D16)**

Ascaso et al. 2017
Gehrels et al. 2015
Sartoris et al. 2016

Selection Function





Forecasts: impact of HMF

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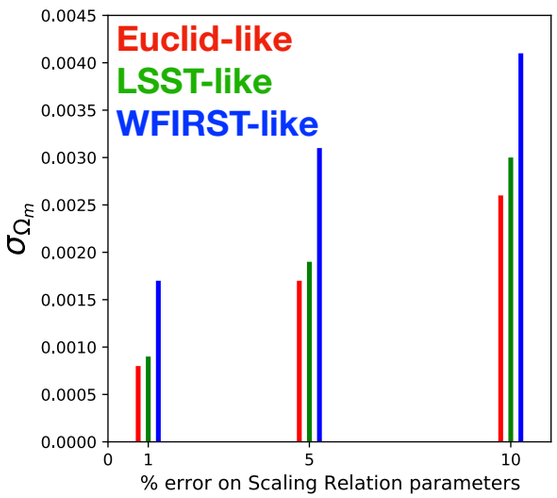
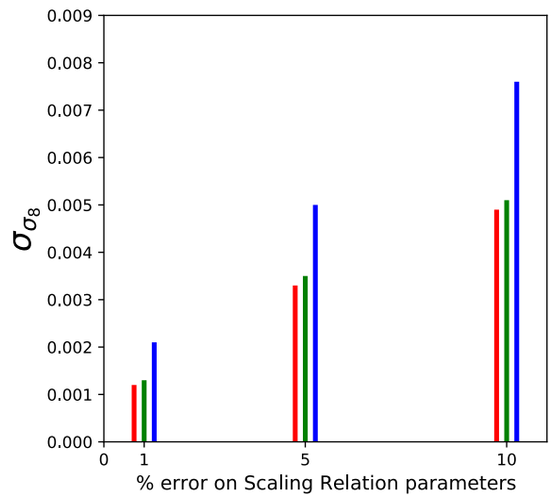
A&A 643, A20 (2020)

Impact of survey area and SR accuracy





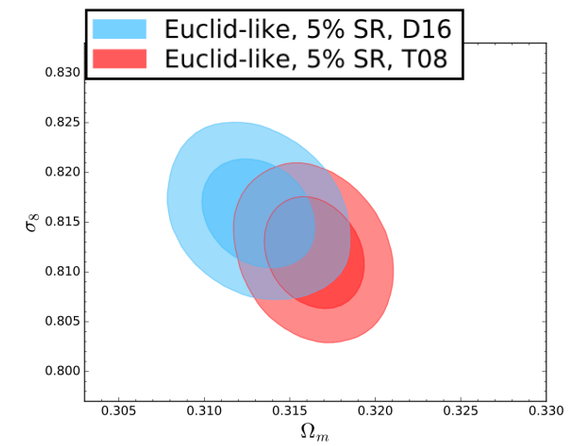
Increasing accuracy on cosmological parameters

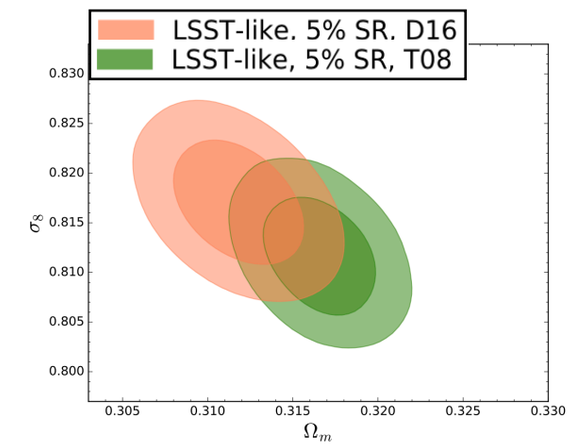
- Larger survey area: larger cluster sample
- More accurate calibration for SR

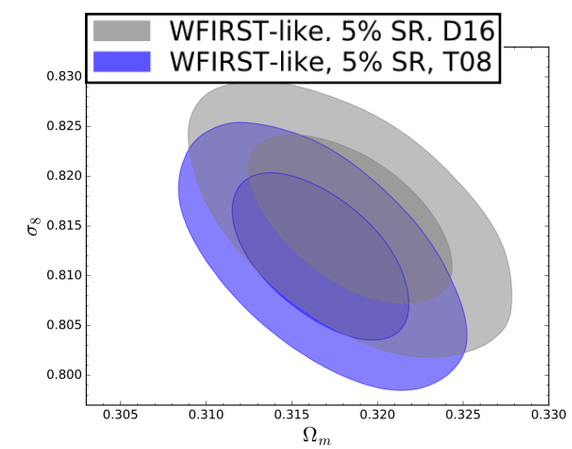
Planck results:
$\sigma_{\sigma_8} = 0.03, \ \sigma_{\Omega_m} = 0.03$

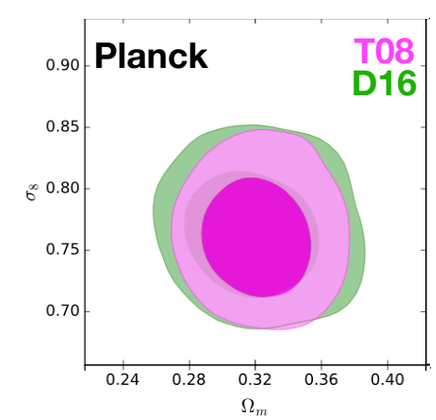
Impact of Mass Function

NON NEGLIGIBLE!









Forecasts: impact of HMF

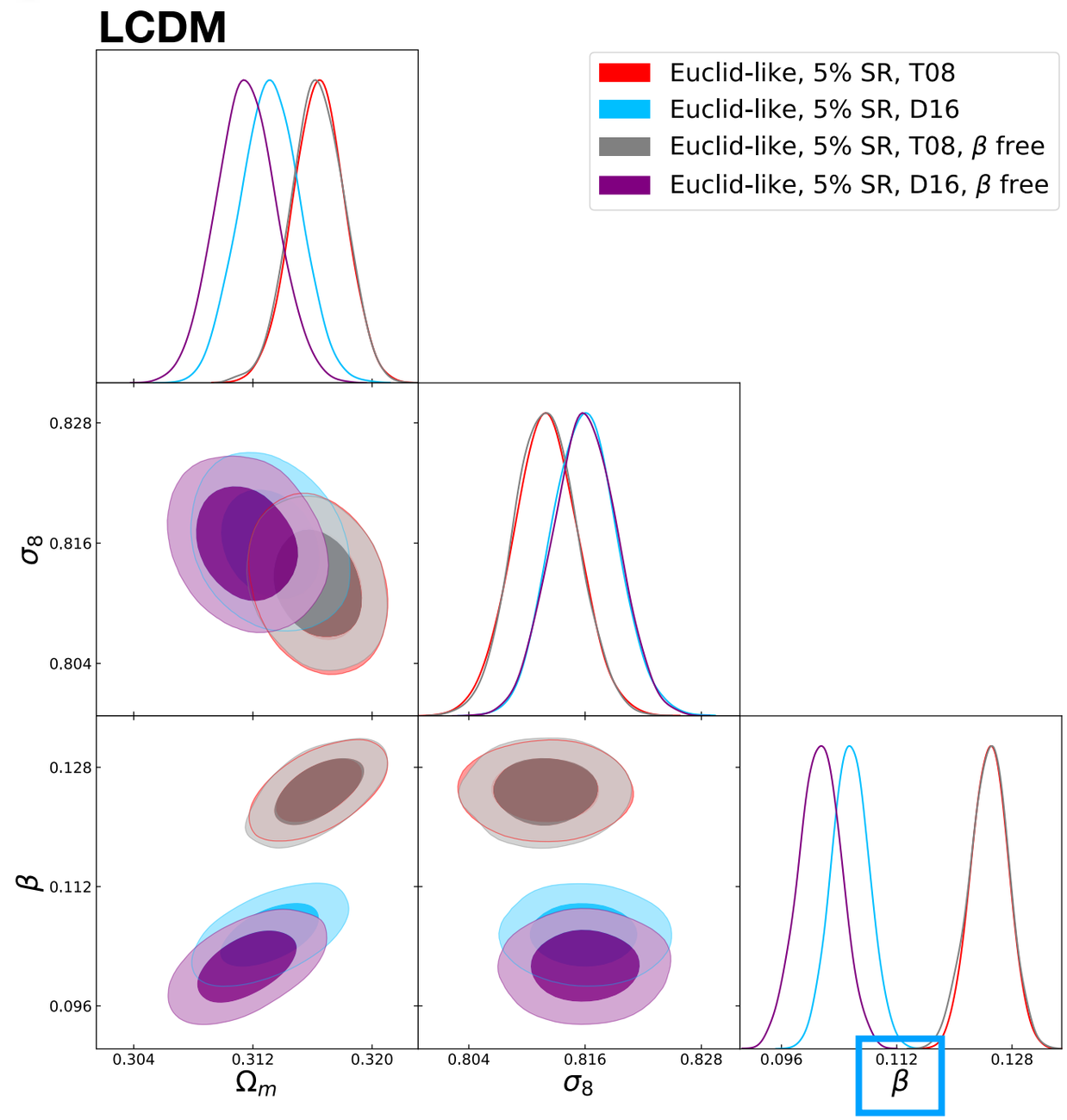
Salvati+
A&A 643, A20 (2020)

Evidence for different z-evolution for T08 and D16

D16 vs T08

- Consistent in the intermediate mass range
- D16 predicts more clusters at high z
- Compensating for different z-evolution

$\beta_{\rm D16} < \beta_{\rm T08}$



z-evolution of the scatter

$$\sigma^2_{\ln M}(z) = \sigma^2_{\ln M,0} - 1 + (1+z)^{2\beta}$$

Forecasts: impact of HMF

Salvati+
A&A 643, A20 (2020)

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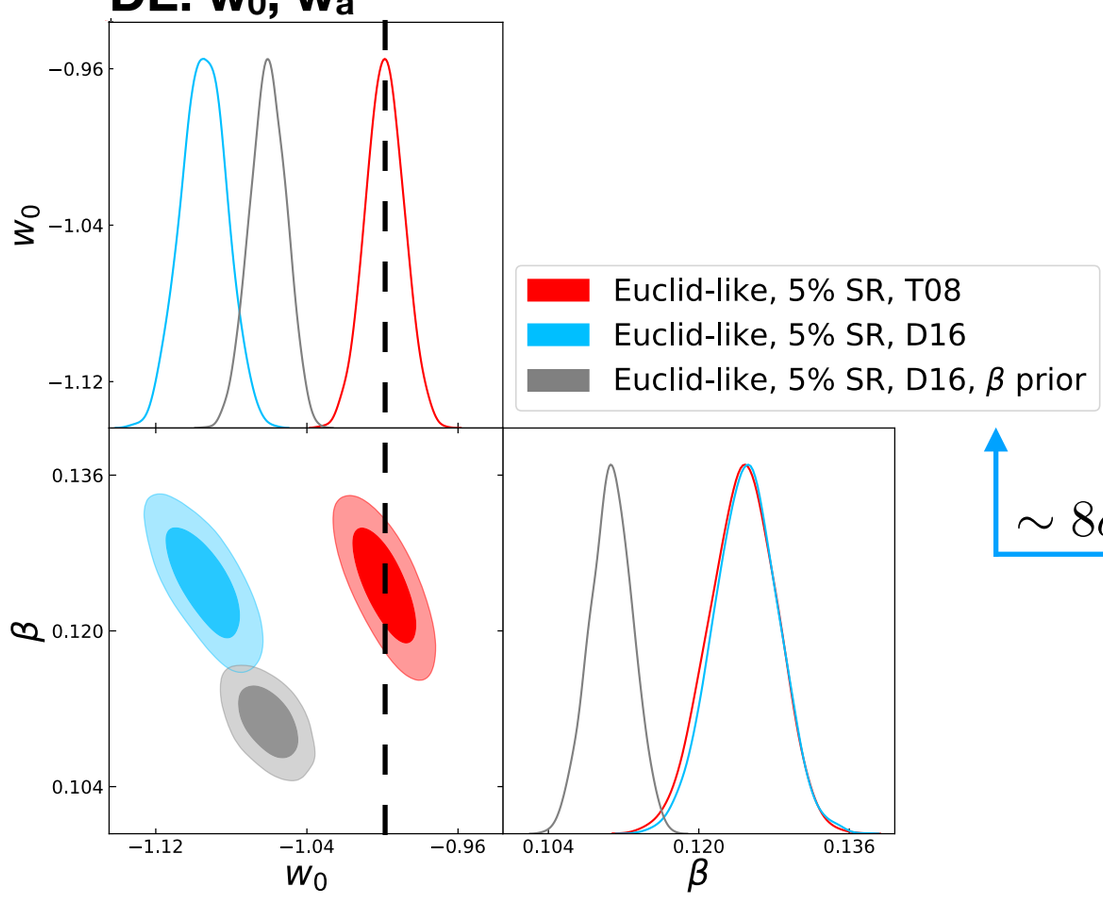
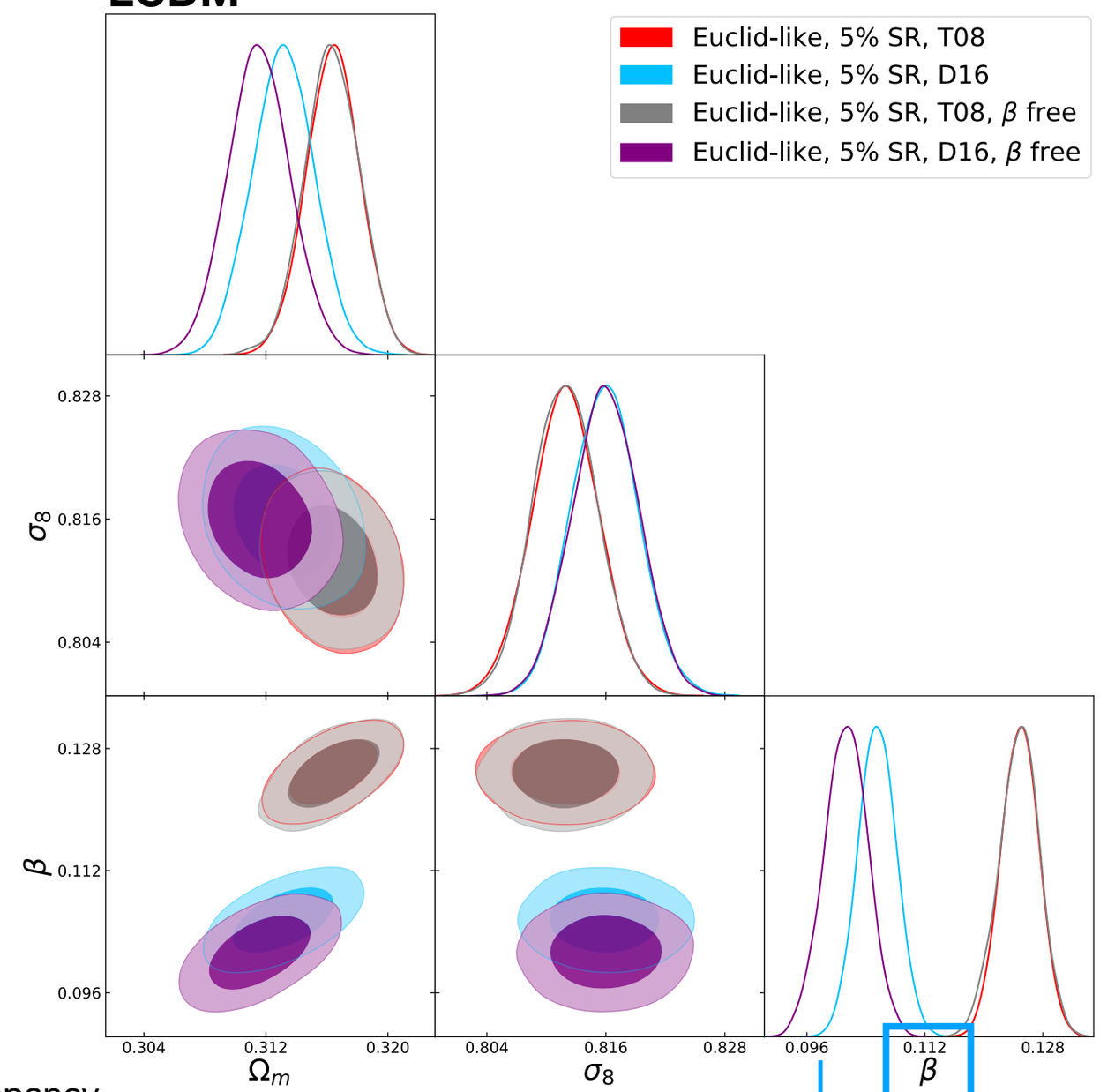
DE: w_0, w_a



LCDM



$\sim 8\sigma$ discrepancy

z-evolution of the scatter

$$\sigma^2_{\ln M}(z) = \sigma^2_{\ln M,0} - 1 + (1+z)^{2\beta}$$

Conclusions

- Planck cluster cosmology affected by modelling of
  - Mass calibration
  - Selection function (?)
- tSZ power spectrum
  - Independent information but low constraining power
- Upcoming/future results
  - What will be main systematics?
  - Calibration of HMF?
- Impact of other SZ effects (relativistic SZ, kinetic SZ) on SZ detection? (from Jean-Baptiste talk)