SZ(=Sunyaev-Zeldovich) selection

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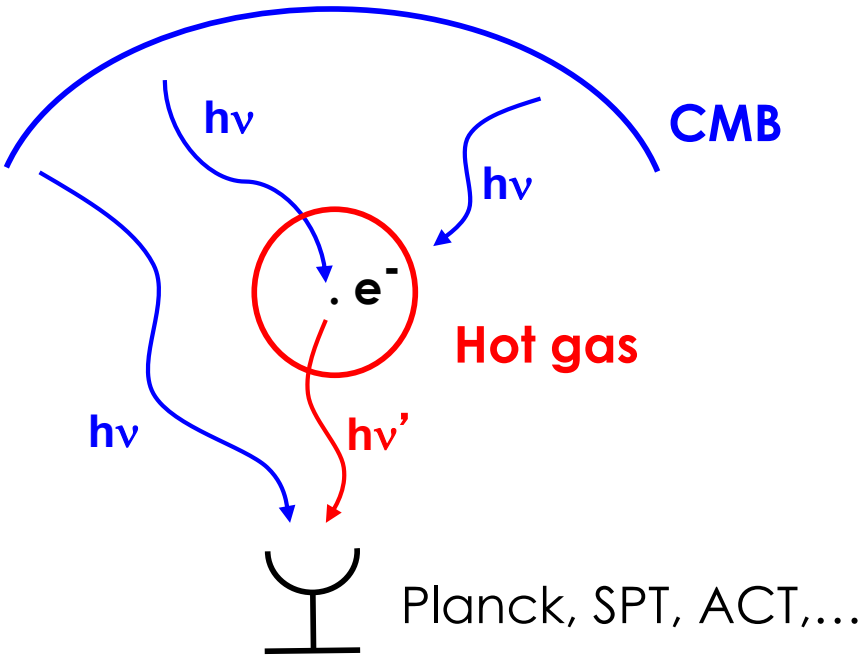
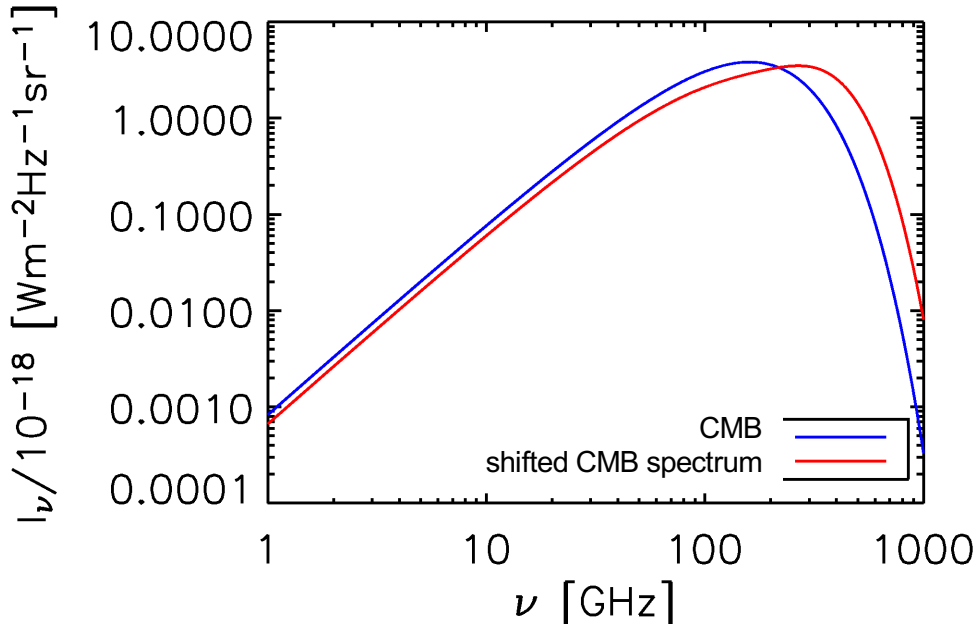
Paris-Saclay

The Sunyaev-Zeldovich (SZ) effect

Detecting the hot gas in halos with the SZ effect

Sunyaev & Zeldovich 1970, 1972





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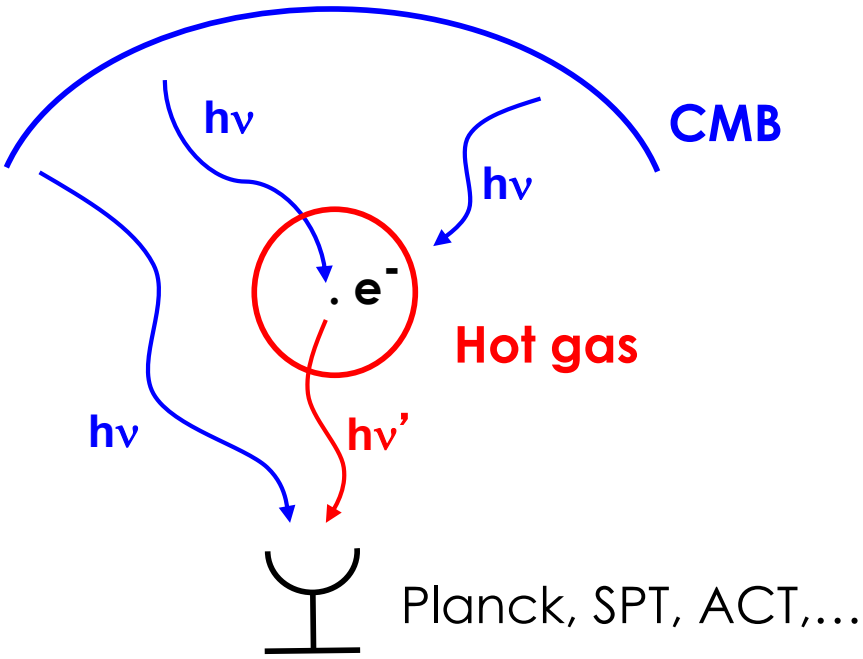
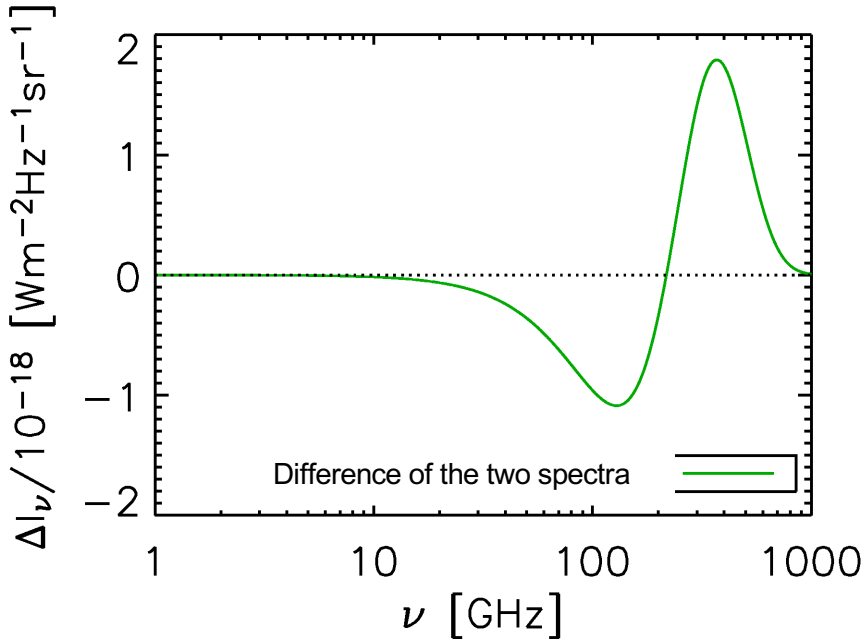
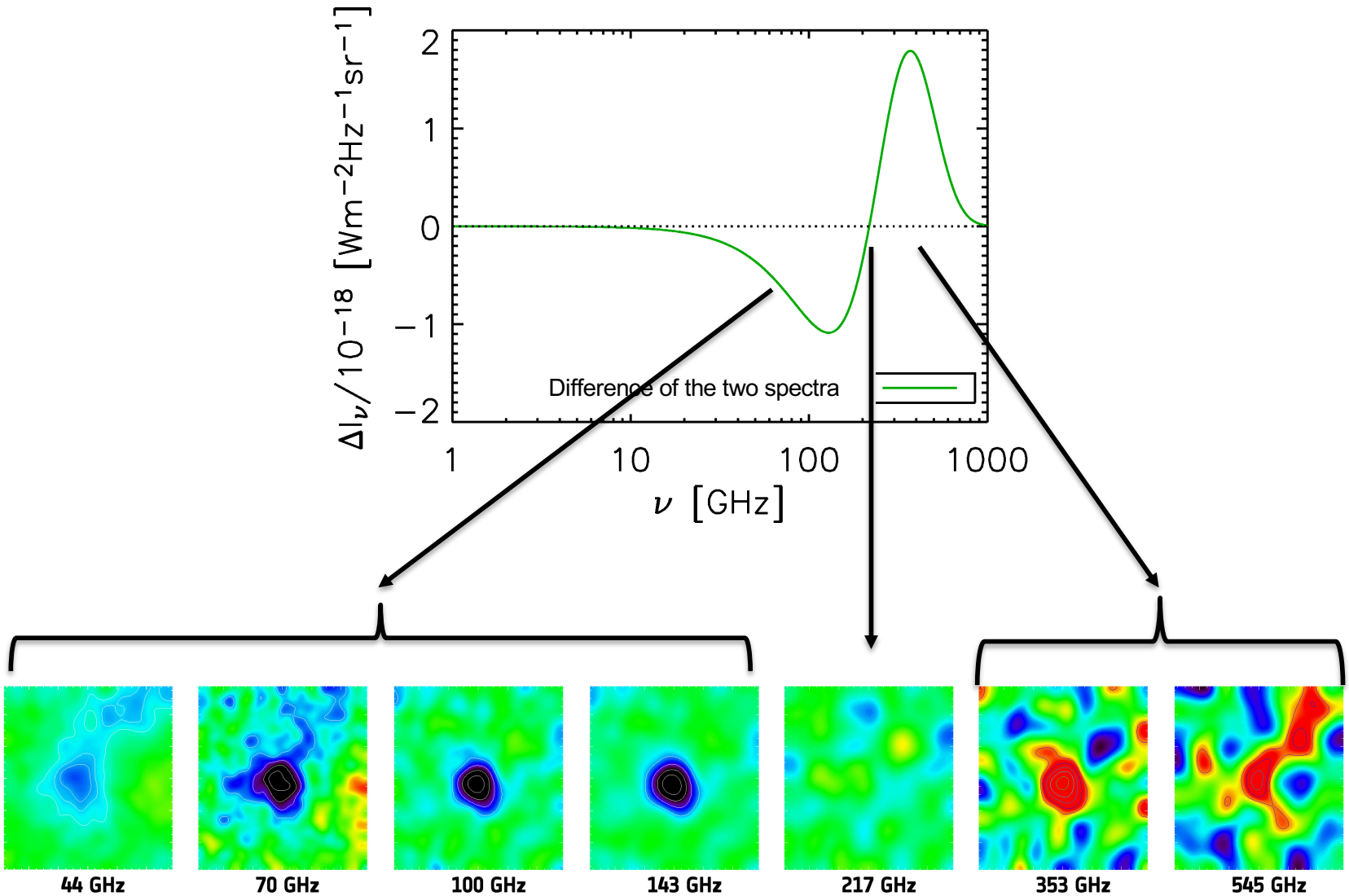




The SZ effect is not a light emitted by the cluster.
It is a modification of the CMB spectrum [=secondary anisotropy]

⇒ **UNIQUE** properties

Abell 2319 as seen by Planck



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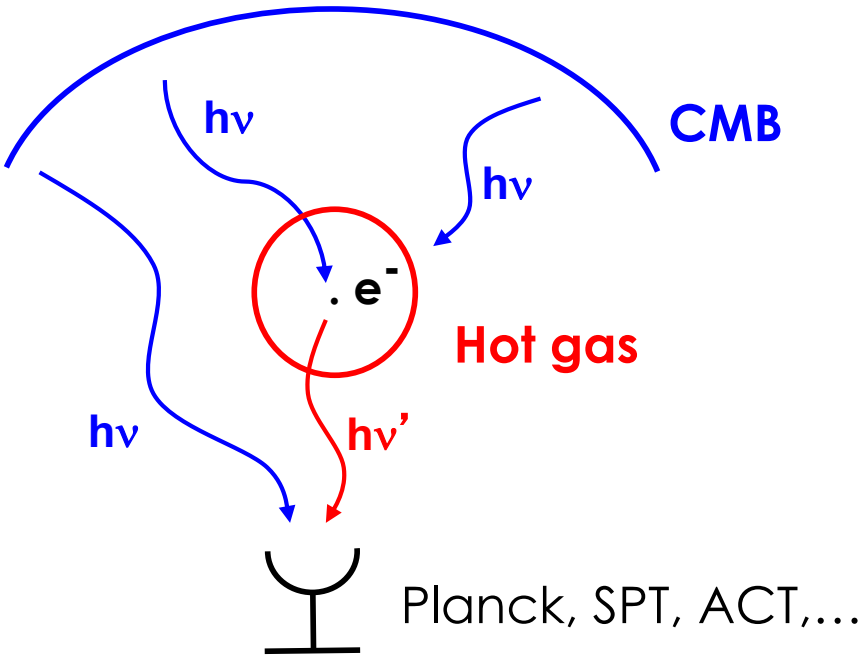
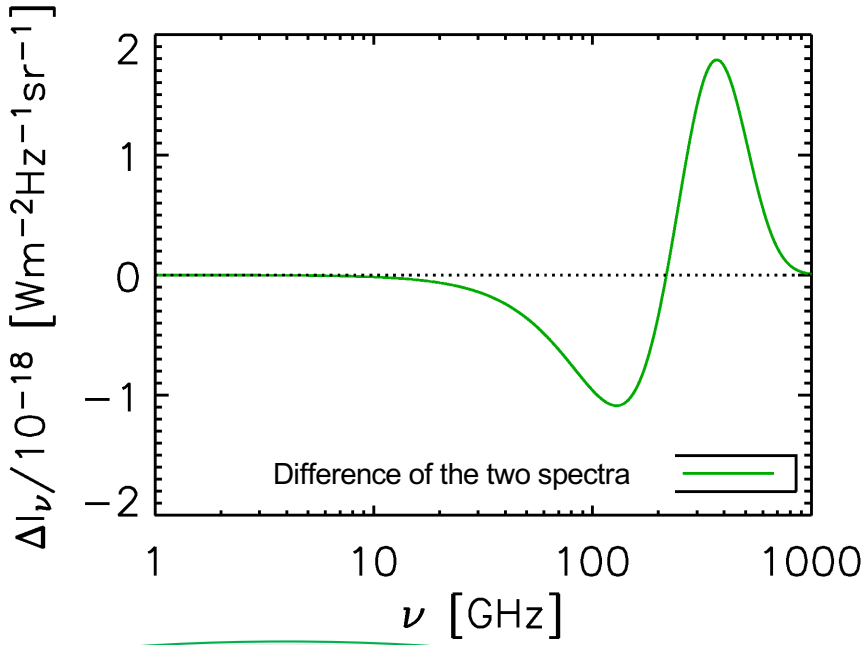


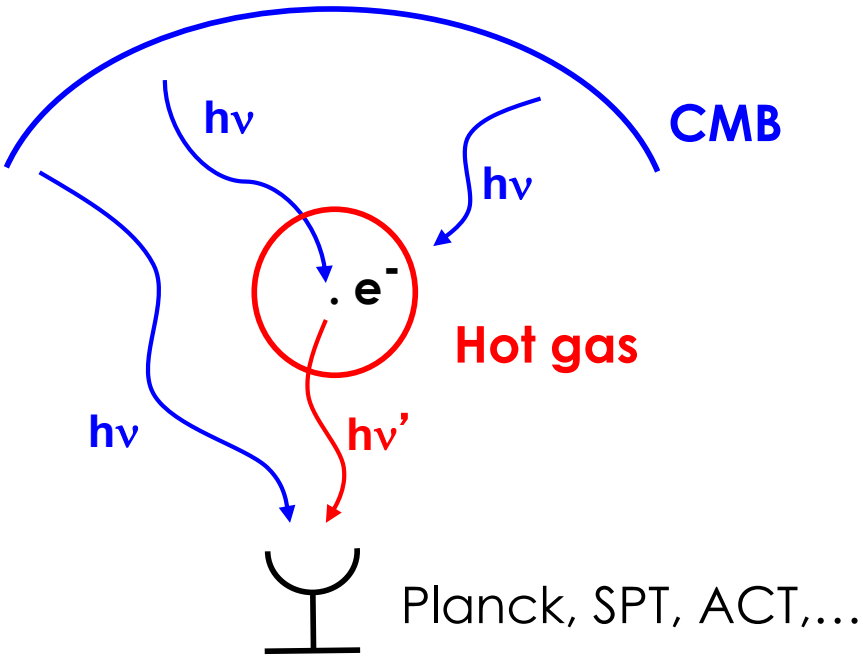


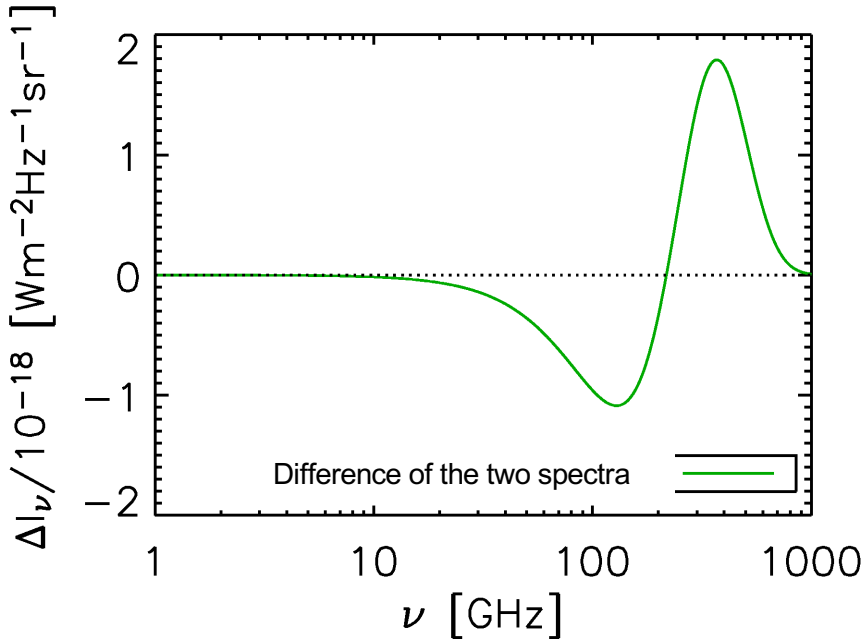
⇒ UNIQUE properties

- universal spectrum (~independent of cluster)
- no redshift dimming

Detecting the hot gas in halos with the SZ effect

Sunyaev & Zeldovich 1970, 1972





⇒ UNIQUE properties

- universal spectrum (~independent of cluster)
- no redshift dimming
- amplitude closely related to the total mass

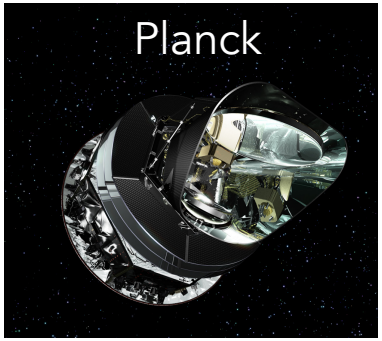
Amplitude depends on $$Y \propto \int P_e dl d\Omega$$

$$\sim M_g T$$

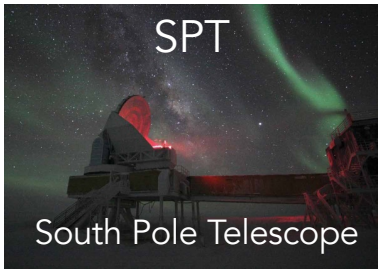
Some current and former SZ instruments

Survey

Large sky fraction
Moderate resolution
fwhm~1-5 arcmin



Credit: ESA



Credit: SPT, K. Vanderlinde

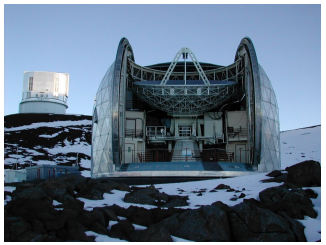
Credit: ACT

Pointed

Small field of view
Moderate to high resolution
fwhm~1 arcsec-1 arcmin

Credit: GBT

Credit: IRAM


Credit: CSO

Credit: AMI

Credit: ALMA

Mustang, NIKA2, Bolocam, AMI, CARMA, ALMA, etc.

Some current and former SZ instruments

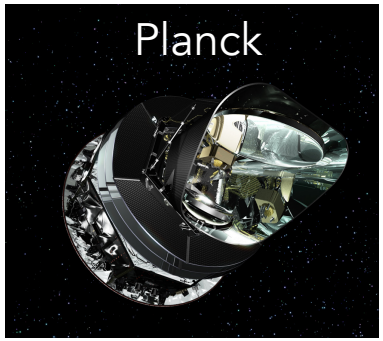
Space

Large frequency coverage (all ν)

No filter transfer function

Low spatial resolution (mirror)

Limited sensitivity



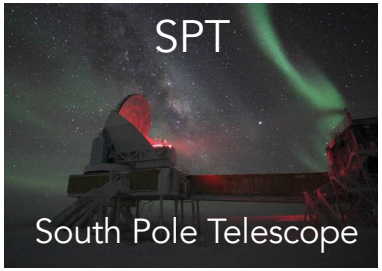
Ground

Restricted frequency coverage (ν<300GHz)

Filter transfer function (scales> ½ degree)

High spatial resolution (single dish or interferometers)

High sensitivity



...

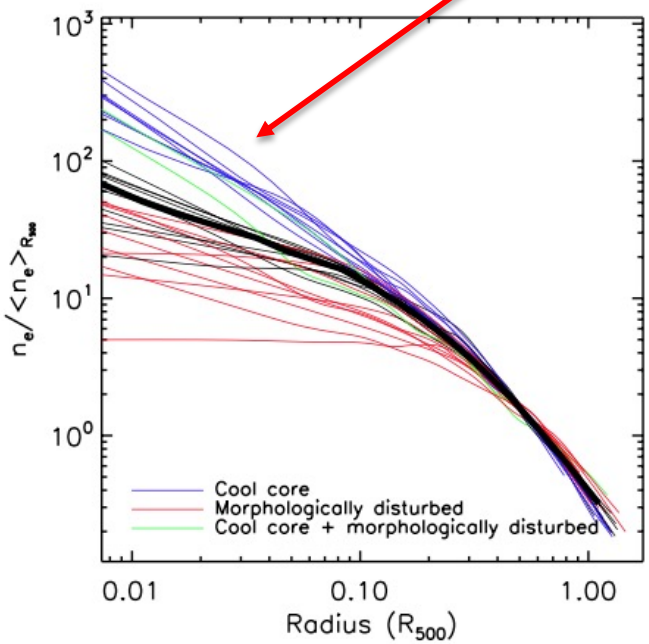
SZ selection properties

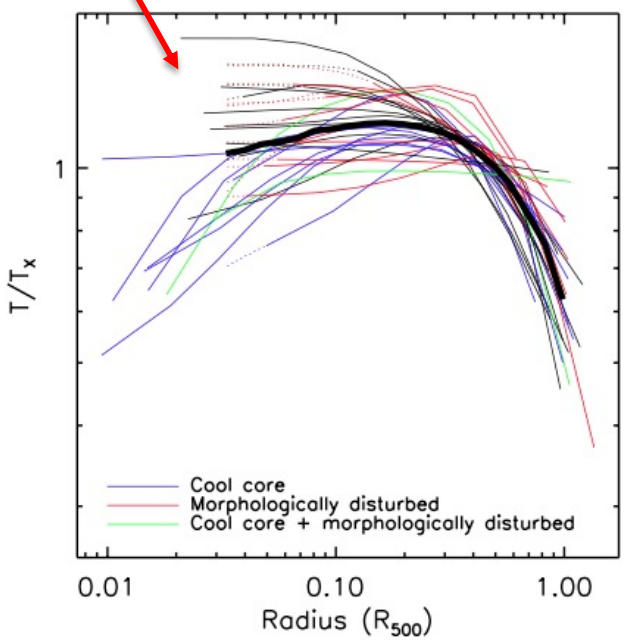
SZ cluster catalogues

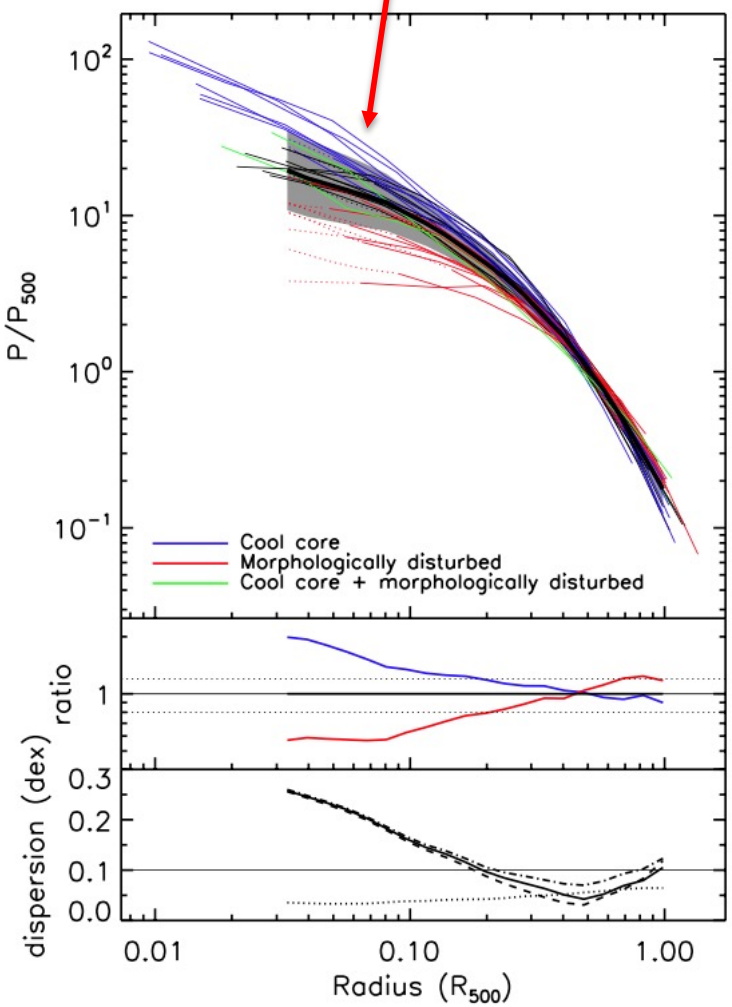
A selection closely related to the mass

Large scatter in the core ($R<0.2R_{500}$)

Low scatter





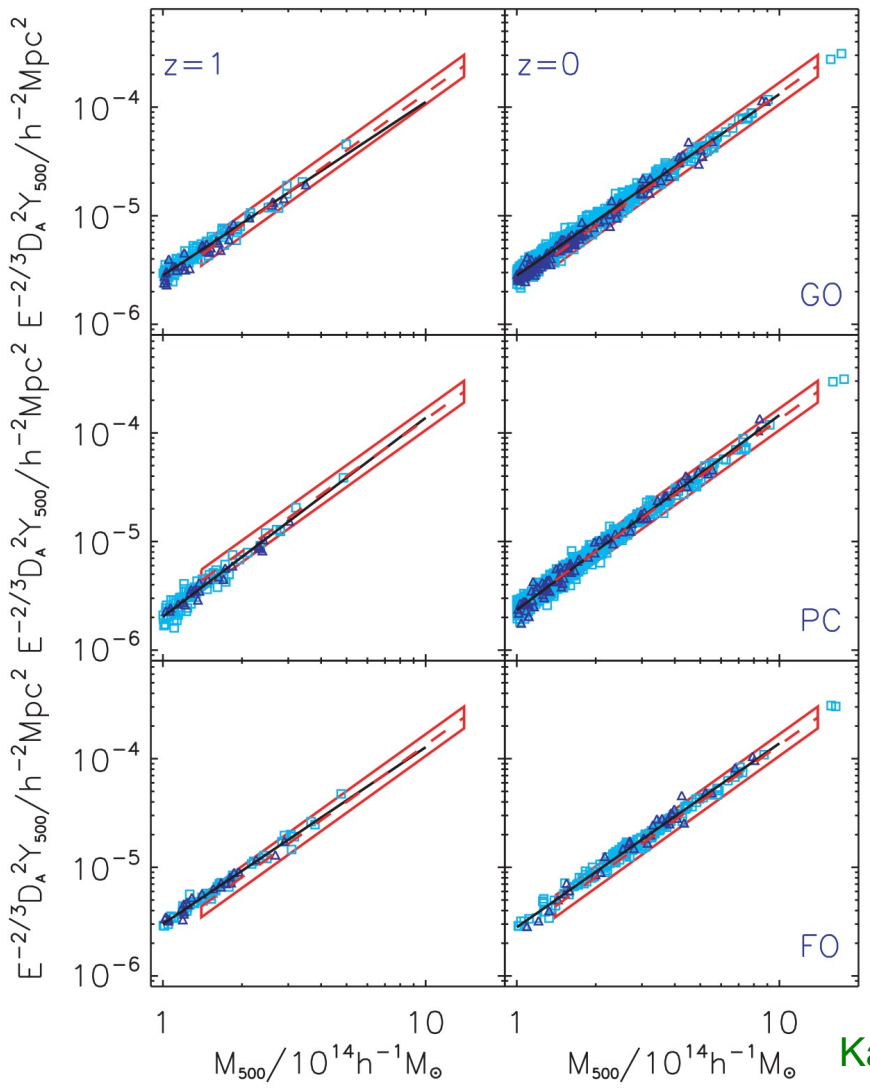


Arnaud et al. 2010
see also Nagai et al. 2007

Anti-correlation of density and temperature in cluster cores

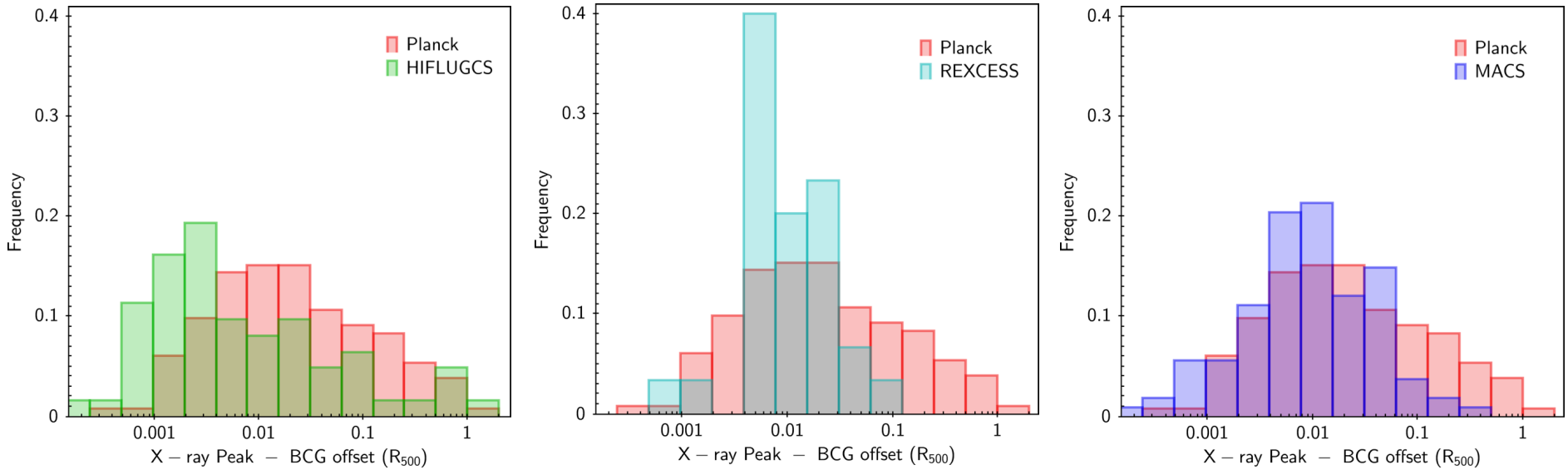
A selection closely related to the mass

Simulations (intrinsic scatter in the Y-M relation small σ_{lnY}~0.12)



Kay et al. 2012
see also e.g. da Silva et al. 2004, Nagai 2006, Le Brun et al. 2017, …

Are SZ selected clusters more or less disturbed than X-ray selected clusters?



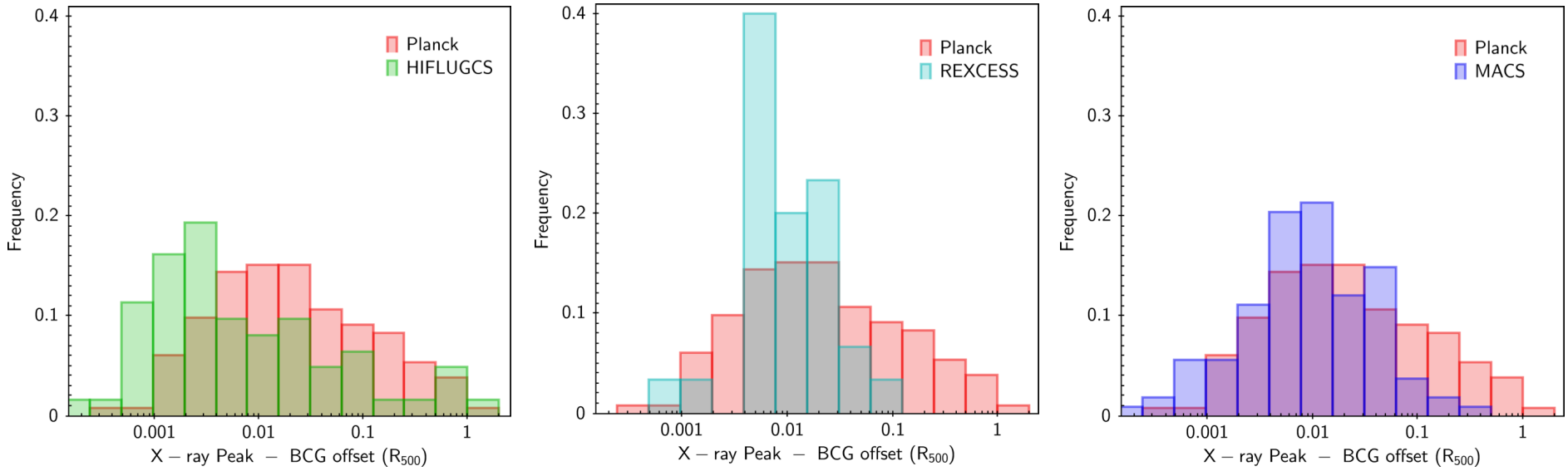
Rossetti et al. 2016

see also Lovisari et al. 2017

Planck (~52% relaxed clusters), X-ray samples (~74% relaxed clusters)

Fraction of relaxed clusters is smaller in Planck SZ than in X-ray selected catalogues

Are SZ selected clusters more or less disturbed than X-ray selected clusters?



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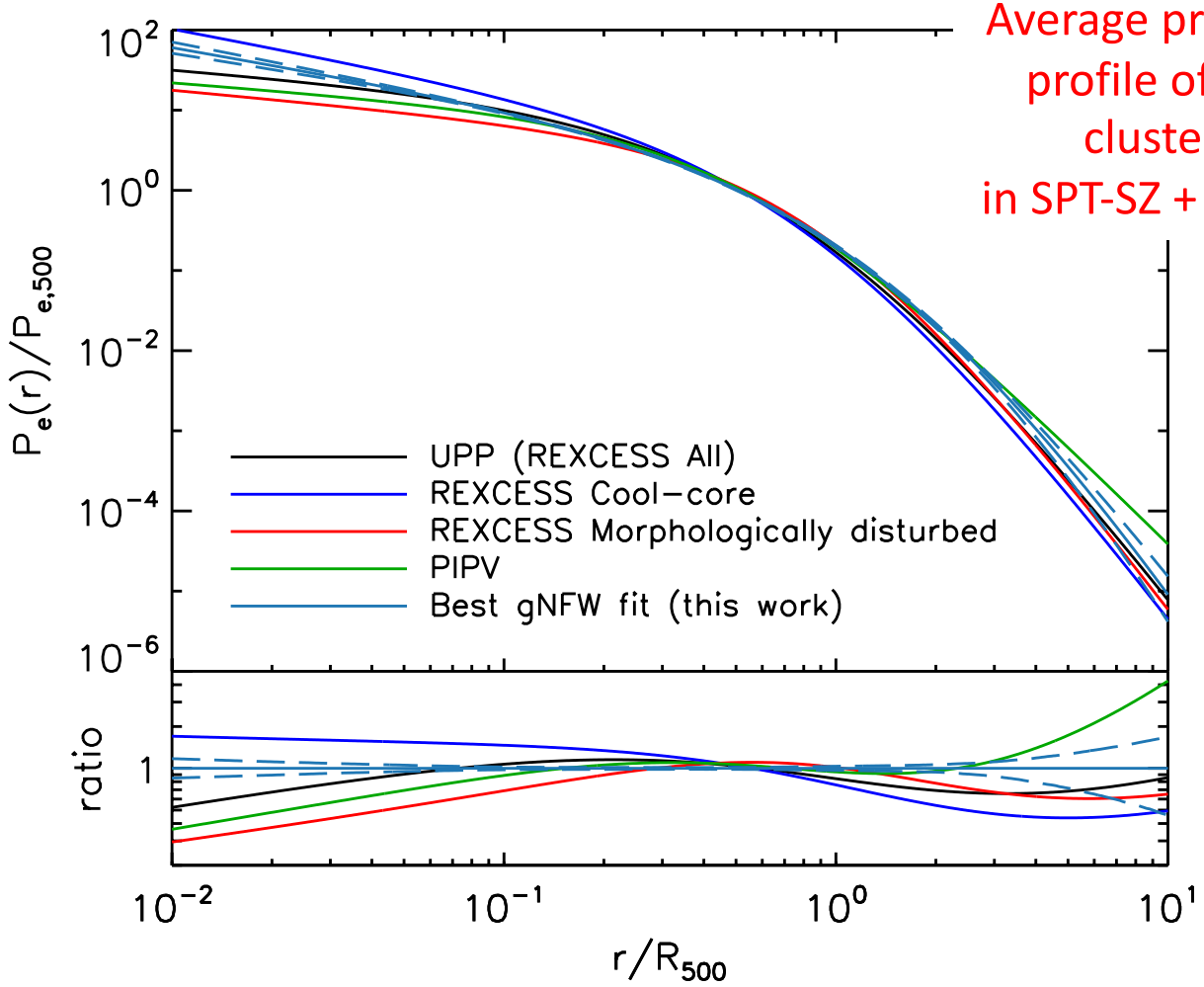
Fraction of relaxed clusters is smaller in Planck SZ than in X-ray selected catalogues

But this conclusion does not seem to hold for SPT SZ clusters…

Are SZ selected clusters more disturbed than X-ray selected clusters?



Average pressure profile of SPT clusters in SPT-SZ + Planck

Melin & Pratt 2023

see also Zenteno et al. 2020 **No evidence that SPT SZ clusters includes a higher fraction of mergers than X-ray selected cluster samples**

Blind SZ catalogues today

Credit: ACT

91 optically confirmed clusters (504 deg^2)

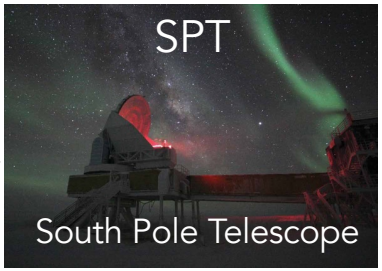
Hasselfield et al. 2013

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)

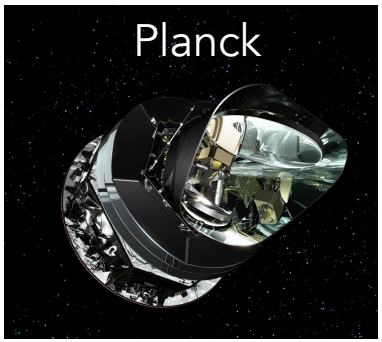
Bleem et al. 2015

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

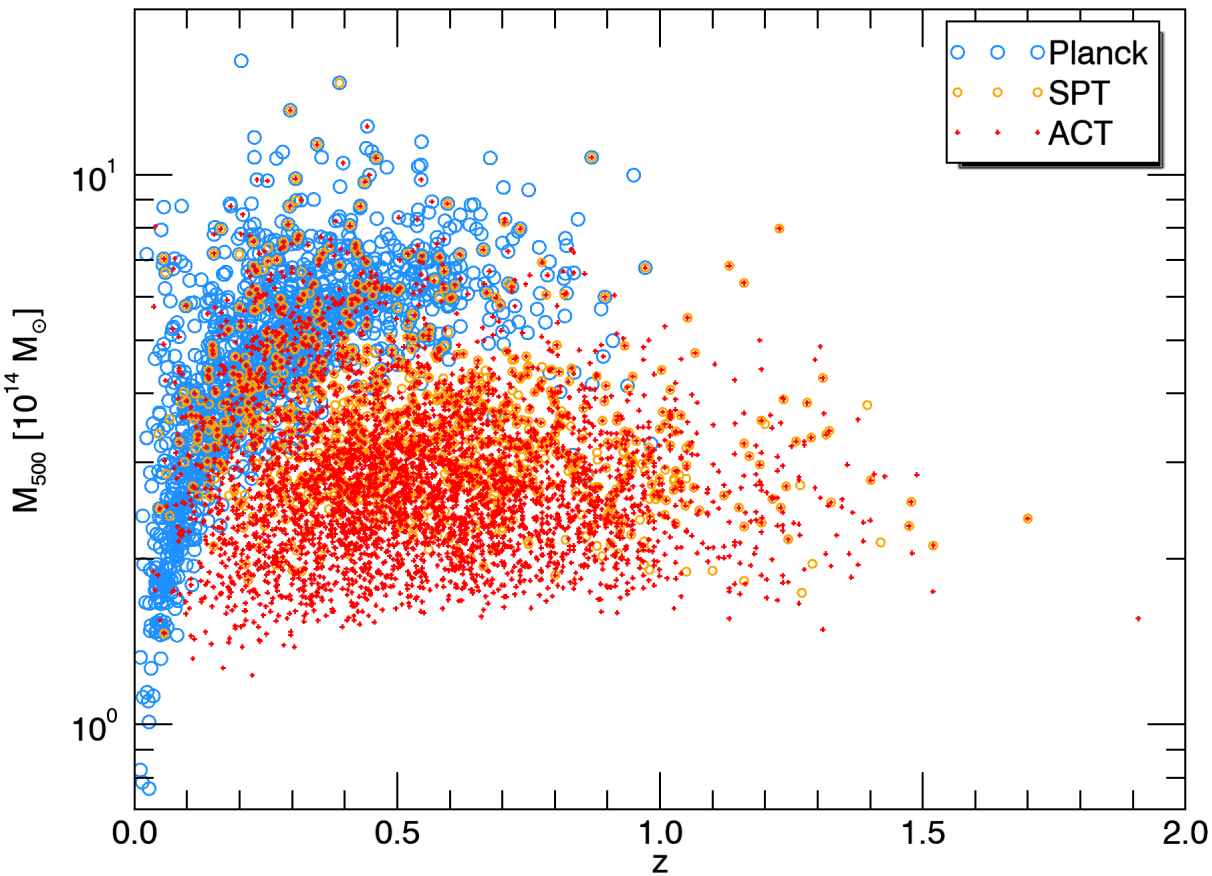


Credit: ESA

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

Planck Collaboration XXVII 2015

The MCSZ



Tarrío et al. in prep

- Meta-Catalogue of SZ detected Clusters of galaxies
- Based on Planck, South Pole Telescope and Atacama Cosmology Telescope surveys: ESZ, PSZ1, PSZ2, PLCKG, SPT2500, SPTECS, SPT, ACT2014, ACT2018, ACT2021
- 6244 entries
- Common objects identified (no duplicates)
- Planck redshifts and associated masses updated
- Cross-identification with MCXC

The cosmological SZ 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, Bocquet et al. 2019

Planck

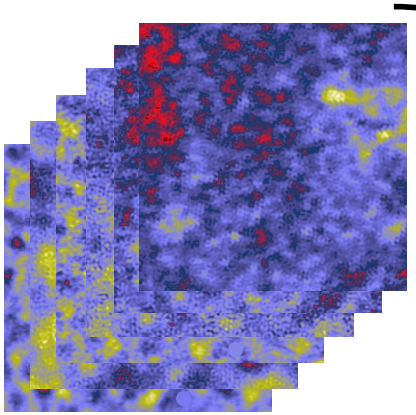
S/N>7 ➔ 189 clusters — Planck Results XX 2015

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

SZ selection in practice

The tSZ Matched Multi-Filter (MMF)

6 **Planck** HFI maps

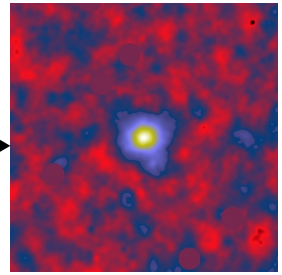


MMF

assumes
- SZ frequency spectrum
- cluster profile (UPP, *Arnaud et al. 2010*)

Herranz et al. 2002
Melin, Bartlett, Delabrouille 2006

Filtered map
(one map per cluster scale θ_{500})



$$\sigma_{Y_{500}}(\theta_{500})$$

Noise of the map filtered at scale θ_{500}

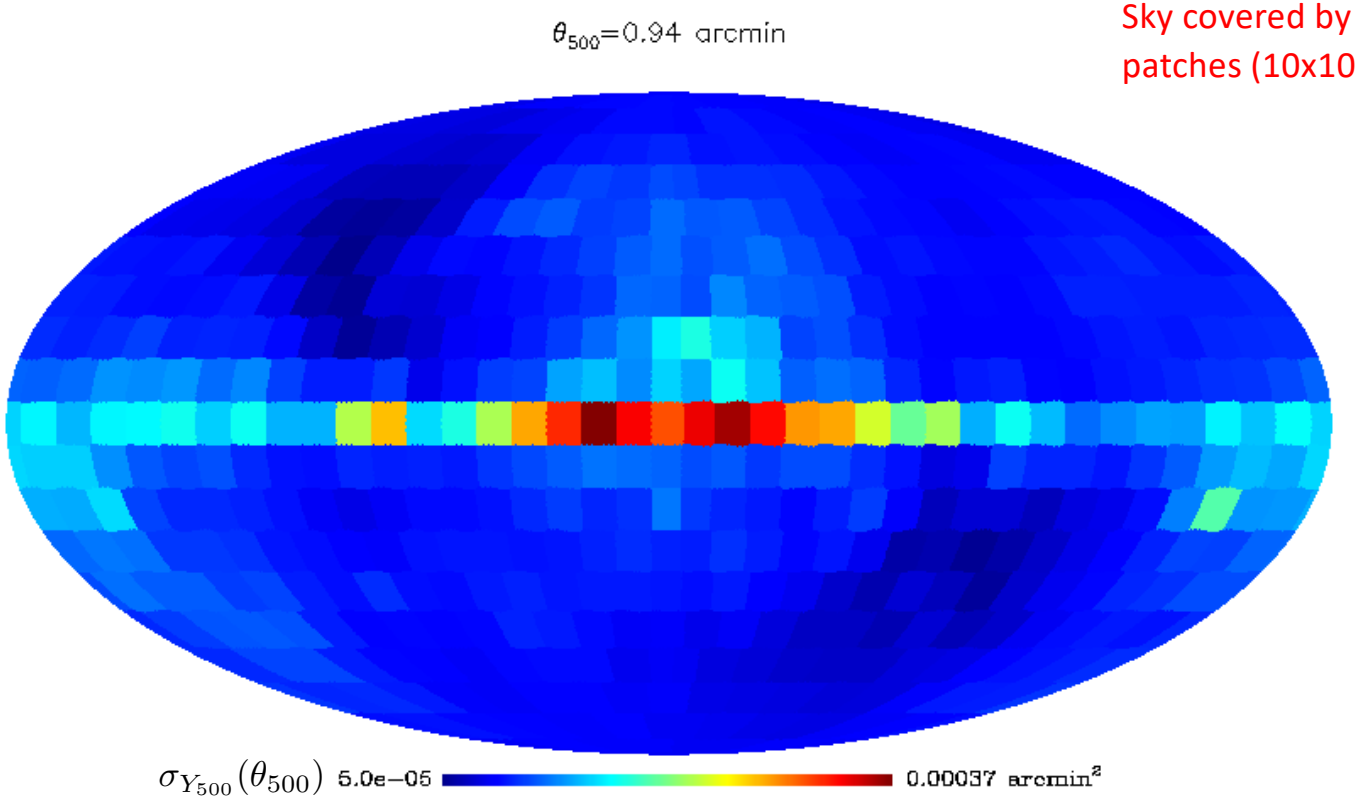
Error on Y_{500} for a cluster of size θ_{500}

⇒ This is Planck SZ selection but SPT and ACT are using a very similar extraction and modelling.

MMF noise maps

Planck maps filtered at **32 scales** (θ_{500} log spaced)

Galactic coordinates
Sky covered by 504 overlapping patches (10x10 deg^2)



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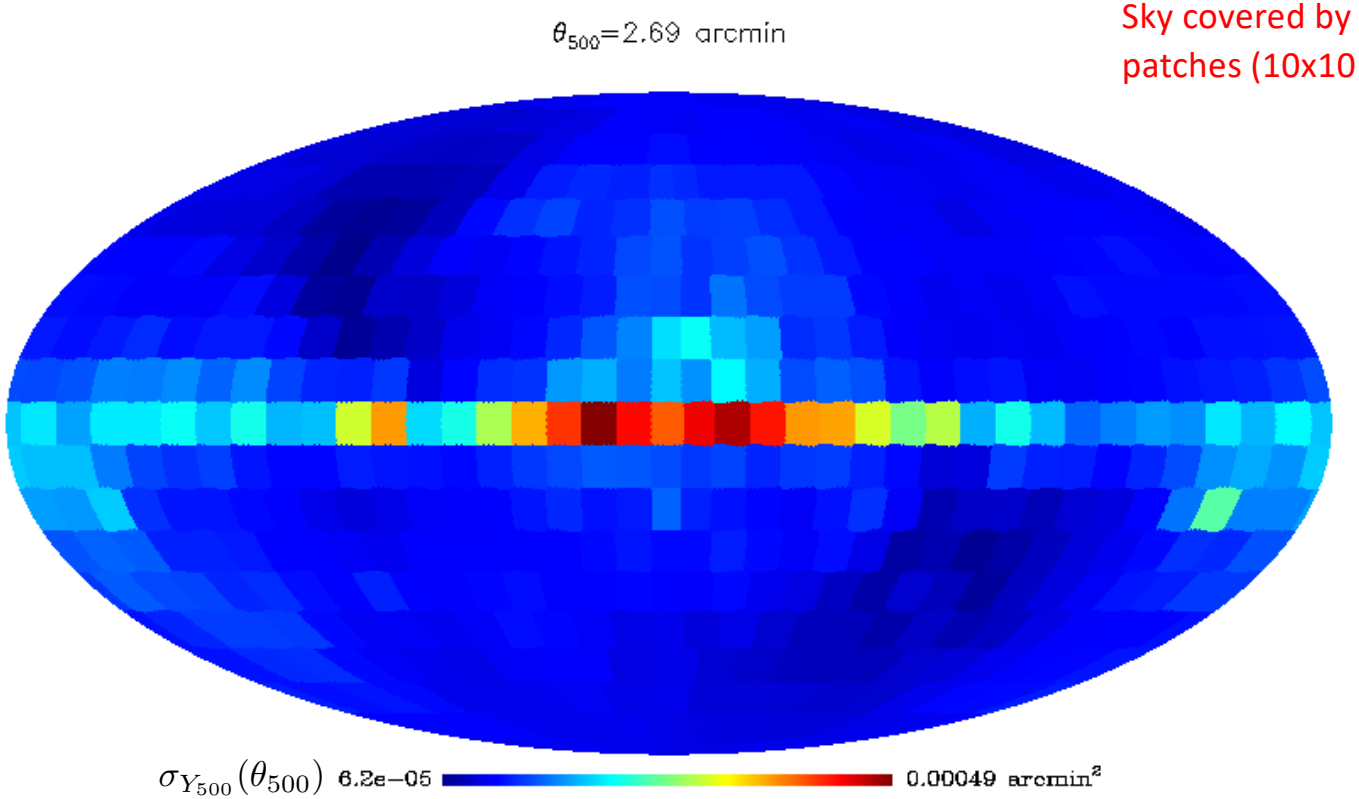

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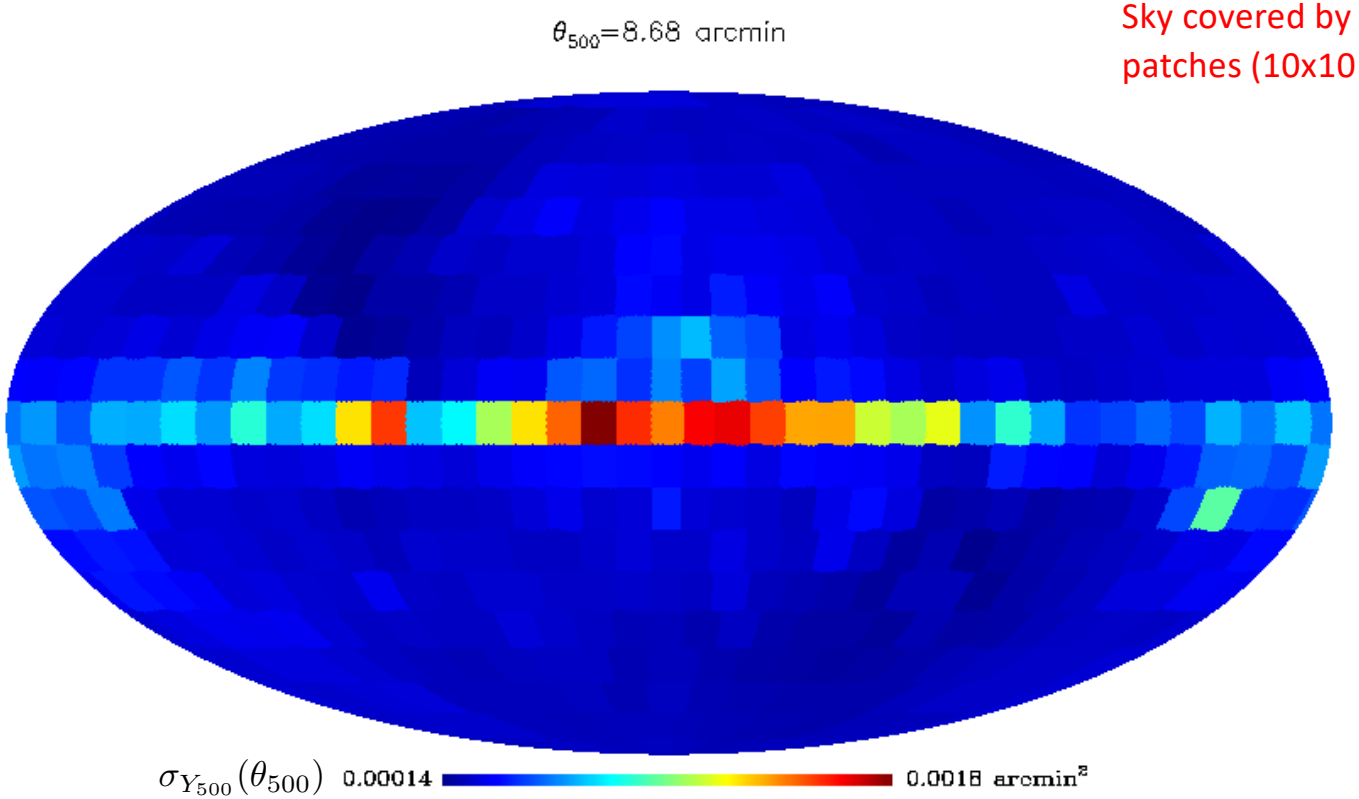

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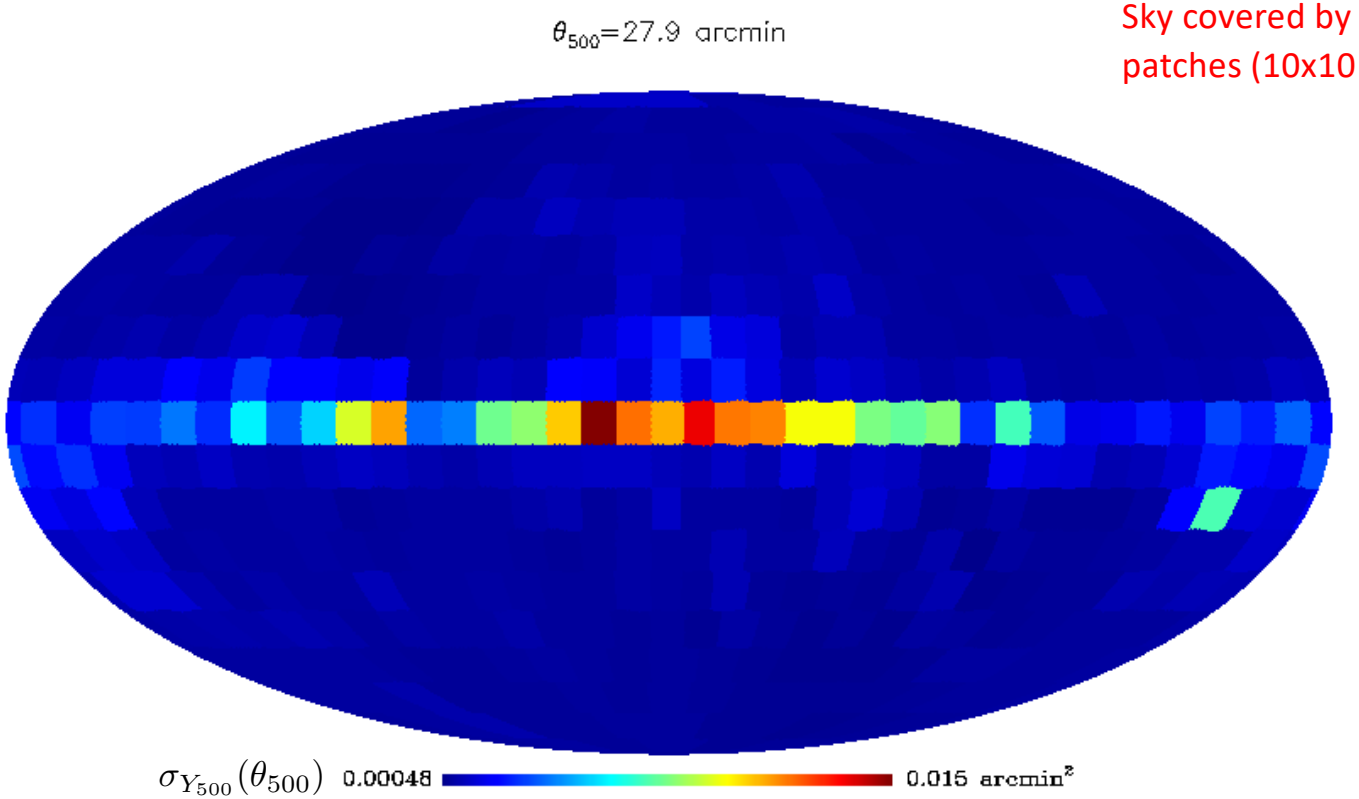

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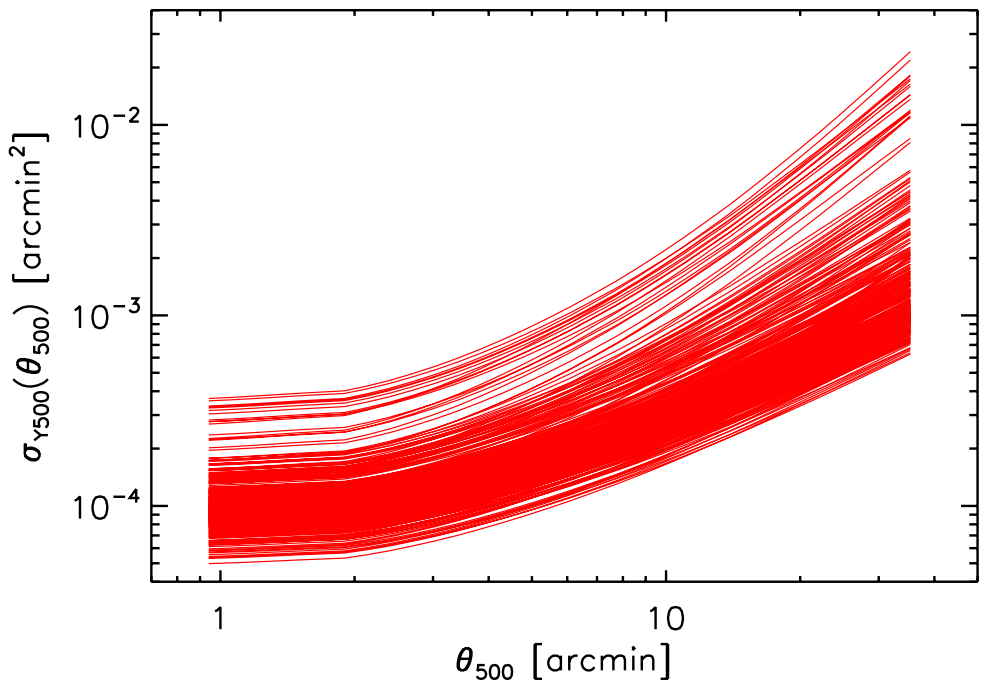
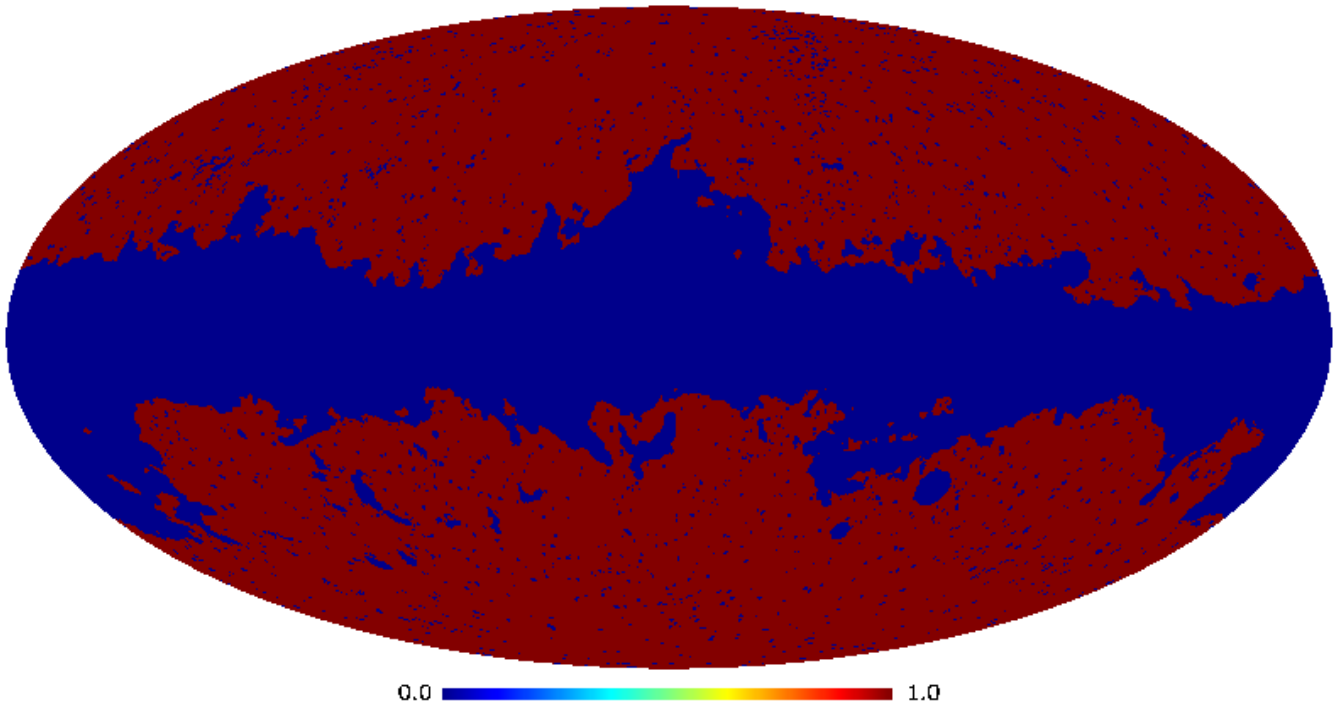


Mask

Galactic coordinates

Planck cosmology mask



Completeness $\chi(Y_{500},\theta_{500})$

Under the assumption that **noise fluctuations of the filtered maps are Gaussian**, the completeness can be written as

(l,b) galactic coordinates

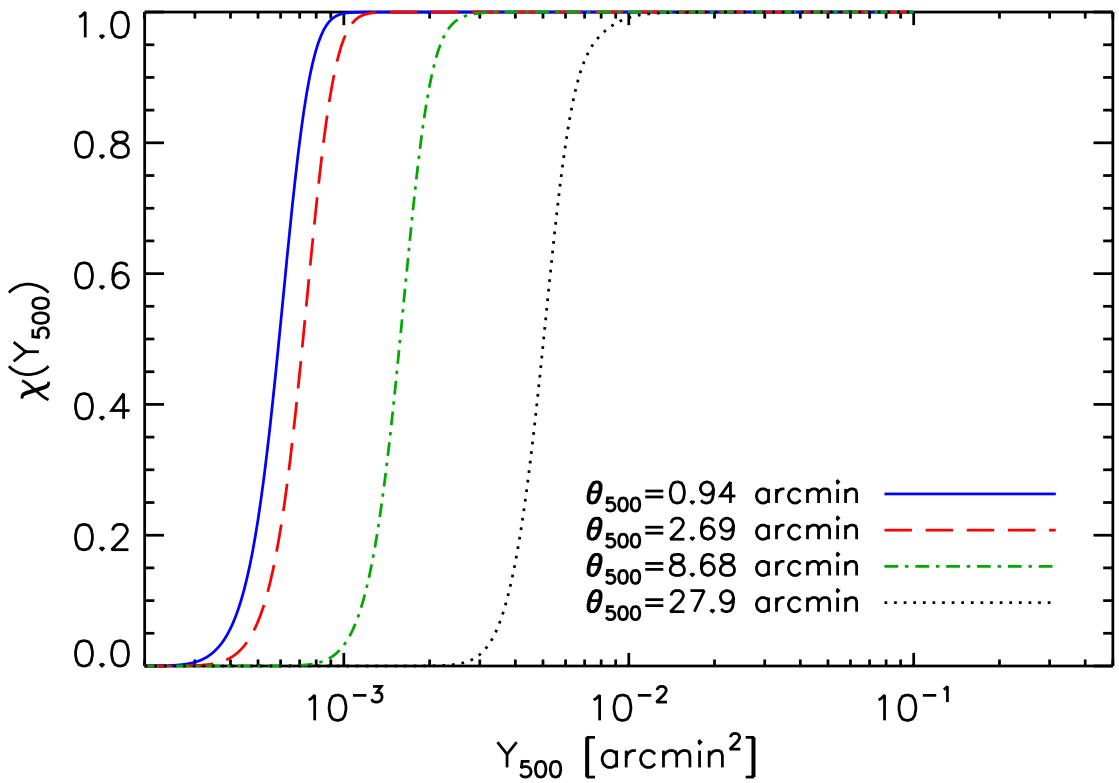
$$\chi(Y_{500},\theta_{500},l,b) = \frac{1}{2}\left[1 - \mathrm{erf}\left(\frac{q_{\mathrm{thres}} - q_{\mathrm{m}}(Y_{500},\theta_{500},l,b)}{\sqrt{2}}\right)\right]$$

$$q_{\mathrm{m}}(Y_{500},\theta_{500},l,b) = \frac{Y_{500}}{\sigma_{Y500}(\theta_{500},l,b)}$$

Planck 2015 Results. XXIV. Cosmology from Sunyaev-Zeldovich cluster counts

$q_{\mathrm{thres}} = 6$ for the Planck cosmological analysis

Completeness $\chi(Y_{500},\theta_{500})$



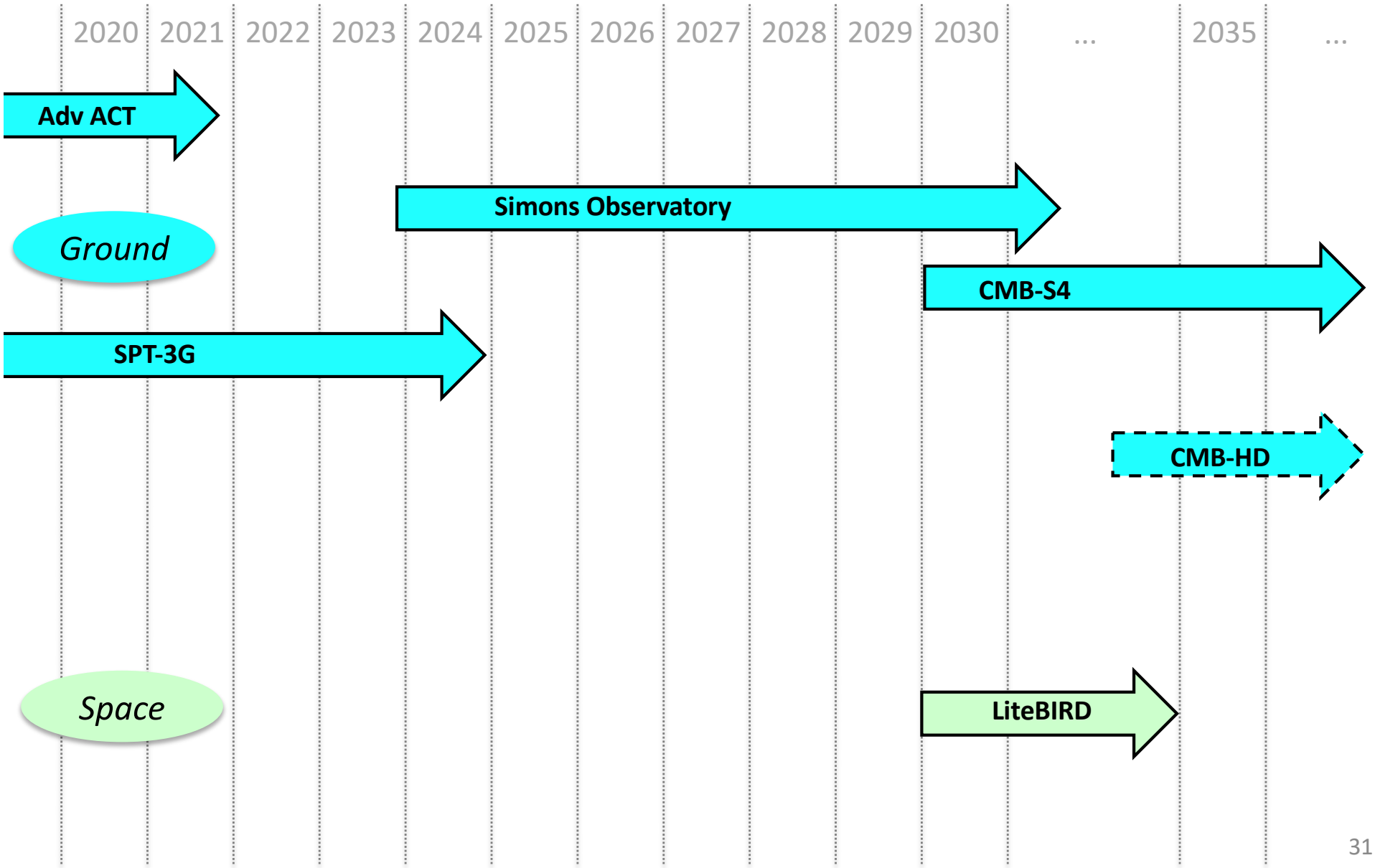
Future of SZ detection/observations

Future ground based SZ instruments

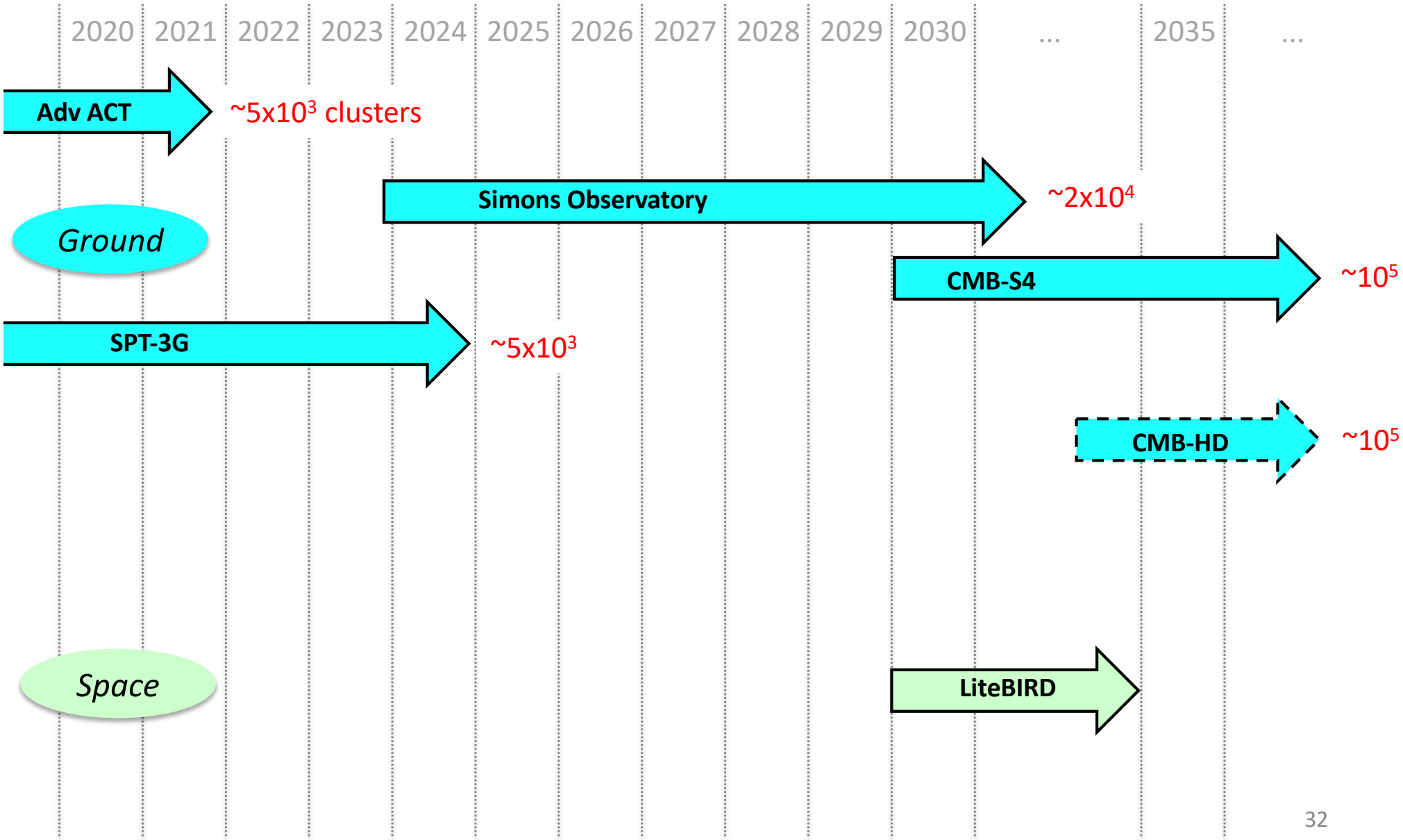
Survey SPT, Simons Observatory (SO), CMB-S4, (CMB-HD?)

Pointed ALMA, TolTEC, CCAT

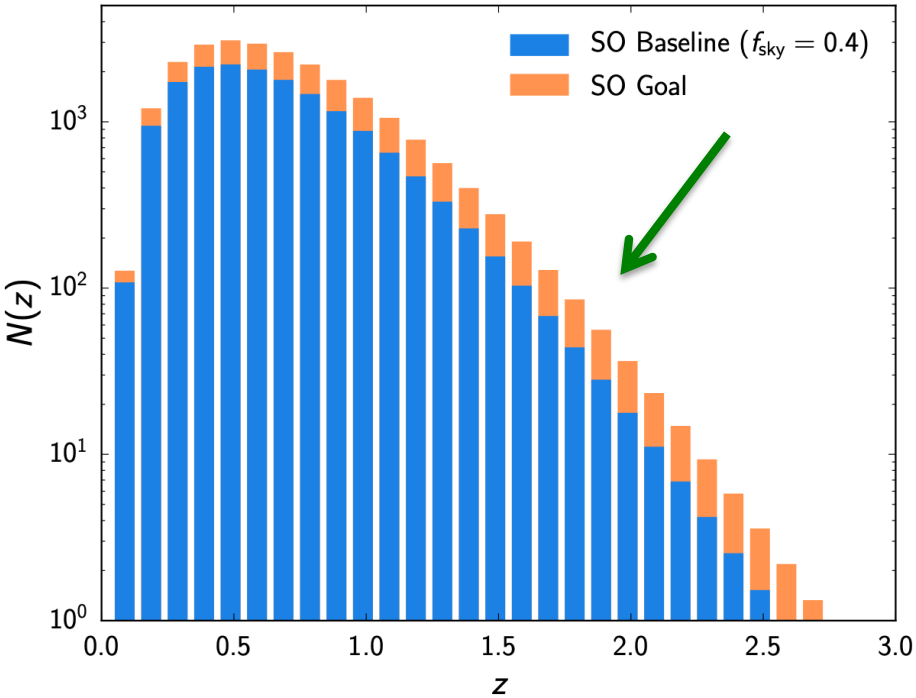
Current and future SZ surveys



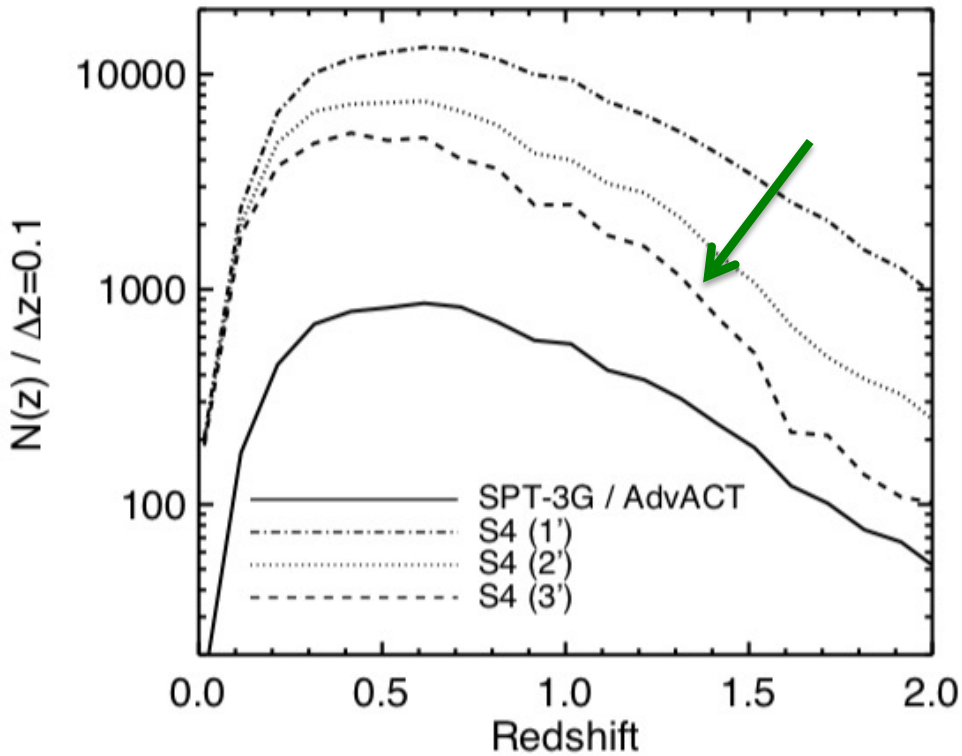
Current and future SZ surveys



Future SZ cluster catalogues



Ade et al. 2019



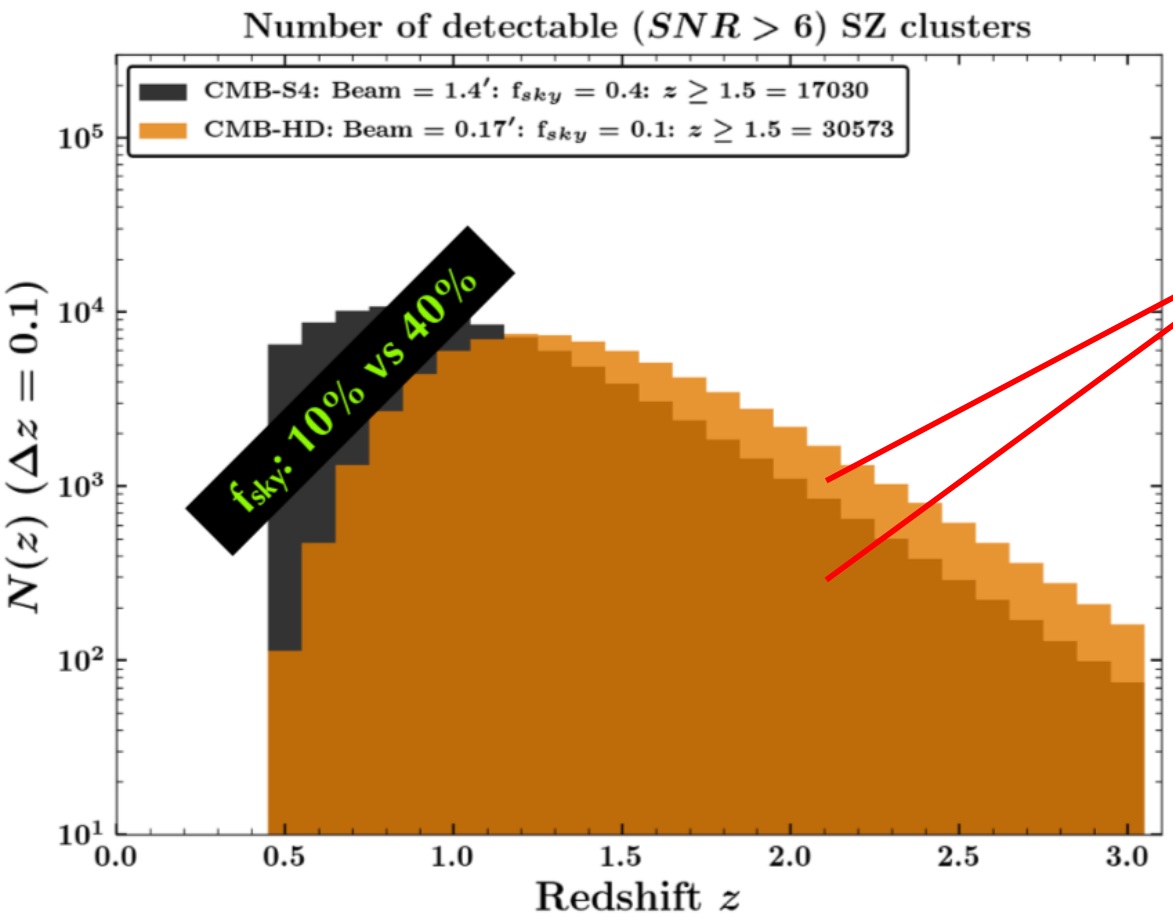
CMB-S4 science book

- thousands of clusters at z>1 with SO
- hundreds of clusters at z>2 with CMB-S4

In the coming years, SZ surveys will:

- detect the first clusters (z>2)
- increase redshift leverage (important for cosmology !)

CMB-HD vs. CMB-S4



2 times more clusters with CMB-HD at z>1.5 compared to CMB-S4

Raghunathan @ CMB in HD 2018

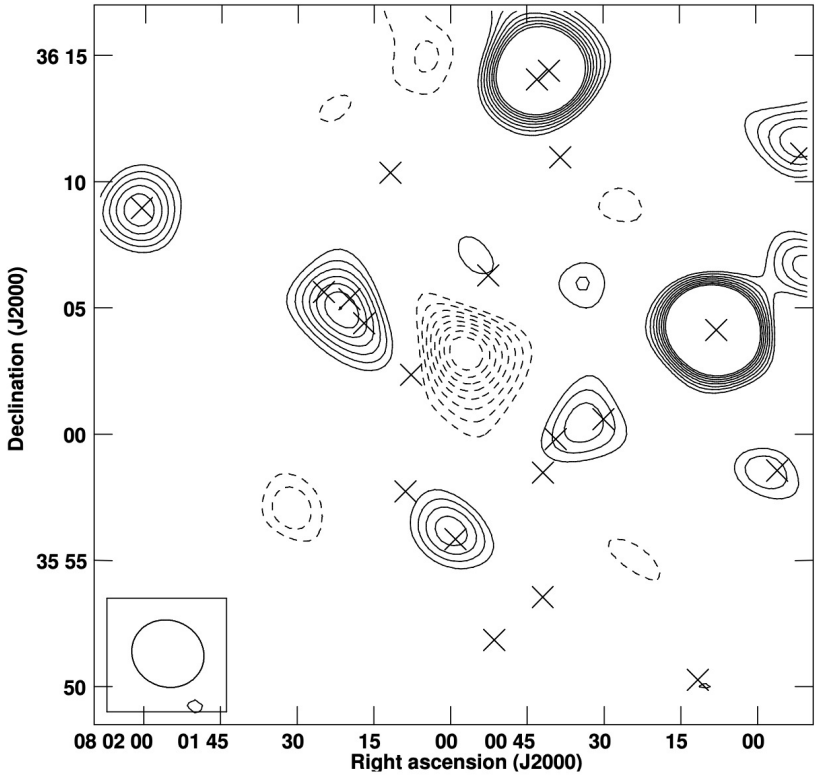
Possible issues
with SZ selection in the future ?

Point sources in clusters

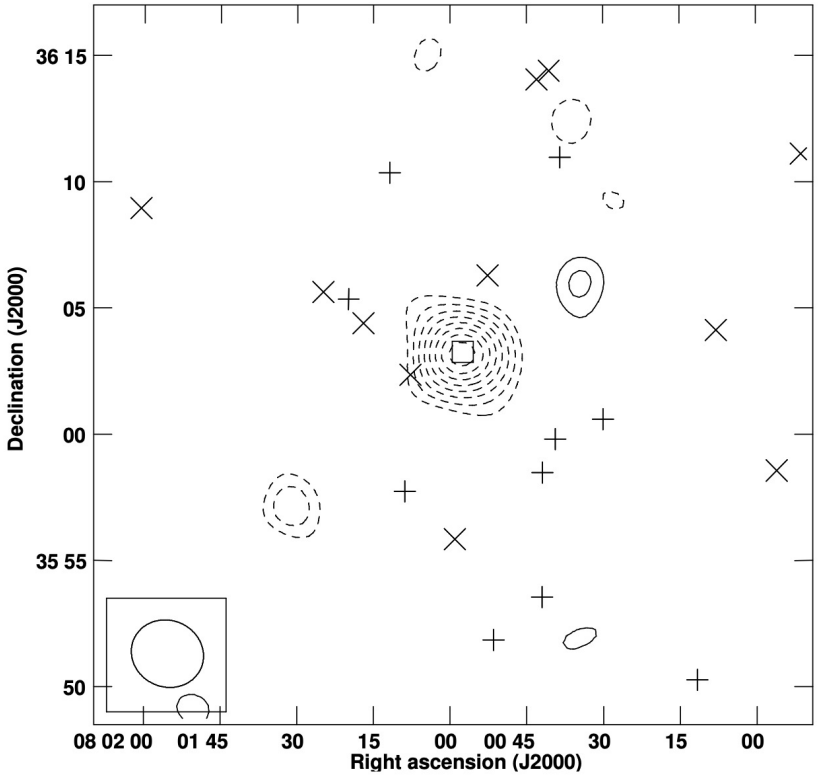
15GHz

Abell 611 as seen by AMI

before radio source subtraction



after radio source subtraction

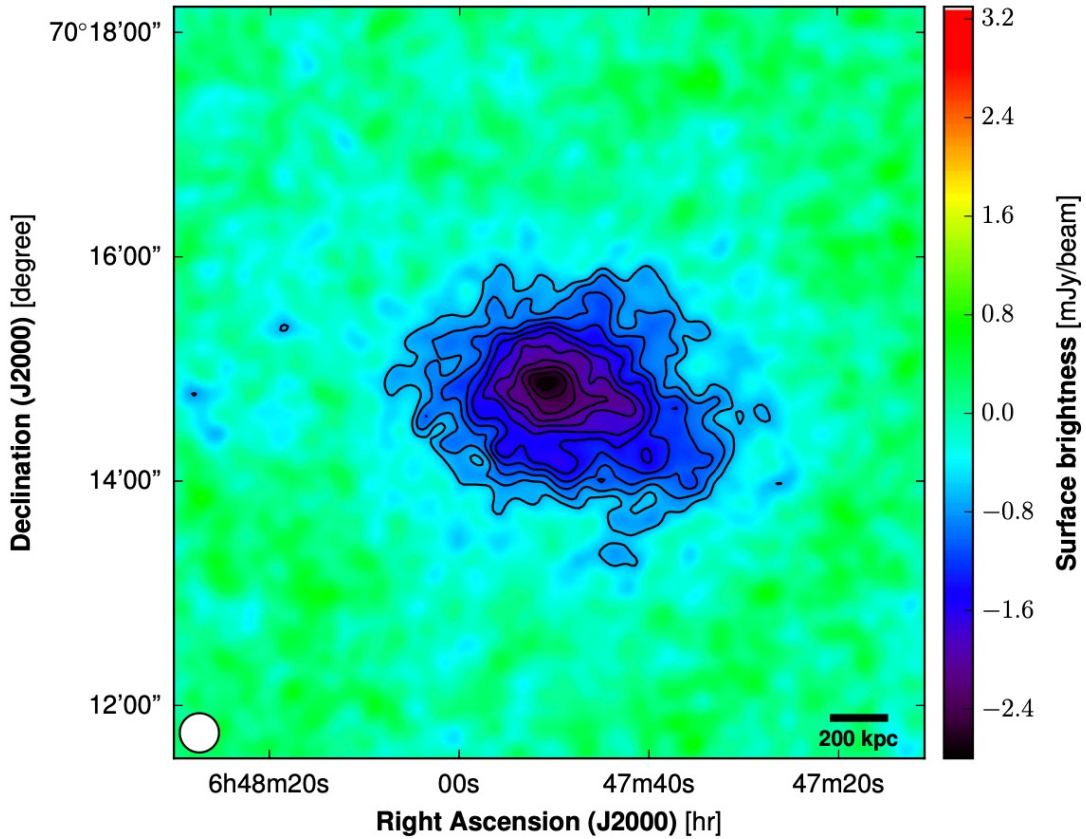


Rumsey et al. 2016

Point sources in clusters

150 GHz

PSZ2 G144.83+25.11 as seen by NIKA2

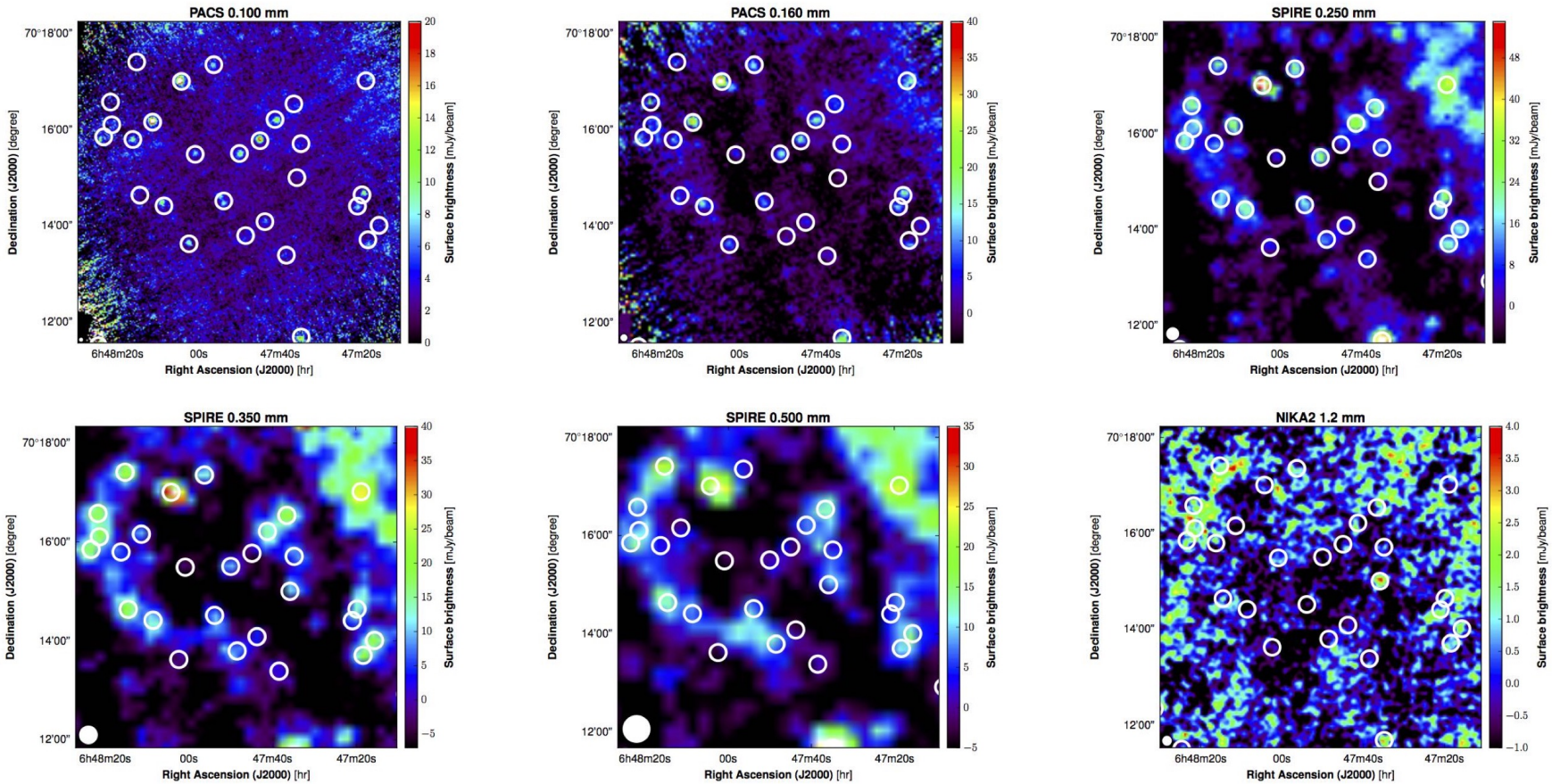


Ruppin et al. 2018

Point sources in clusters

150 GHz

PSZ2 G144.83+25.11 as seen by NIKA2

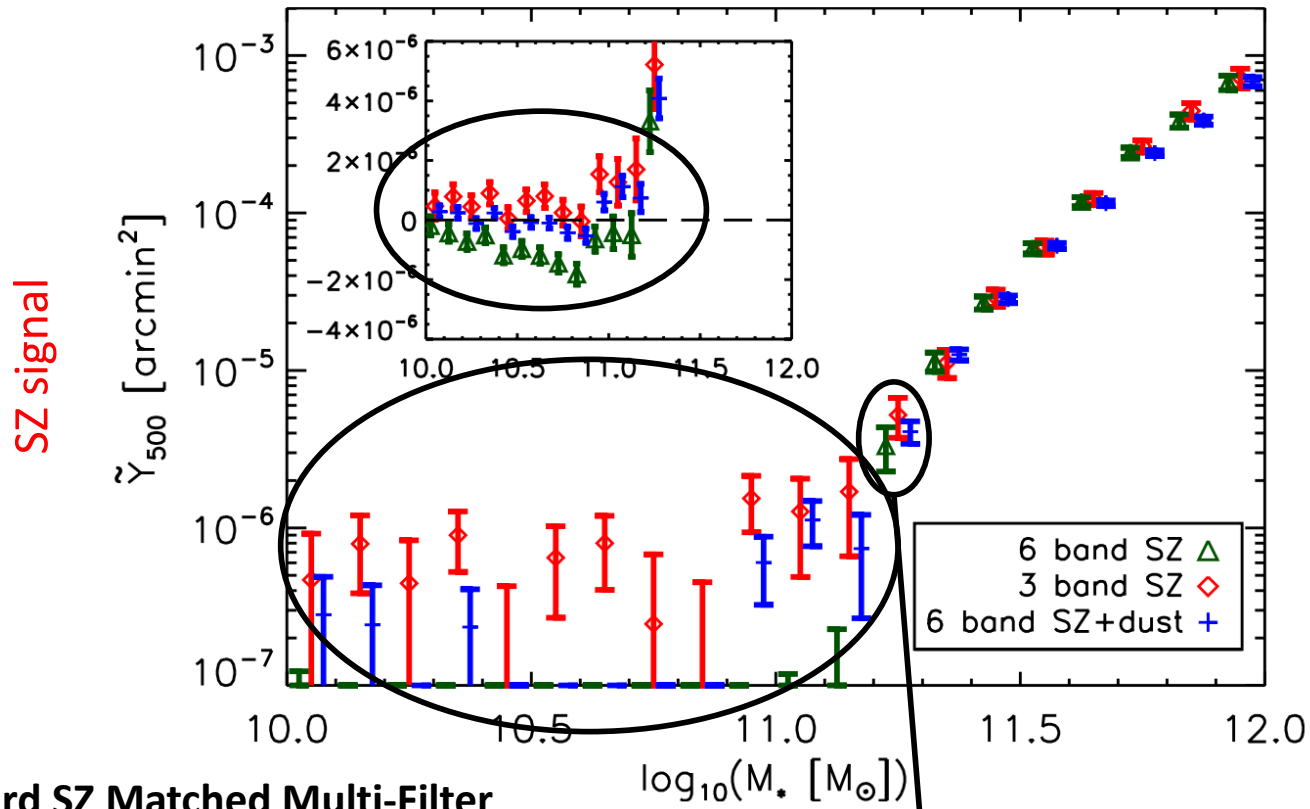


Ruppin et al. 2018

Many infrared sources to subtract

Dust in clusters

Planck SZ "stacks" of ~260,000 Locally Brightest Galaxies @ z~0.1 (SDSS)



Standard SZ Matched Multi-Filter biased at low mass ➔ *dust!*

Planck Intermediate XI 2013

$M_* \sim 2\times10^{11} M_\odot$

$M_{500} \sim 2\times10^{13} M_\odot$

Conclusions

- Three main experiments (ACT, SPT, Planck) have provided blind SZ catalogues up to now.
- SZ selection unique: close to a selection on total mass with small scatter between the observable (Y) and the mass M ⇒ ideal for cosmology
- SZ selection well under control for the current samples (hundreds of galaxy clusters)
- No redshift dimming. Perfect to detect high-z clusters.
- SZ detection will be from the ground in the future with SPT, Simons Observatory and CMB-S4

Questions

- SZ ideal for cosmology (small scatter in Y-M relation). Probably better than X-ray or optical (galaxy) selection? What about weak lensing selection?
- SZ selection currently very well under control but some uncertainty regarding morphology: fraction of relaxed clusters seems different between Planck and SPT-SZ.
- Future SZ selected clusters will have lower masses: how to deal with contamination by radio and infrared point sources?
- What will be the role/impact of high resolution pointed observations with respect to this uncertainty? Will we lack ν>300GHz information from ground?
- Can spectrometers play a role?
- Impact of other SZ effects (relativistic SZ, kinetic SZ) on SZ detection?
- Will we be able to constrain cosmology with z>2 clusters?