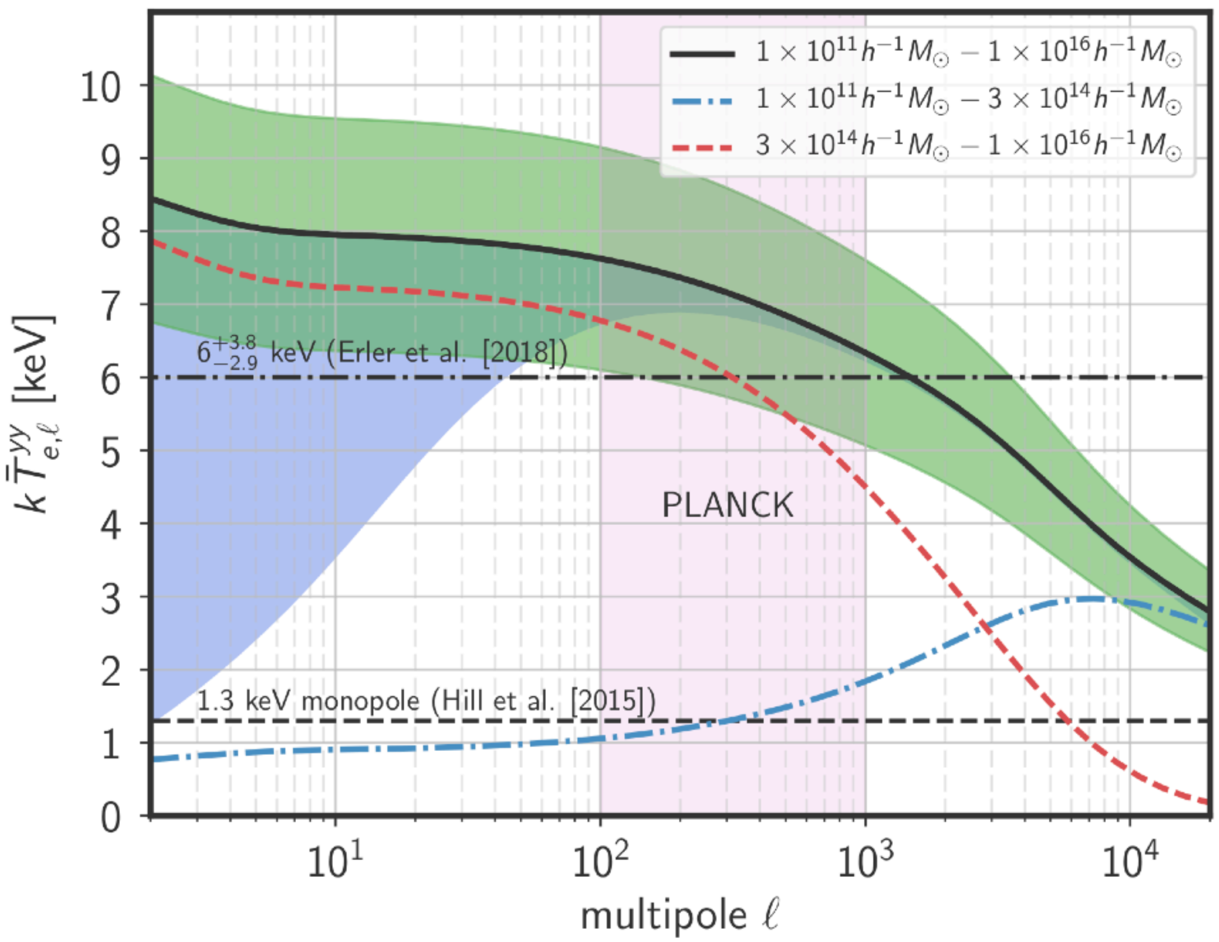
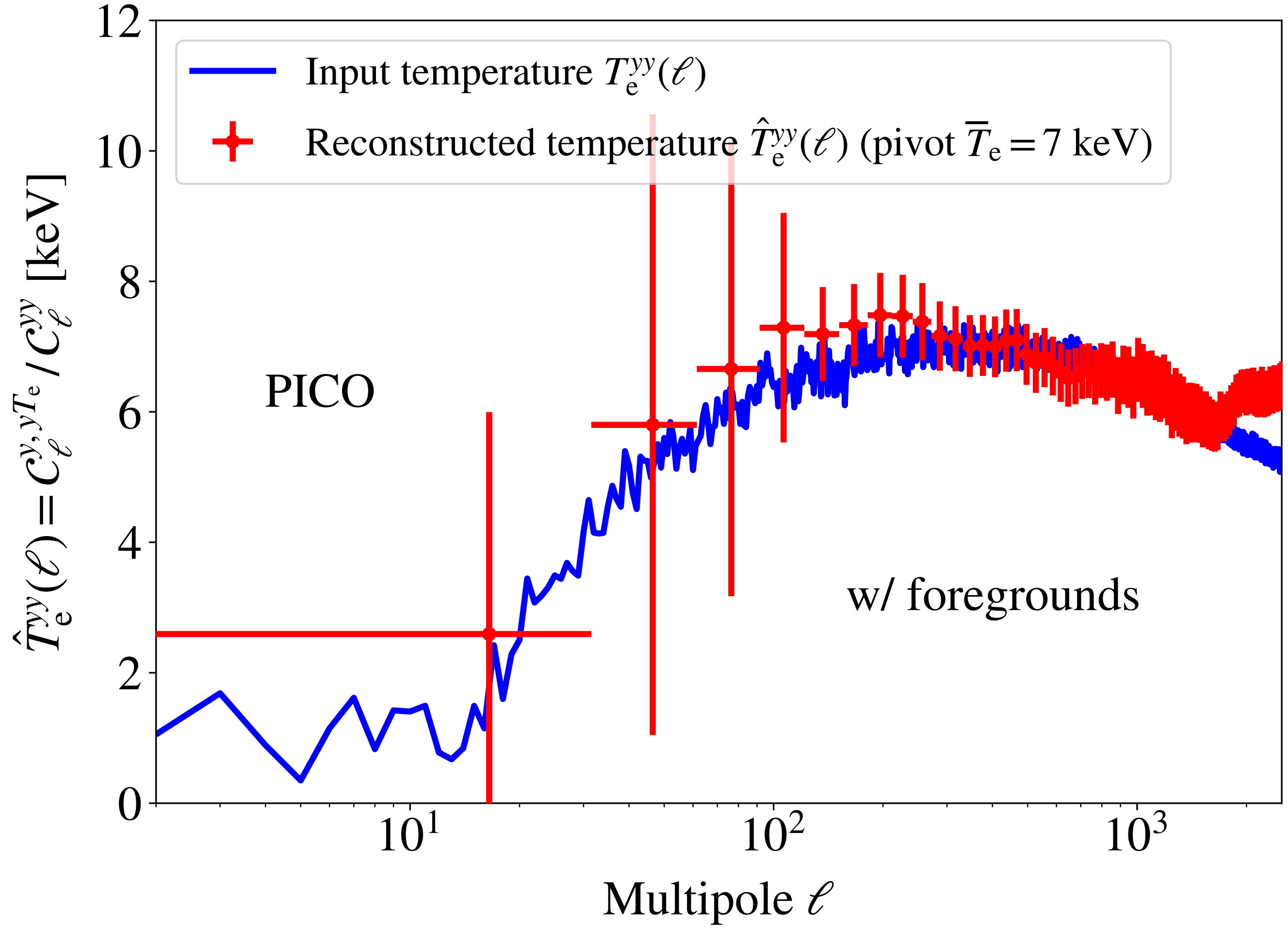
The role of relativistic SZ in cosmology





Jens Chluba

Cosmological Synergies in the Upcoming Decade

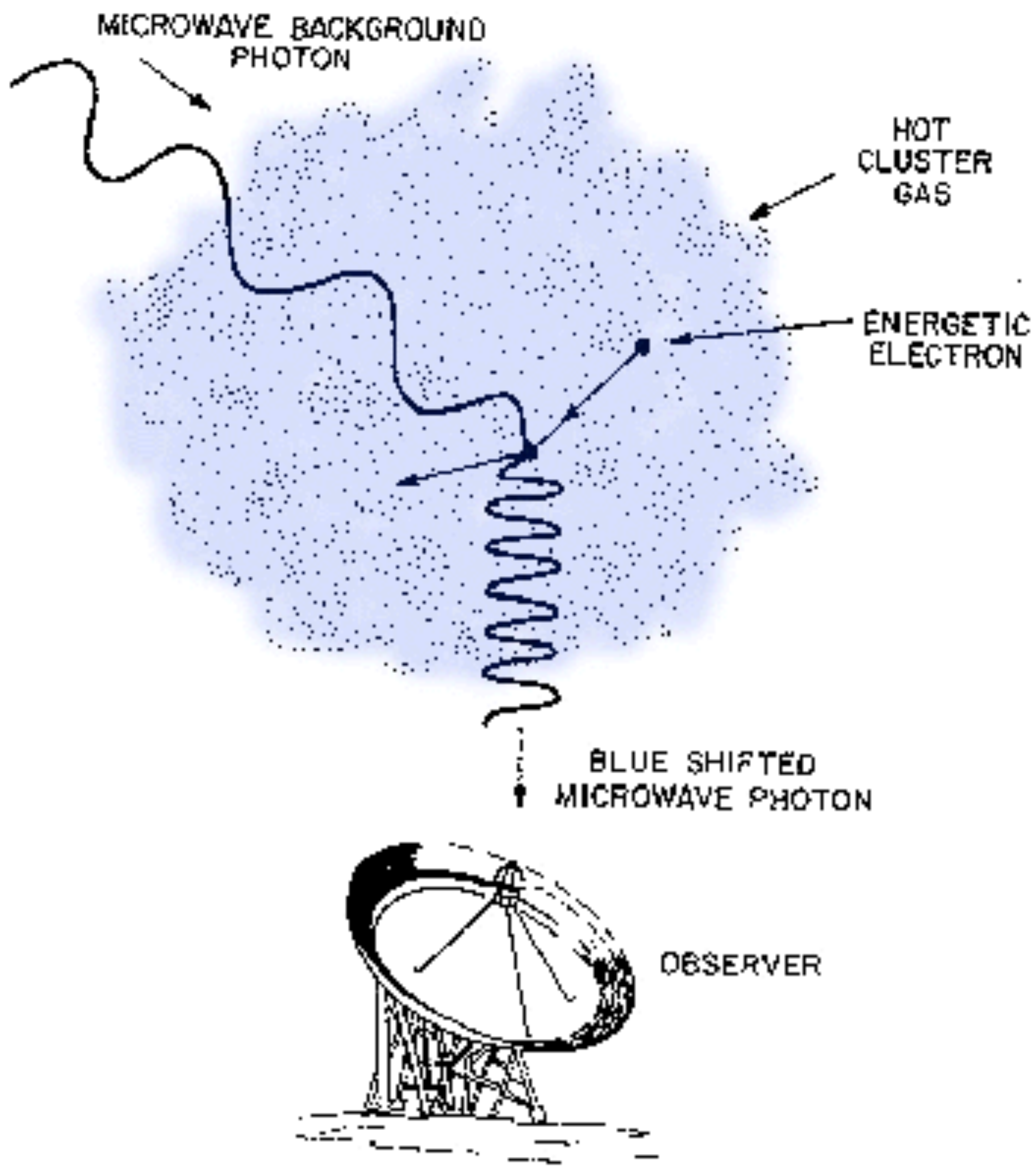
Paris, France, Dec 9th - 12th, 2019

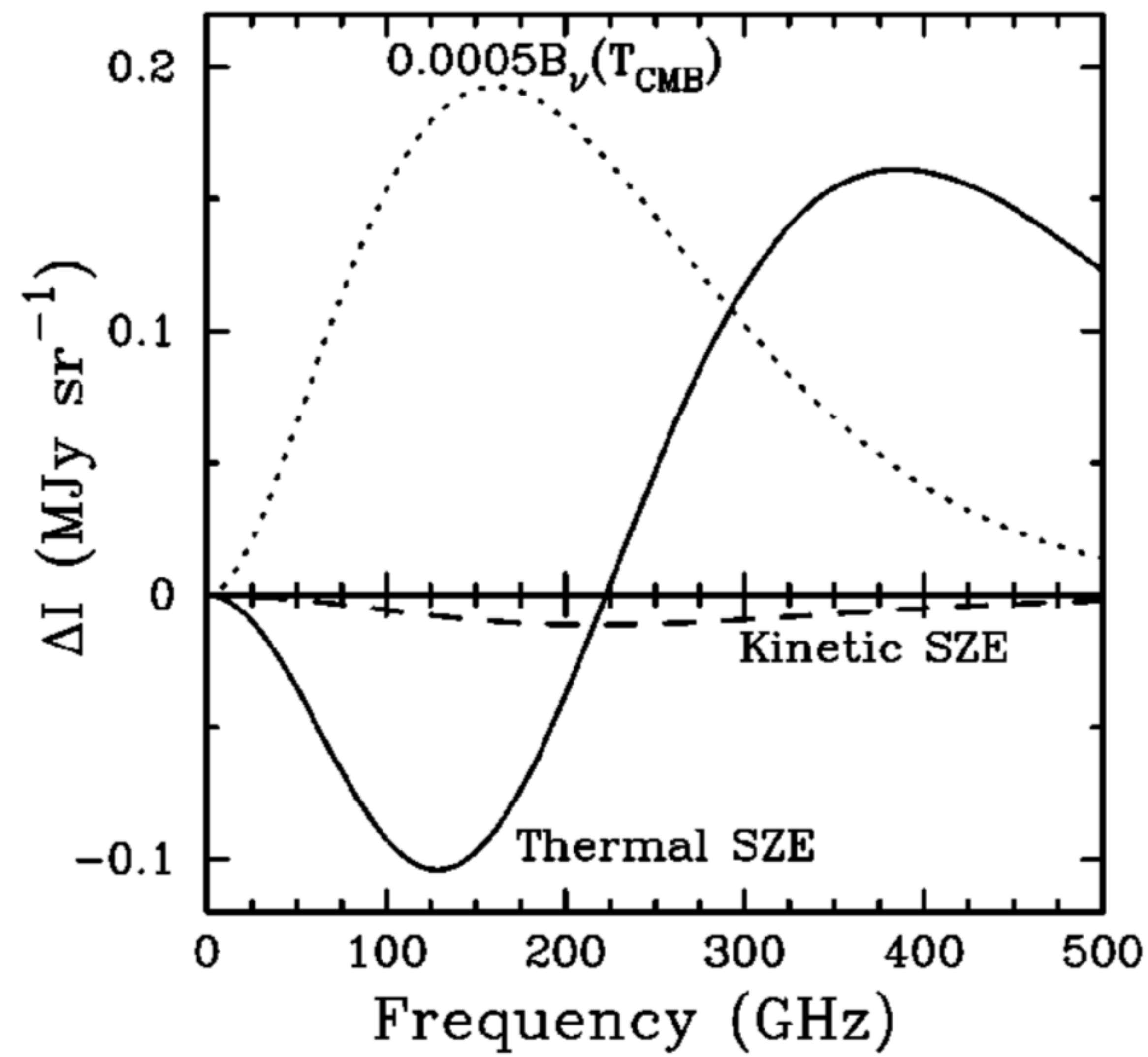
MANCHESTER 1824 The University of Manchester

erc

THE ROYAL SOCIETY

Classical SZ effects

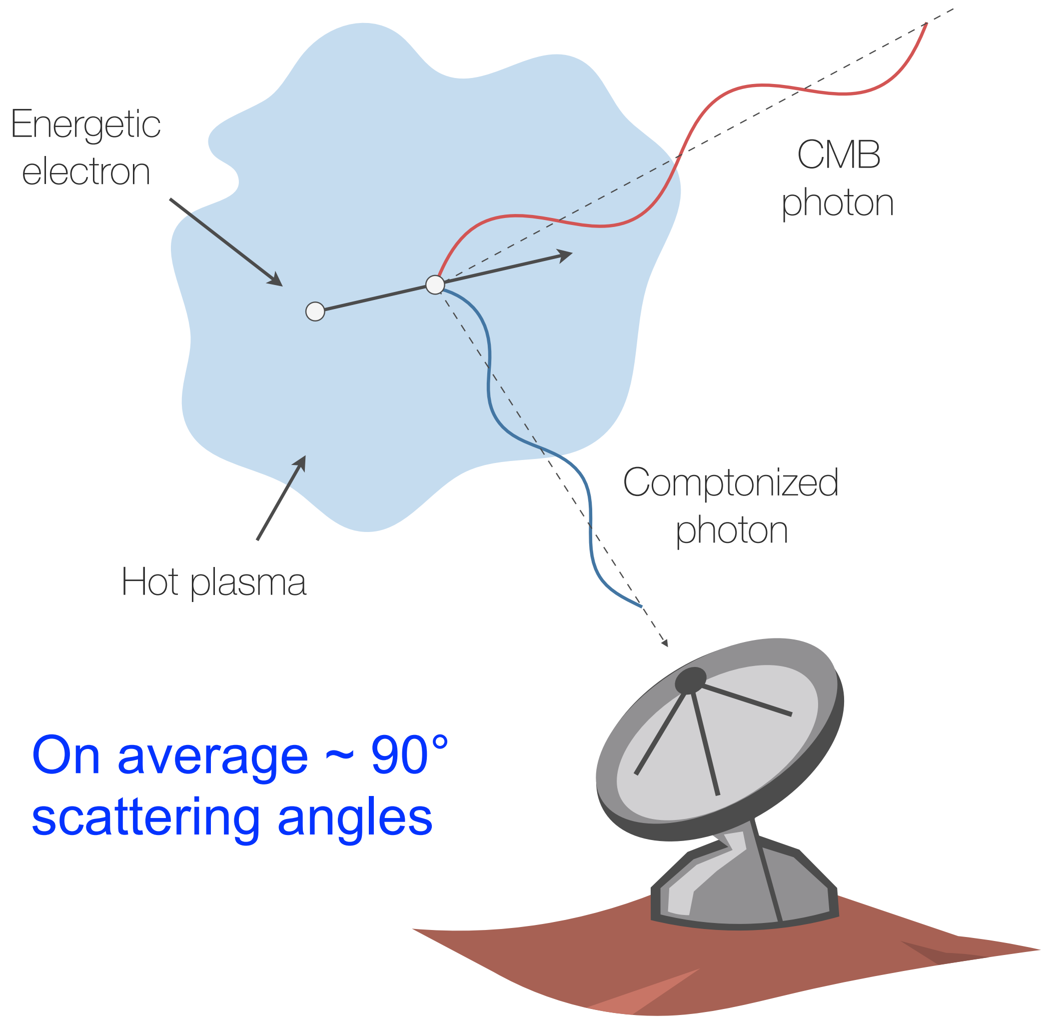




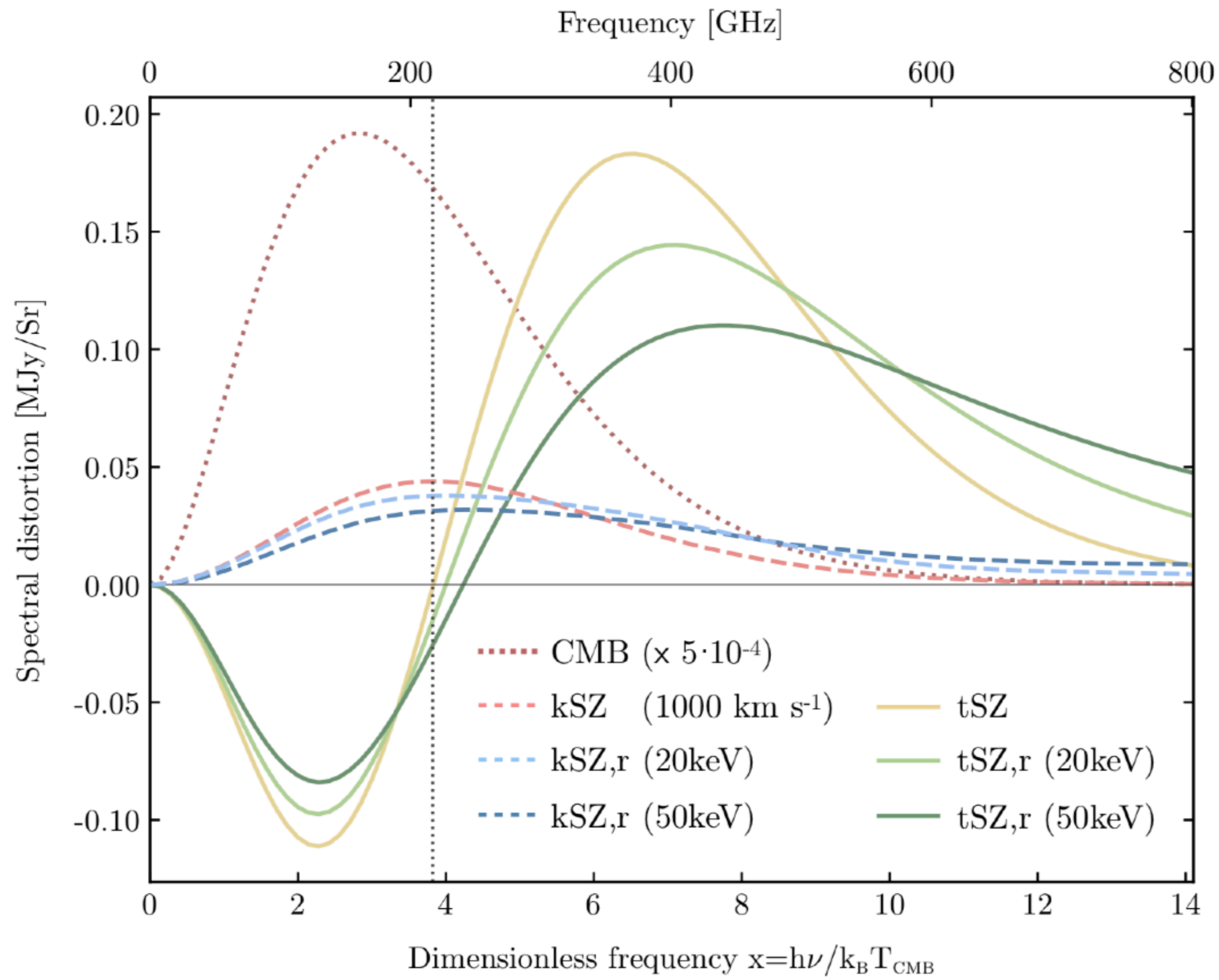
- SZ clusters are a great cosmological probe
- Many years of developments since its first prediction by Zeldovich & Sunyaev, 1969

Sunyaev & Zeldovich, 1980
Rephaeli, 1995
Birkinshaw, 1999
Carlstrom, Holder & Reese, 2002

New Comprehensive Review of SZ effects



On average ~ 90° scattering angles



Astrophysics with the Spatially and Spectrally Resolved Sunyaev-Zeldovich Effects

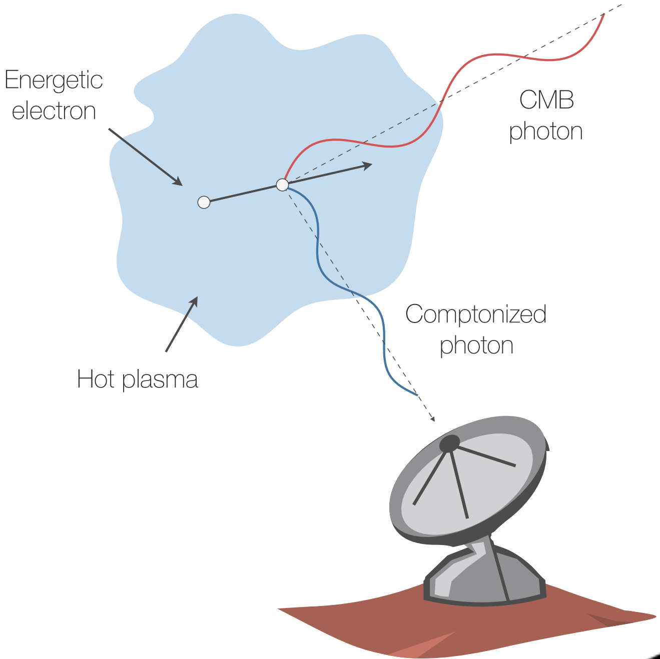
A Millimetre/Submillimetre Probe of the Warm and Hot Universe

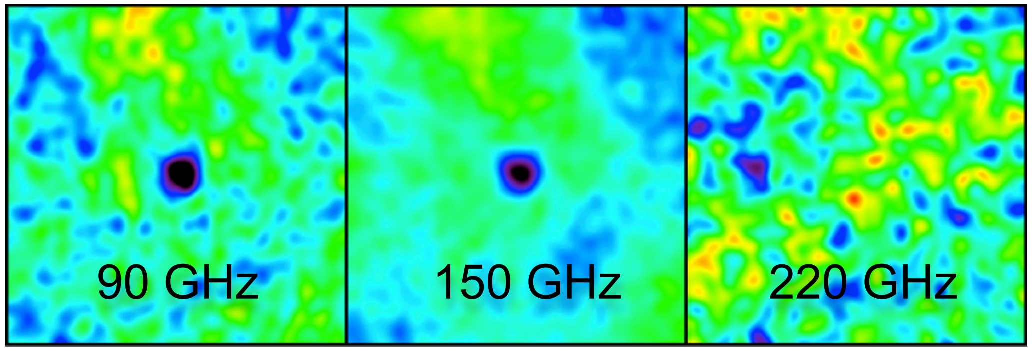
Tony Mroczkowski · Daisuke Nagai · Kaustuv Basu · Jens Chluba · Jack Sayers · Rémi Adam · Eugene Churazov · Abigail Crites · Luca Di Mascolo · Dominique Eckert · Juan Macias-Perez · Frédéric Mayet · Laurence Perotto · Etienne Pointecouteau · Charles Romero · Florian Ruppin · Evan Scannapieco · John ZuHone

- Highlights high-resolution and high-sensitivity SZ
- Illuminates new directions
- Connection to simulations

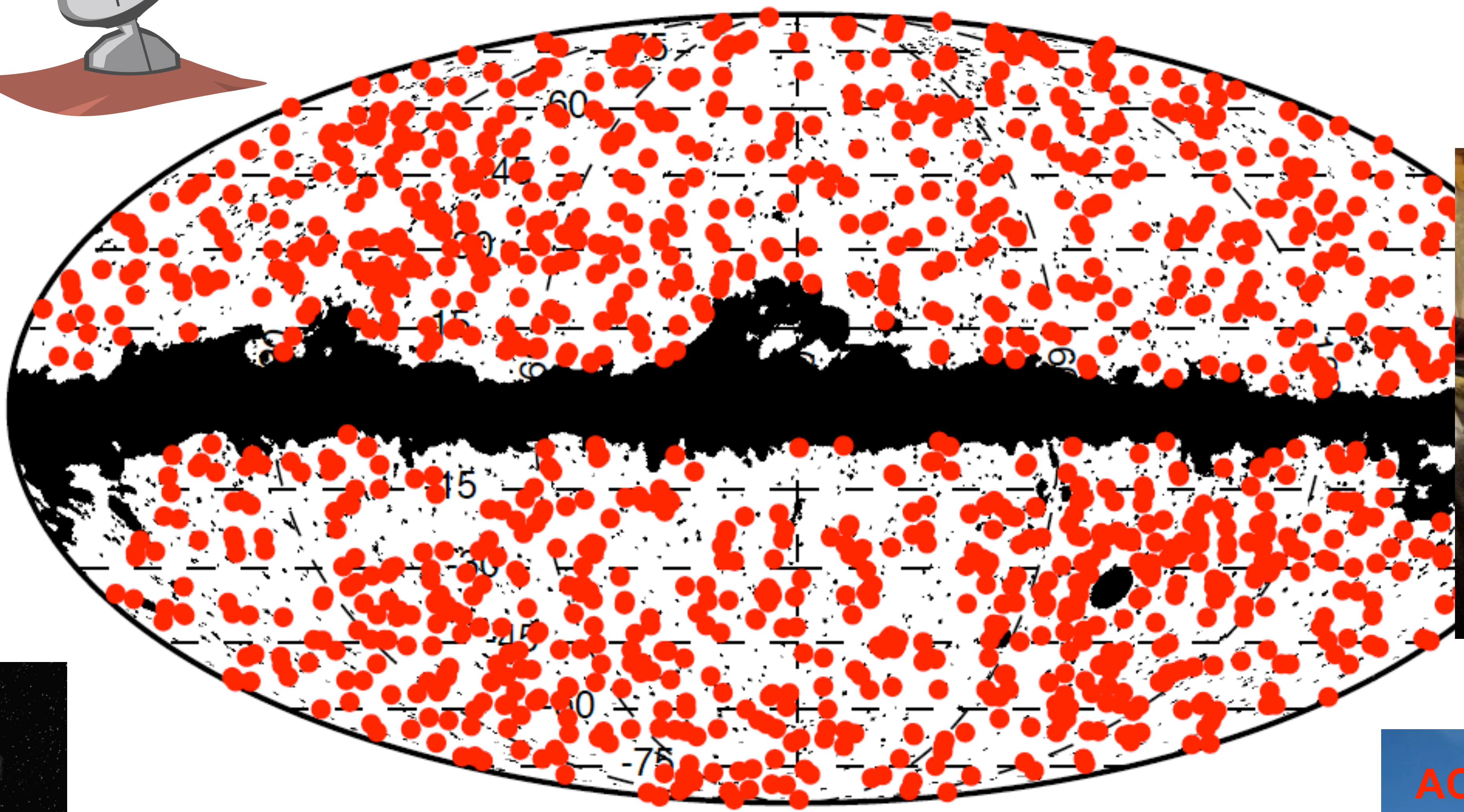
Space Science Reviews, 215, 2019 (arXiv:1811.02310)

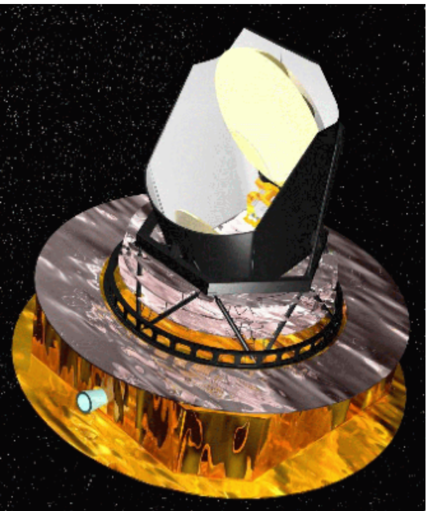
Thermal SZ effect is now routinely observed!





~ 2000 objects





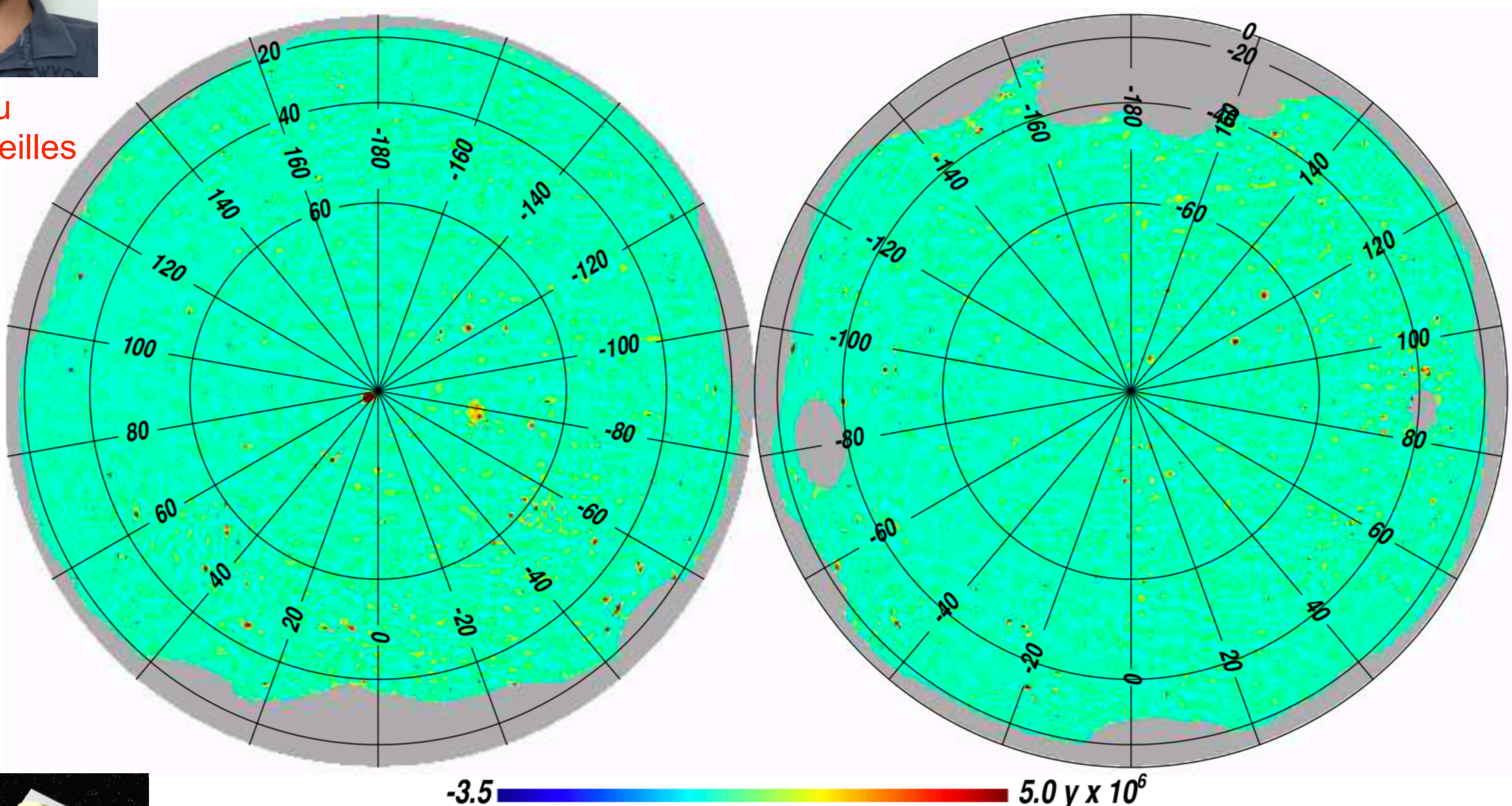
Planck Collaboration, 2013, paper XXIV

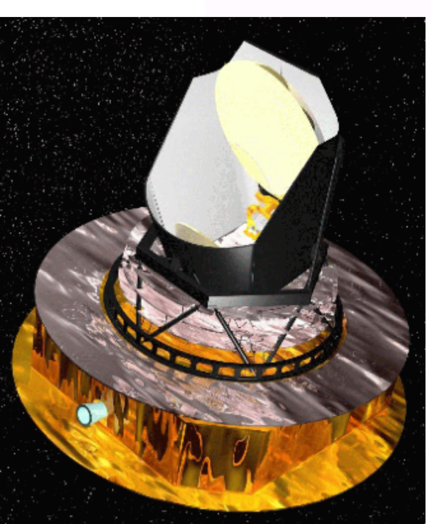
Planck Collaboration, 2015, paper XXIV

Mathieu
Remazeilles

All-sky Compton *y*-map from Planck

NILC tSZ map



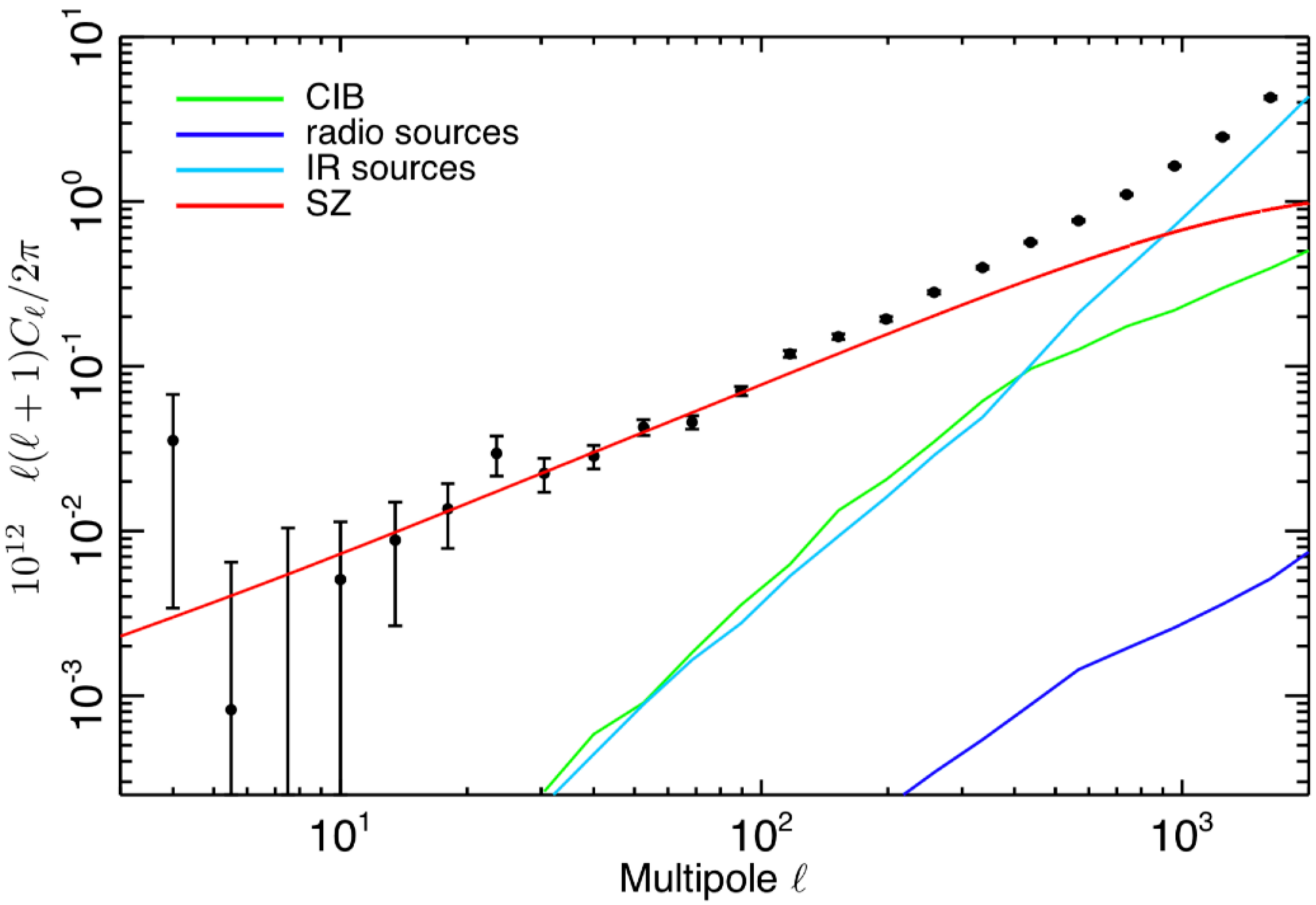


Planck Collaboration, 2013, paper XXI
Planck Collaboration, 2015, paper XXII

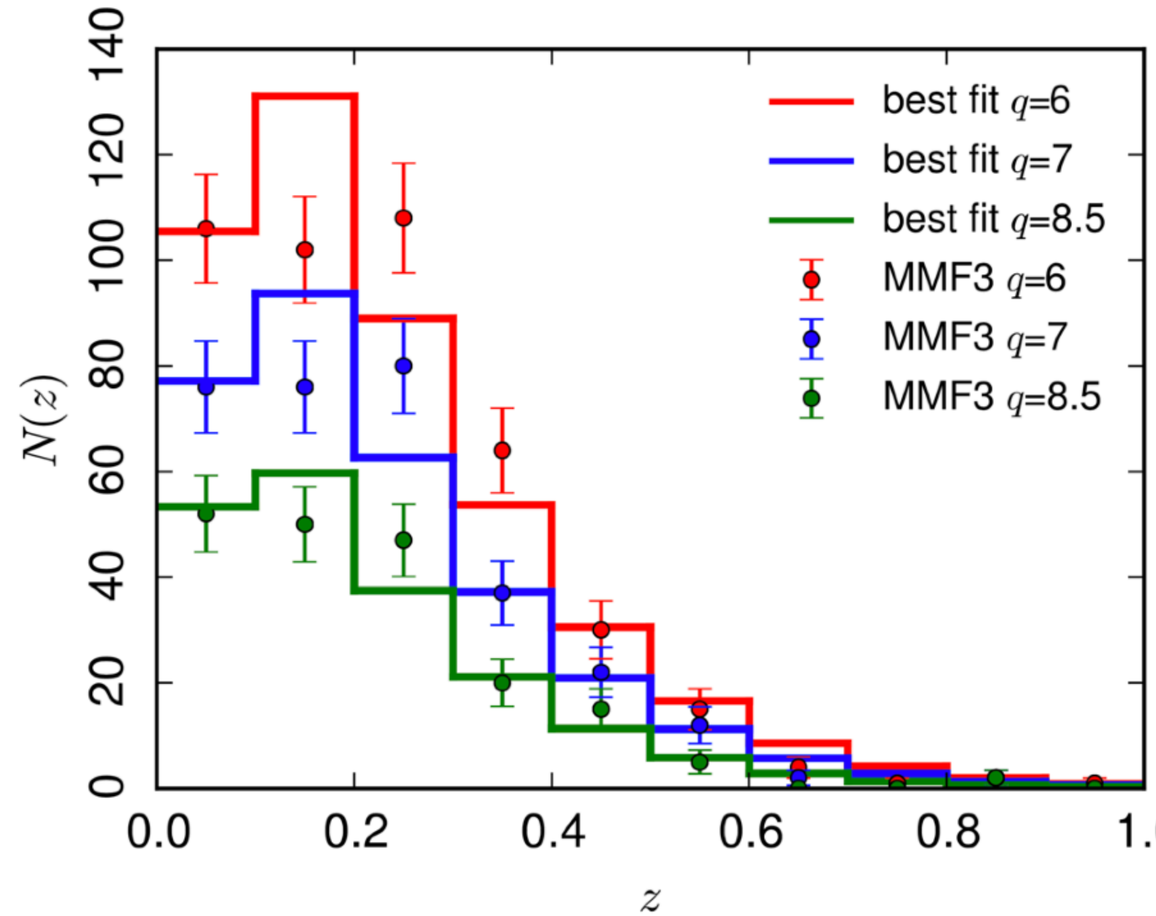
Map was produced by Mathieu Remazeilles

Planck SZ analysis

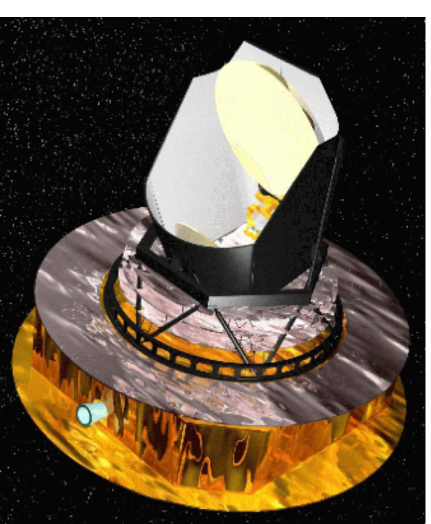
Power spectrum



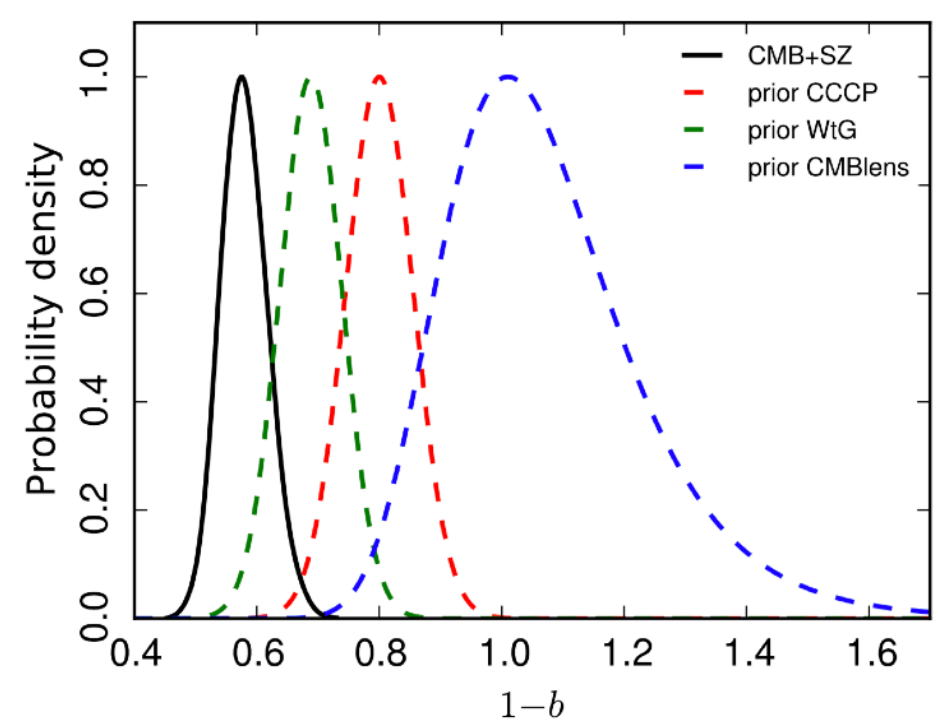
Number counts



- SZ results on σ_8 in tension with CMB only result
- Hydrostatic mass bias
- Dependence on combination of data and modeling details



Planck Collaboration, 2015, paper XXIV
Planck Collaboration, 2015, paper XXII



Future opportunities for rSZ studies

- Tens of thousands of clusters will be detected through the tSZ effect
- Unprecedented sensitivity, frequency coverage and angular resolution (e.g., SO, CCAT-prime, Millimetron, PICO…)
- Complements X-ray and lensing measurements

Individual systems

- y-maps, T_e-maps & velocity (?) maps
- Reconstruction of cluster profiles
- Non-thermal SZ (cosmic rays and turbulence)

Stacking analysis

- rSZ in mass bins
- Self-calibration of SZ temperature-mass relation
- Cosmology with new SZ observables (↔ moments)

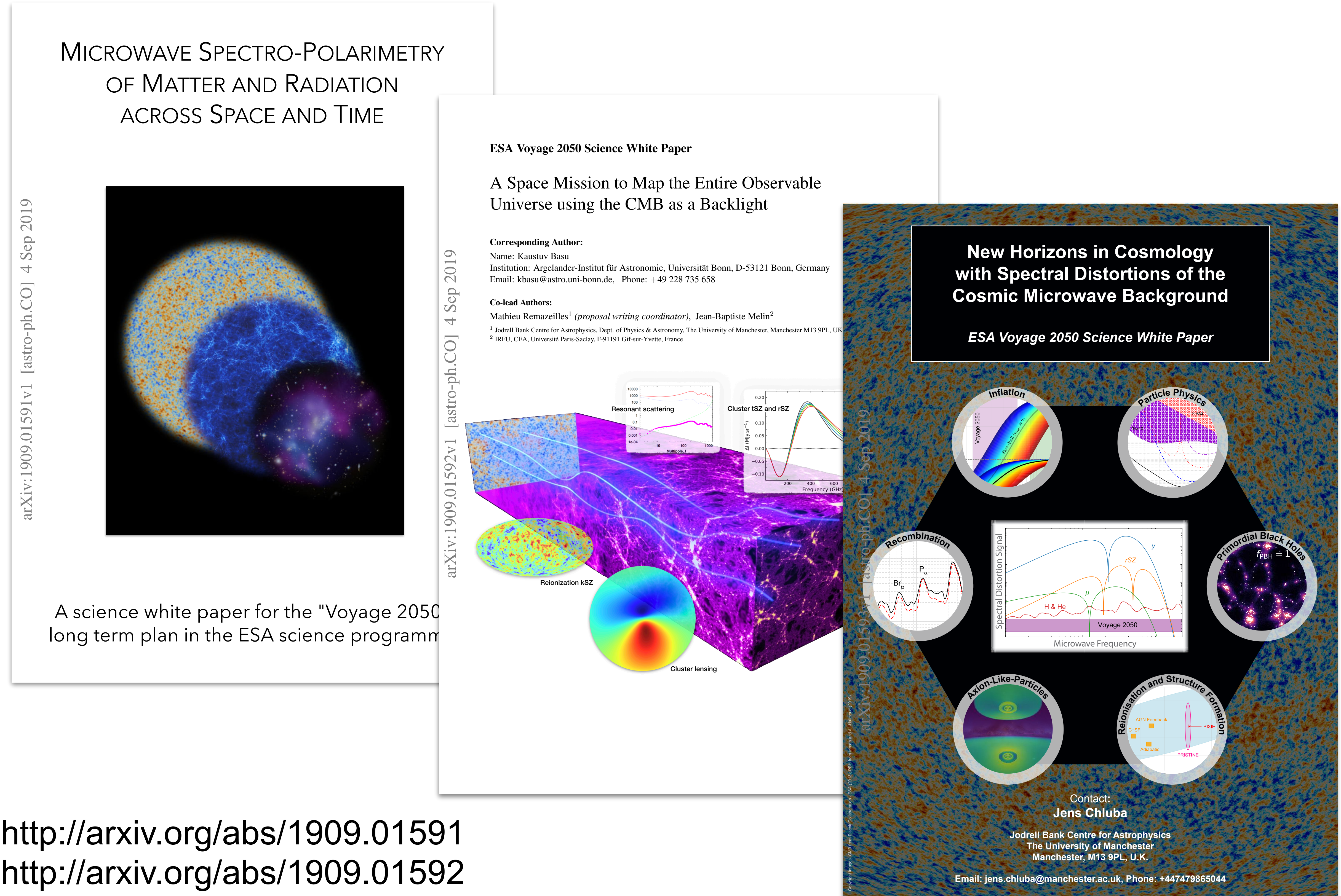
Statistical analysis

- rSZ power spectrum
- Cluster number counts in mass and redshift bins
- Higher order statistics (↔ non-Gaussianity)

Highly relevant when using SZ clusters as a cosmological tool

(↔ neutrino masses, σ_8, dark energy)

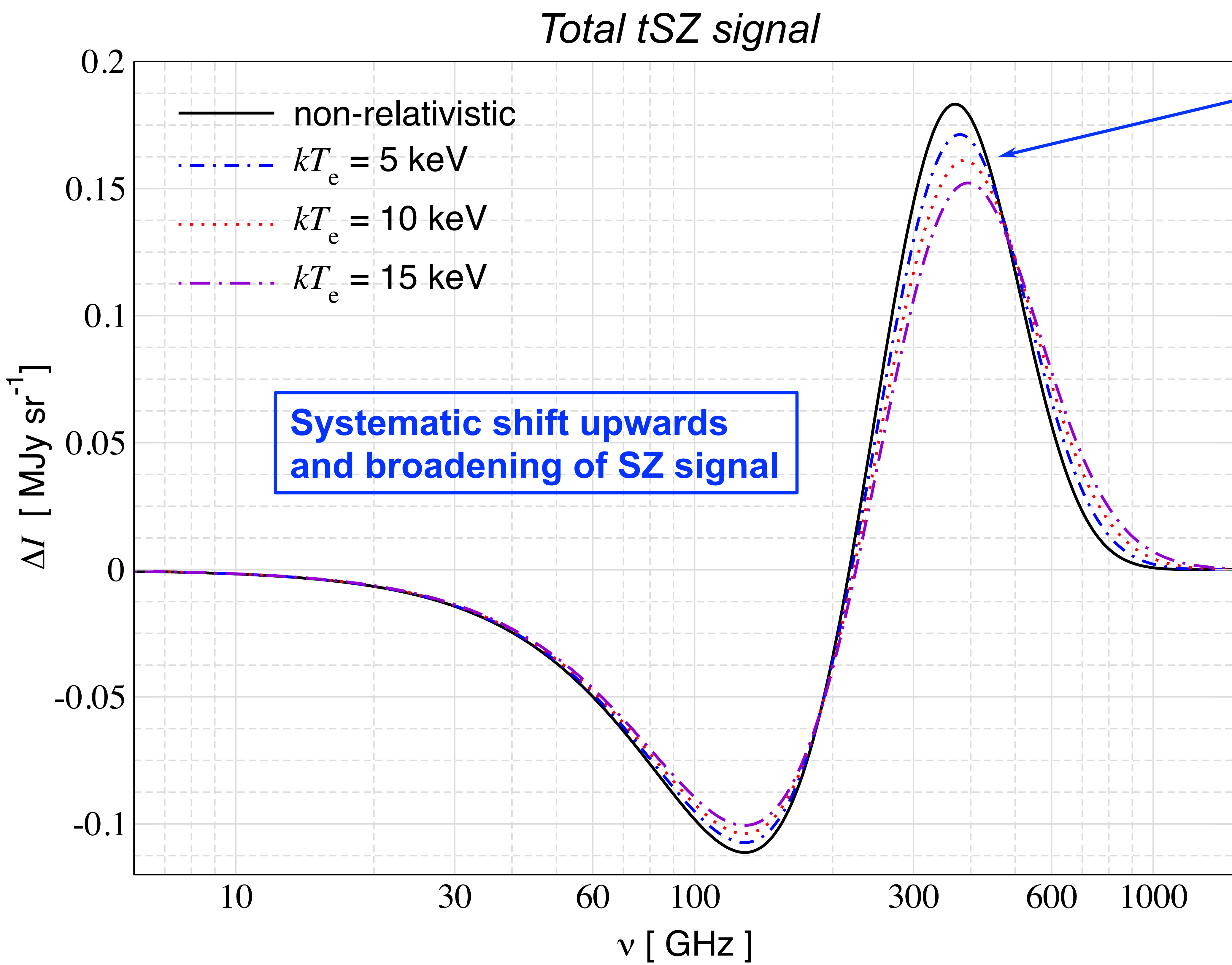
ESA Voyage 2050 White Papers



http://arxiv.org/abs/1909.01591
http://arxiv.org/abs/1909.01592
http://arxiv.org/abs/1909.01593

What is the role of relativistic SZ (rSZ) in this?

Effect of relativistic temperature corrections



A lot of information about rSZ from high frequency part

Classical formula assumes v/c<<1

For 5 keV cluster ⇒

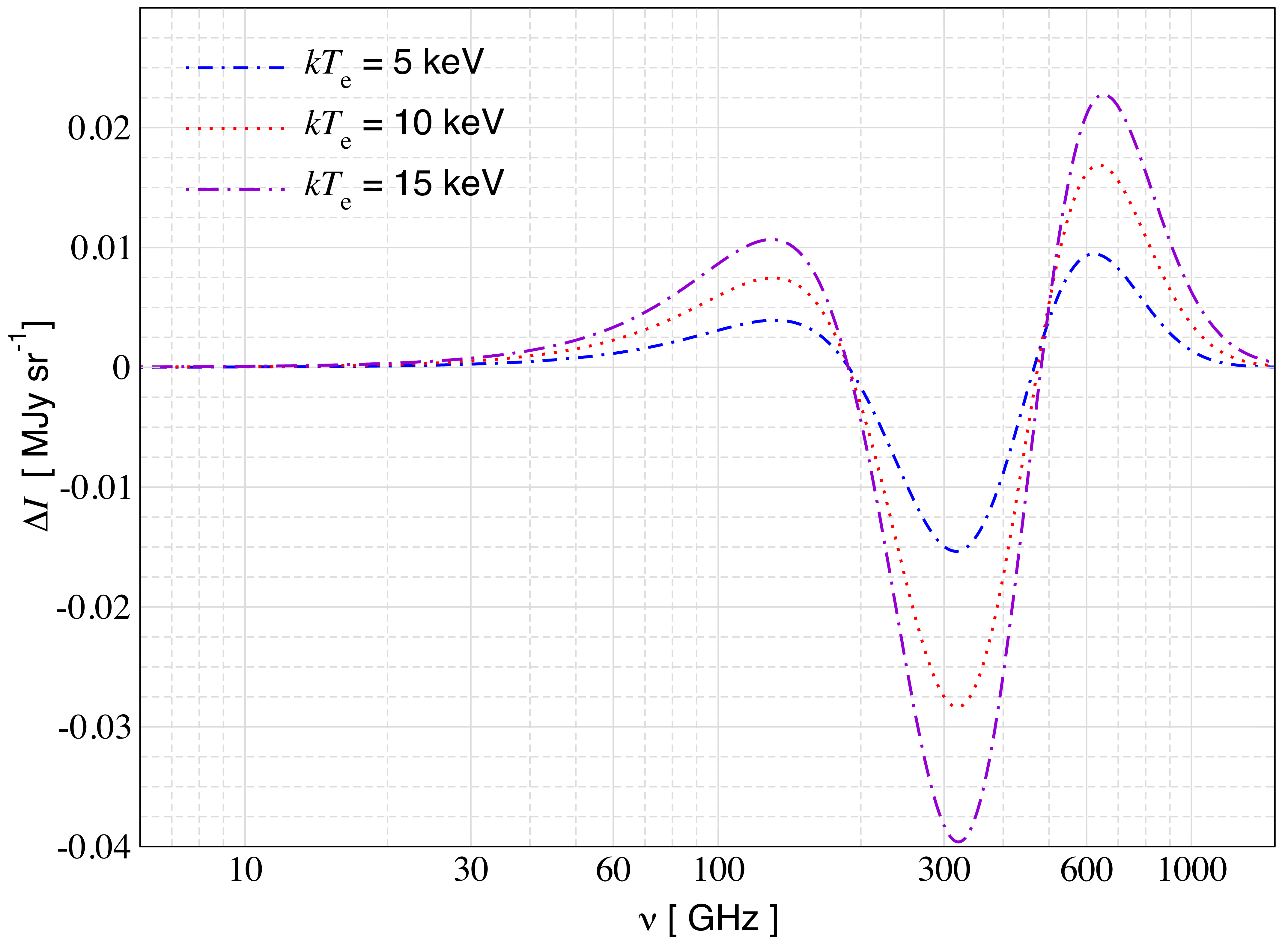
Relativistic electron velocities!

$$v_{\rm th} \simeq 0.1c$$

$y = 10^{-4}$

High frequencies are crucial for rSZ!

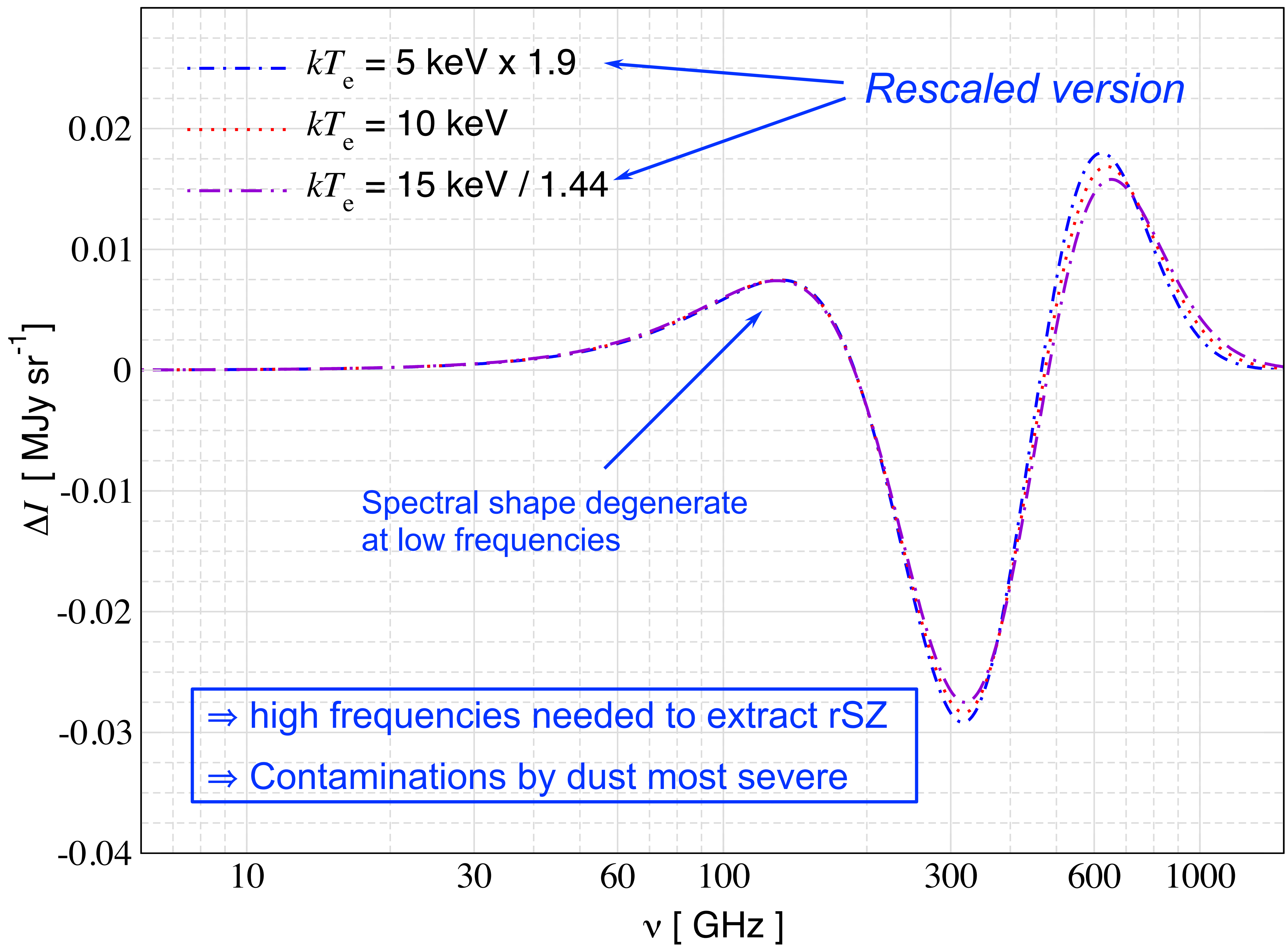
Relativistic correction signal only



$y = 10^{-4}$

High frequencies are crucial for rSZ!

Relativistic correction signal only



$y = 10^{-4}$

High-frequency spectrum has to be computed carefully…

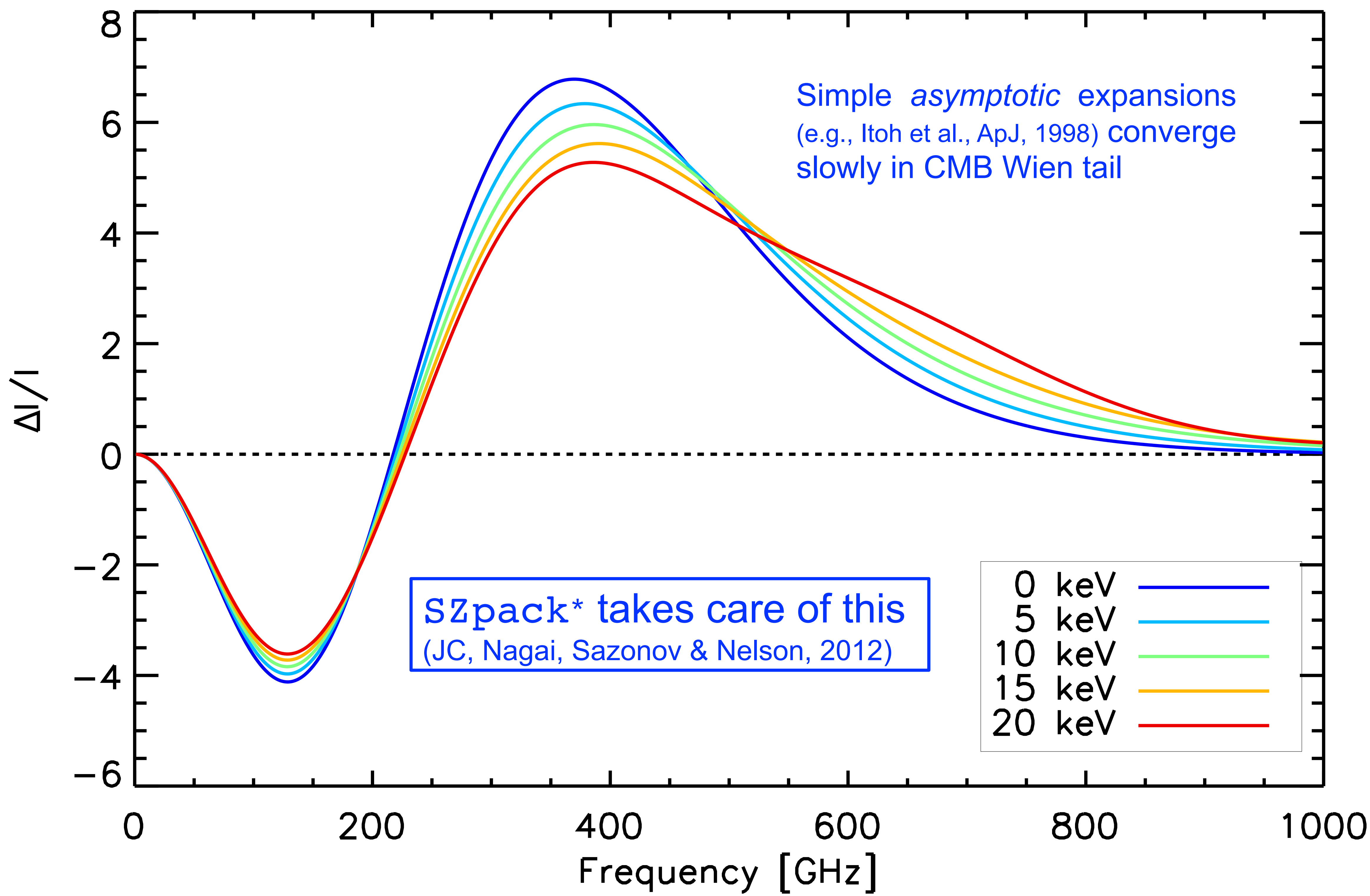
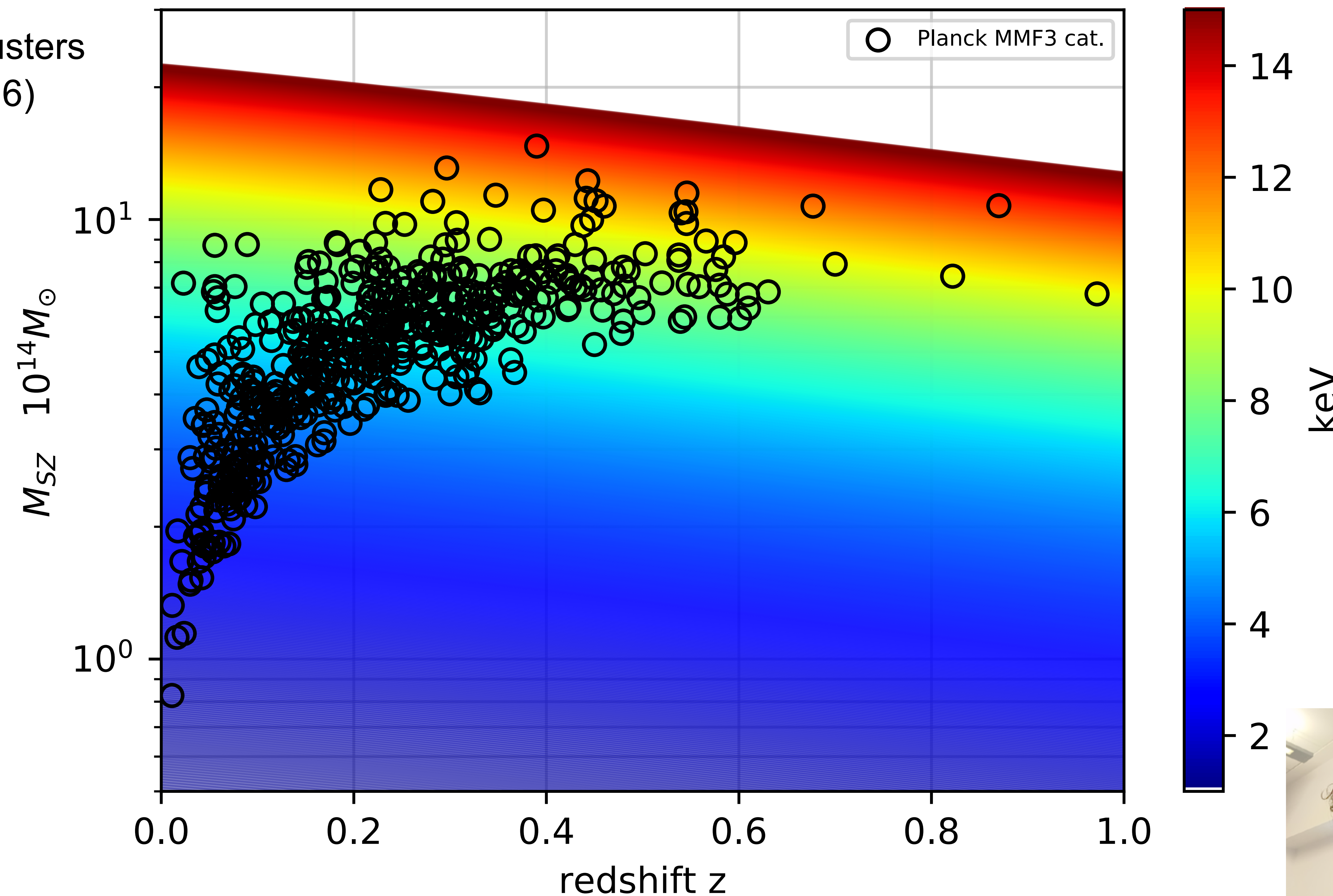


Figure from Hurier, 2016, ArXiv:1701.09020

*www.Chluba.de/SZpack

Clusters seen by Planck are pretty hot!

439 clusters
(S/N > 6)

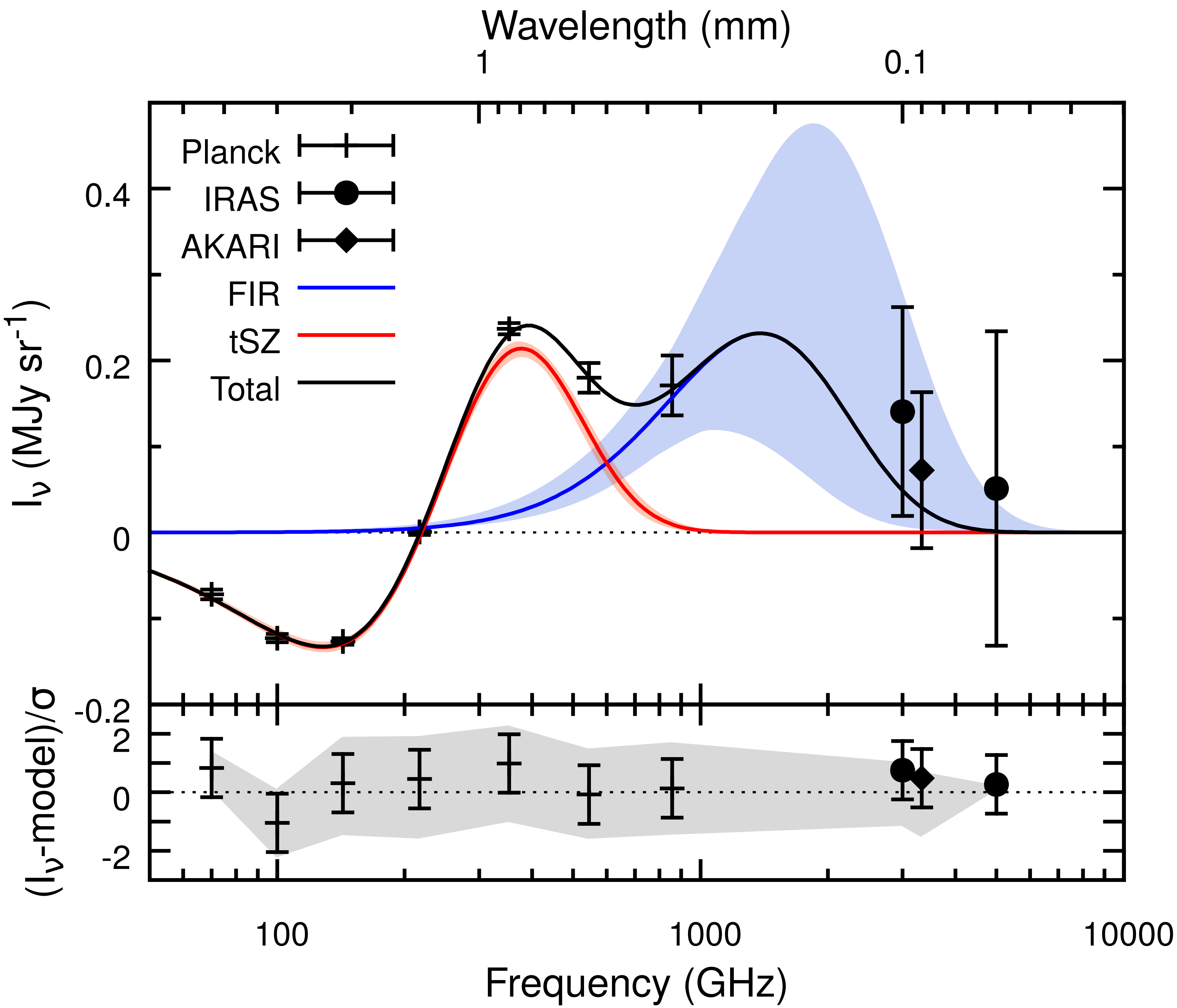


Standard (X-ray)
temperature mass-relation
(e.g., Arnaud et al., 2005, Erler et al. 2018)

$$kT_{\rm e} \simeq 5\,{\rm keV}\left[\frac{E(z)\,M_{500}}{3\times10^{14}h^{-1}\,M_{\odot}}\right]^{2/3}$$

Rotti, Bolliet, Remazeilles & JC, in prep

Stacked Planck tSZ signal + foregrounds



- Matched filter approach
- Combination of data
- 772 clusters (PSZ2)

$$y_0 = 1.24^{+0.04}_{-0.04} \times 10^{-4}$$

$$k_B T_{SZ} = 4.36^{+2.13}_{-1.95}\ \text{keV}$$

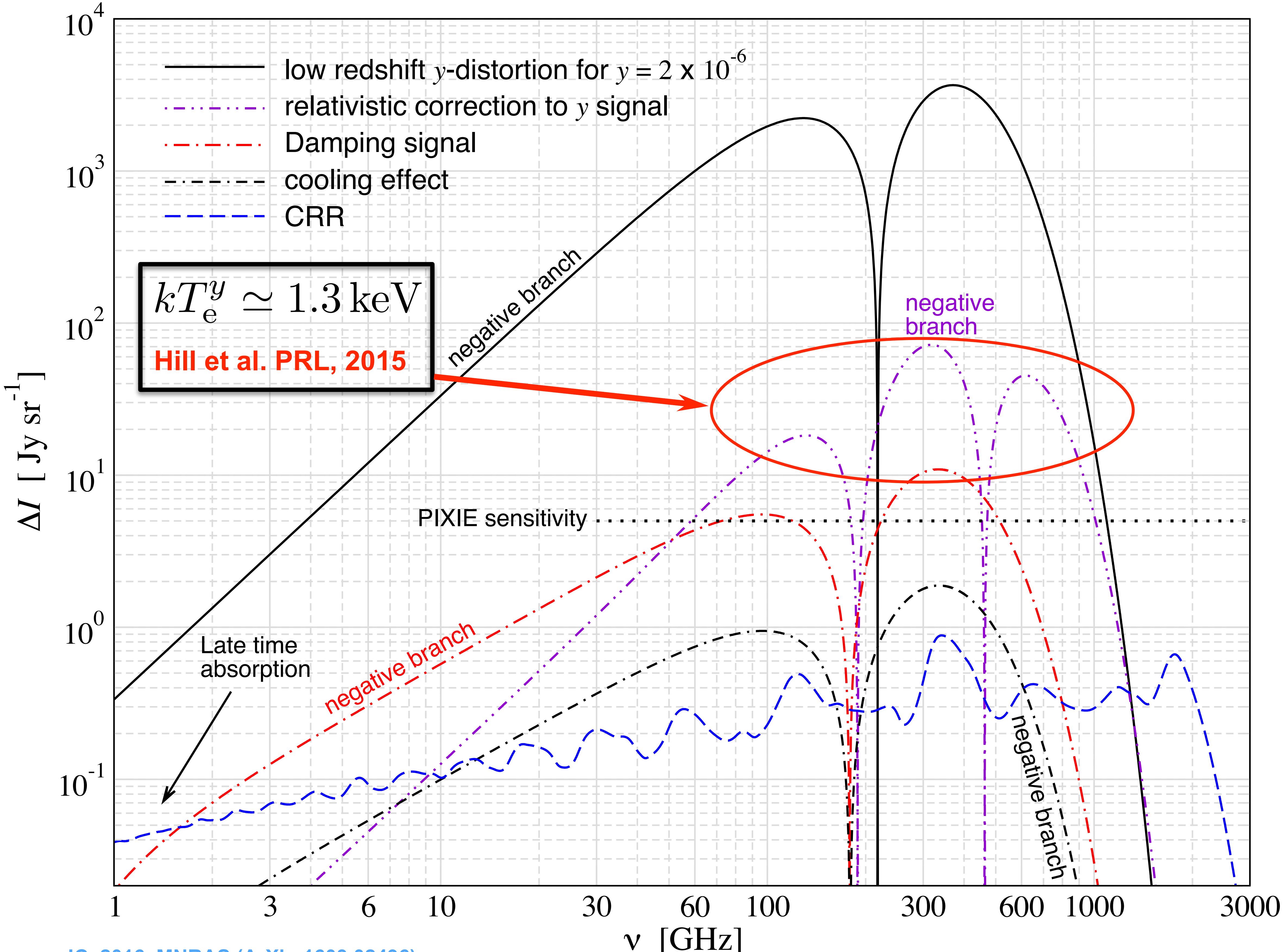
- rSZ at ~2.2 σ level
- In tension with Hurier, A&A, 2016 (claimed ~ 5 σ detection)
- 100 hottest clusters:

$$k_B T_{SZ} = 5.96^{+3.78}_{-2.93}\ \text{keV}$$

Erler, Basu, JC & Bertoldi, 2018, ArXiv:1709.01187

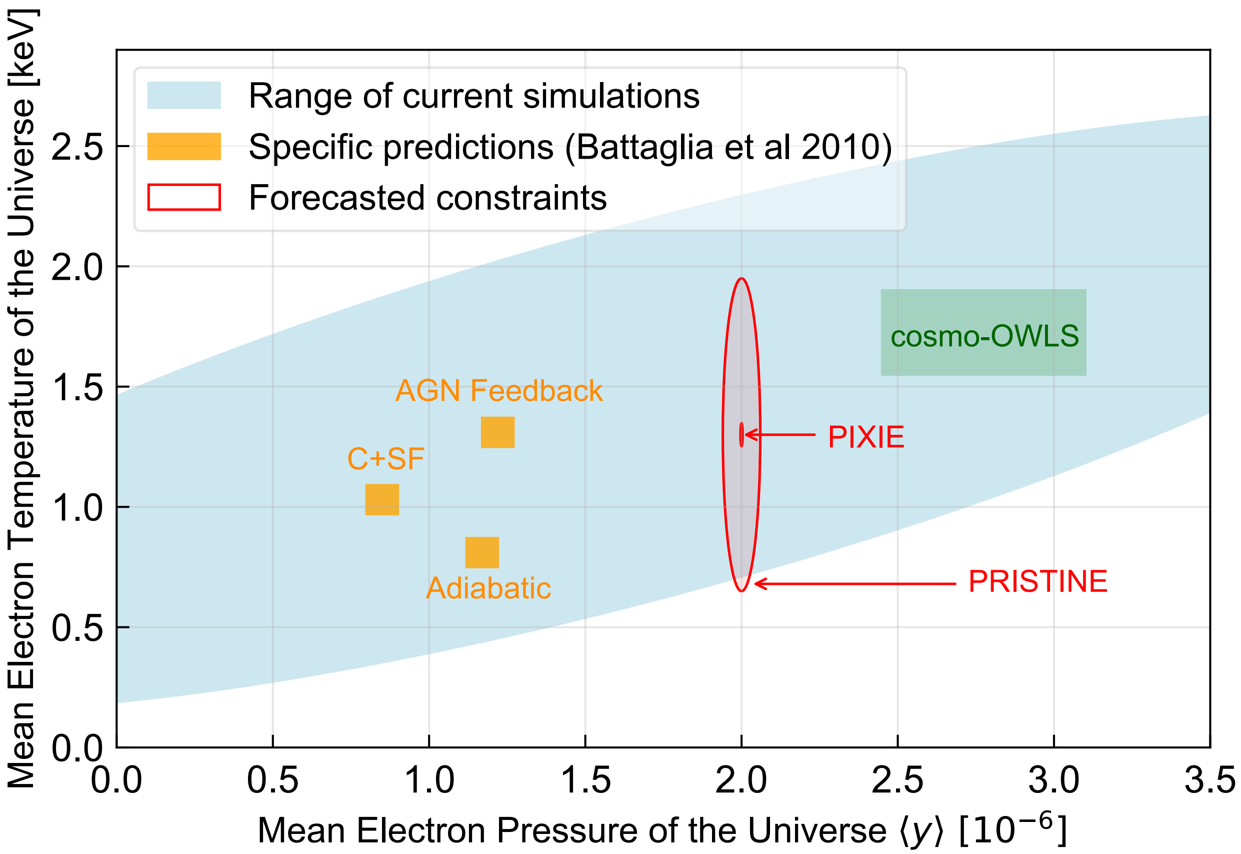
⇒ typical y-weighted temperature of ~ 4-7 keV quite reasonable

Average CMB spectral distortions

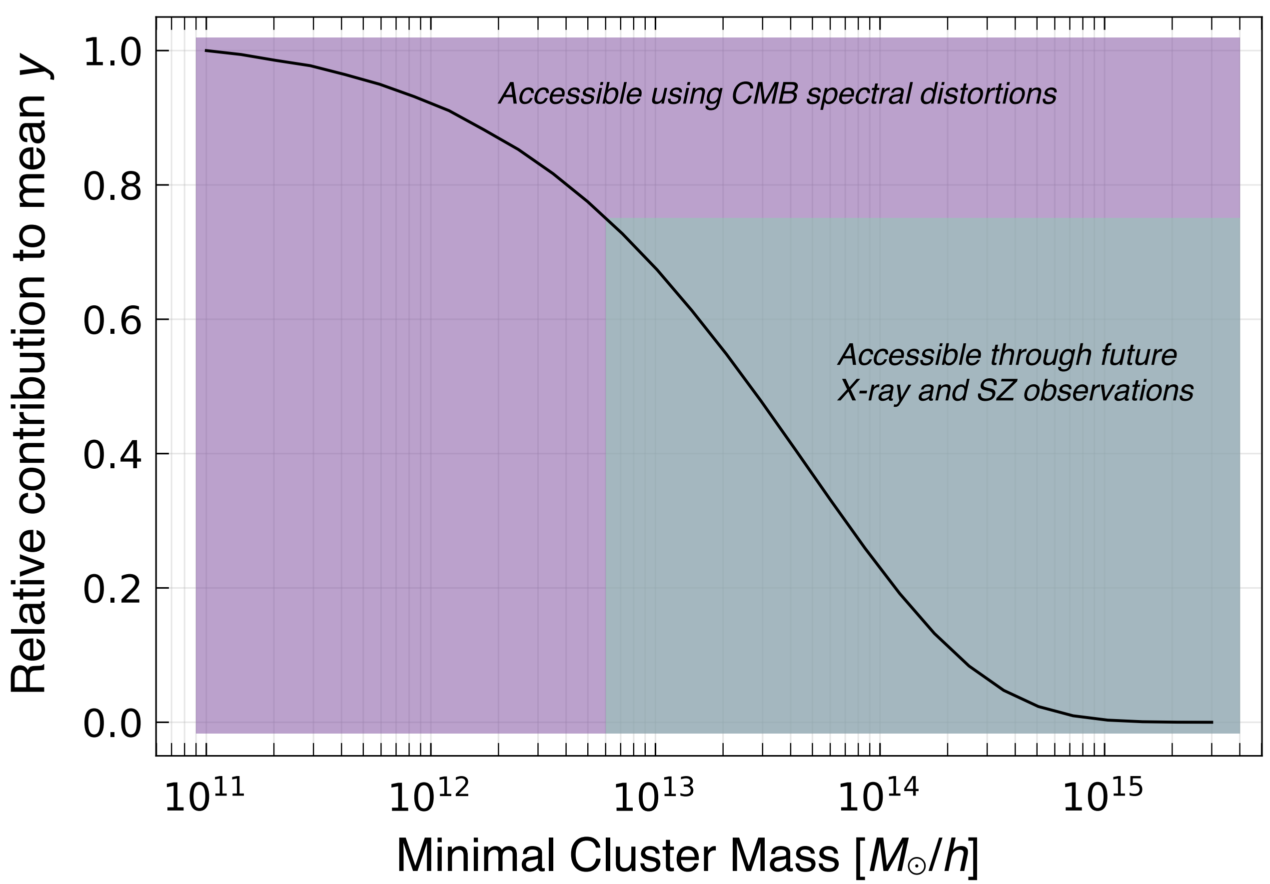


JC, 2016, MNRAS (ArXiv:1603.02496)

Learning about feedback processes using average rSZ



- Models highly uncertain
- Tight constraints from spectral distortions
- *Census* of all the hot gas in the Universe from *y* parameter

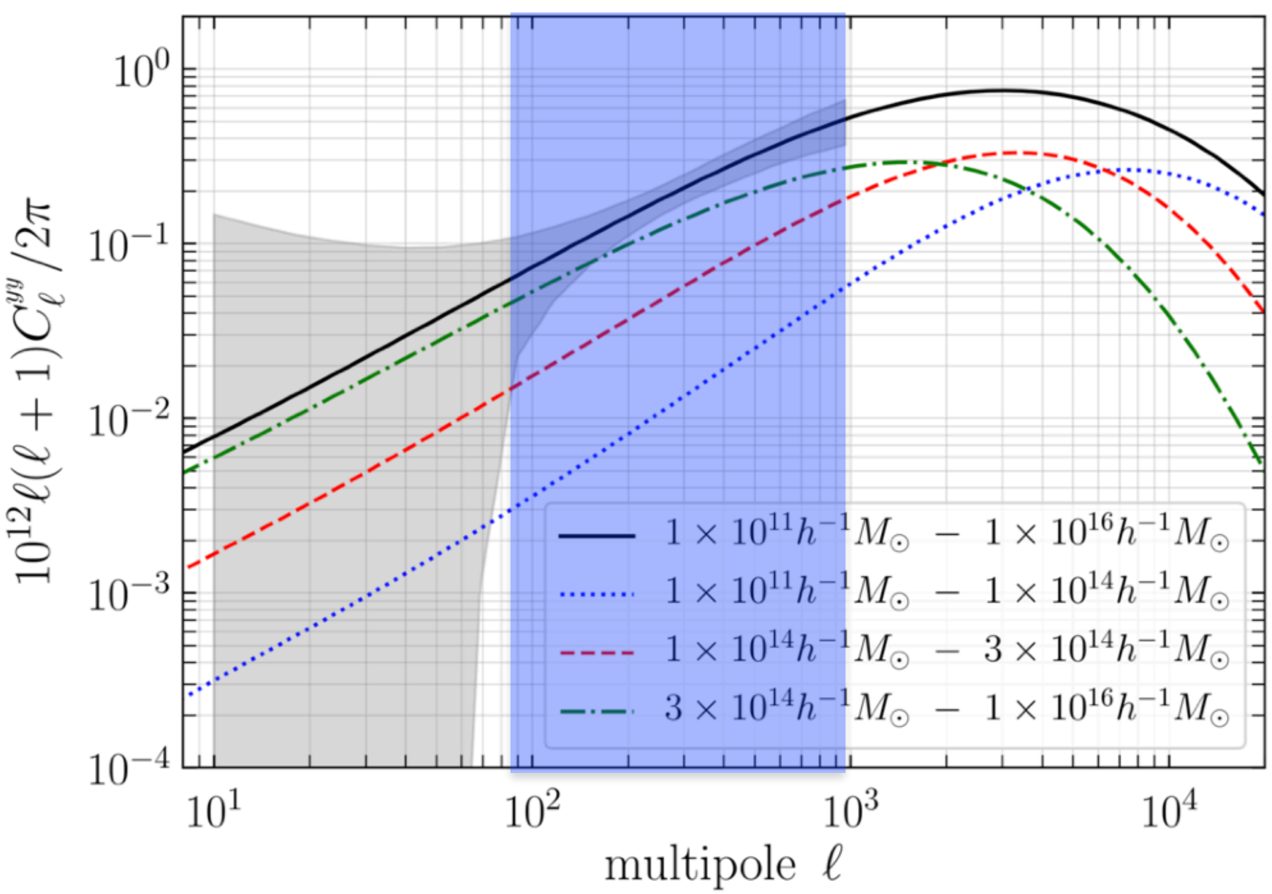


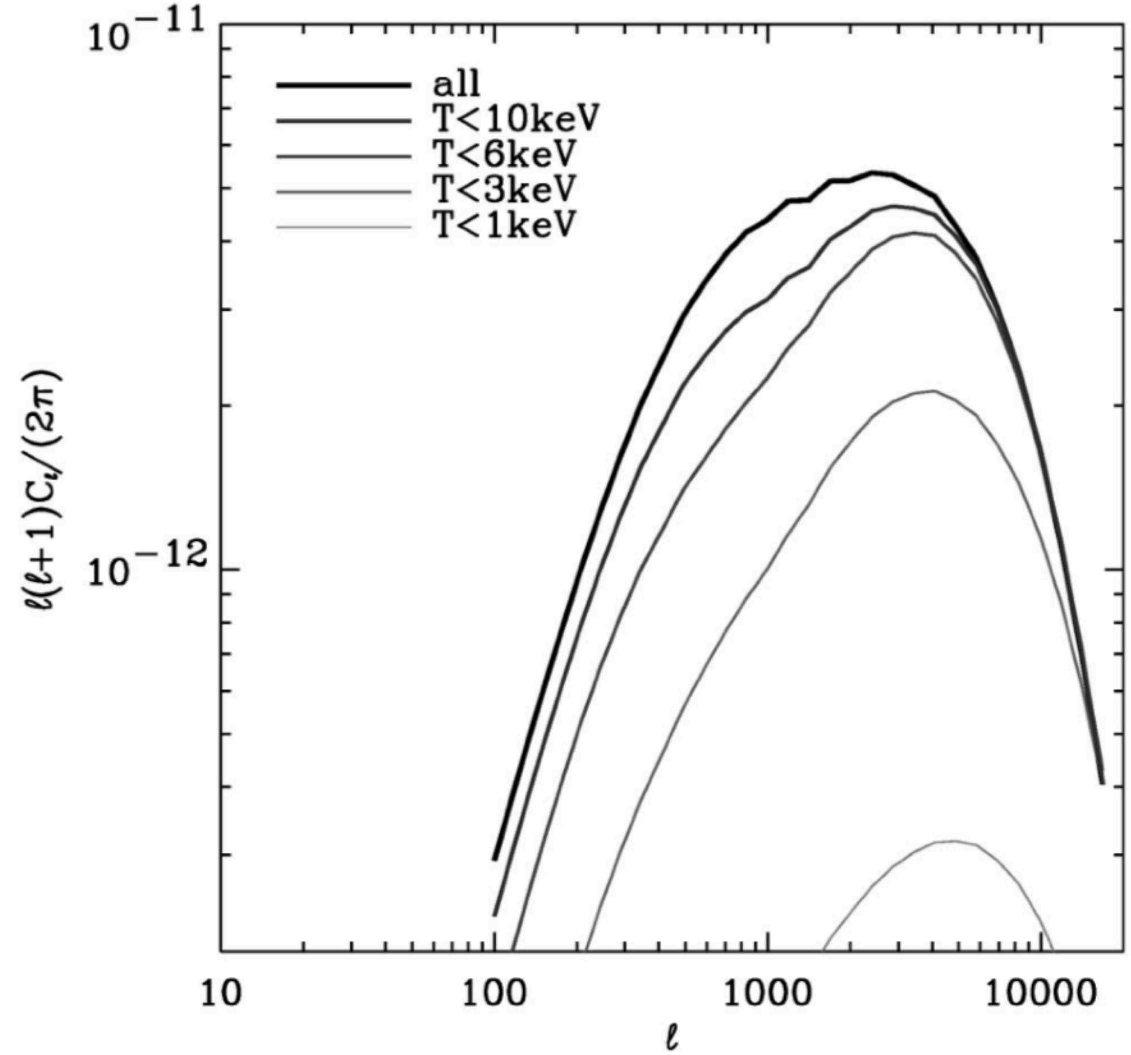
Bolliet et al., in prep

http://arxiv.org/abs/1909.01593

Theoretical SZ power spectrum computations

Computation with `CLASS-SZ` (Bolliet et al., 2017)





Refregier et al., 2000

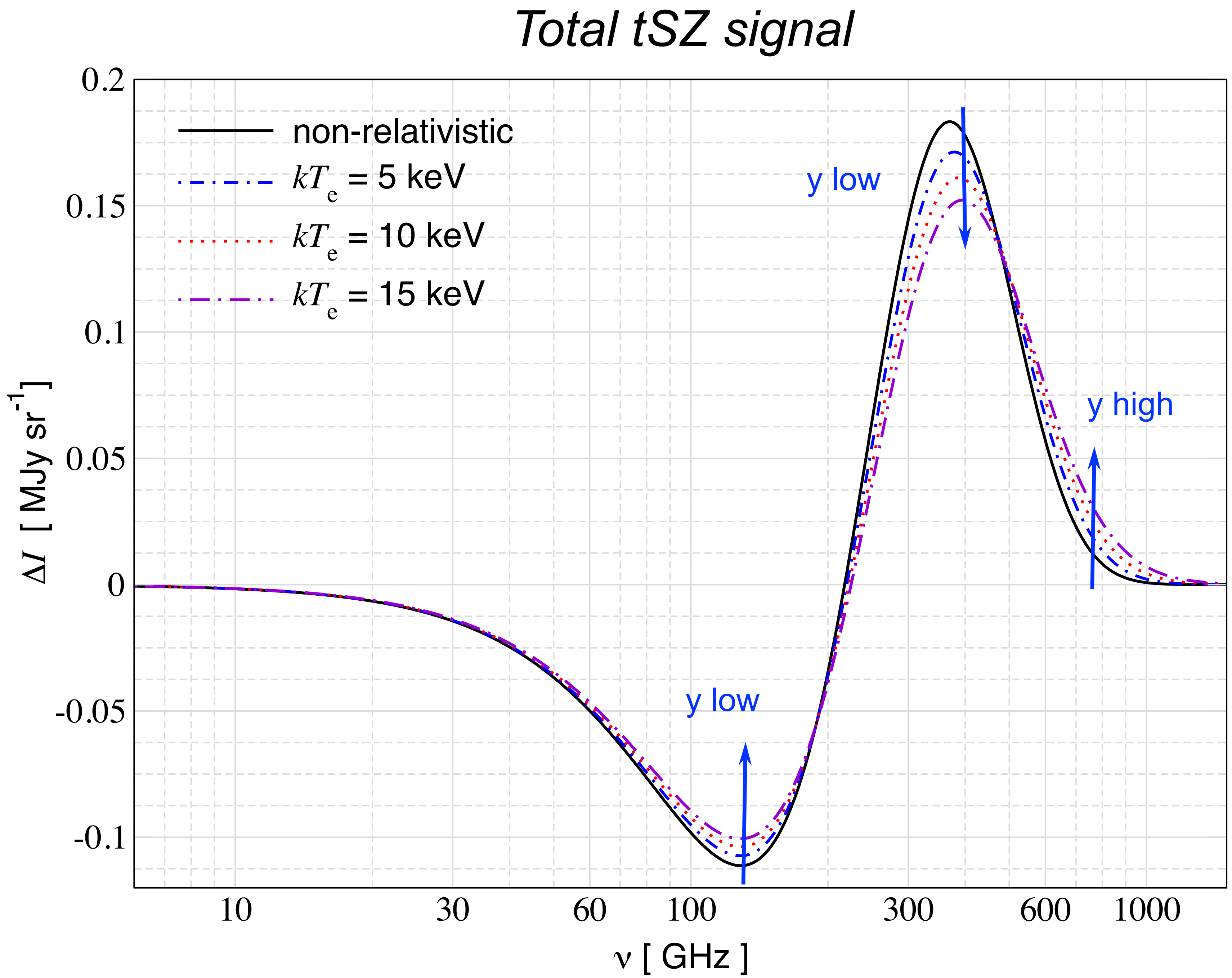
From Komatsu & Seljak, 2002:

$$C_l = \int_0^{z_{\max}} \mathrm{d}z \frac{\mathrm{d}V}{\mathrm{d}z} \int_{M_{\min}}^{M_{\max}} \mathrm{d}M \underbrace{\frac{\mathrm{d}n(M,z)}{\mathrm{d}M}}_{\textit{halo mass function}} \underbrace{|\tilde{y}_l(M,z)|^2}_{\textit{cluster pressure profile}}$$

→ temperature of systems contributing to the multipole range relevant to *Planck*'s C_l analysis seems > 5 keV

Remazeilles, Bolliet, Rotti & JC, MNRAS, 2019

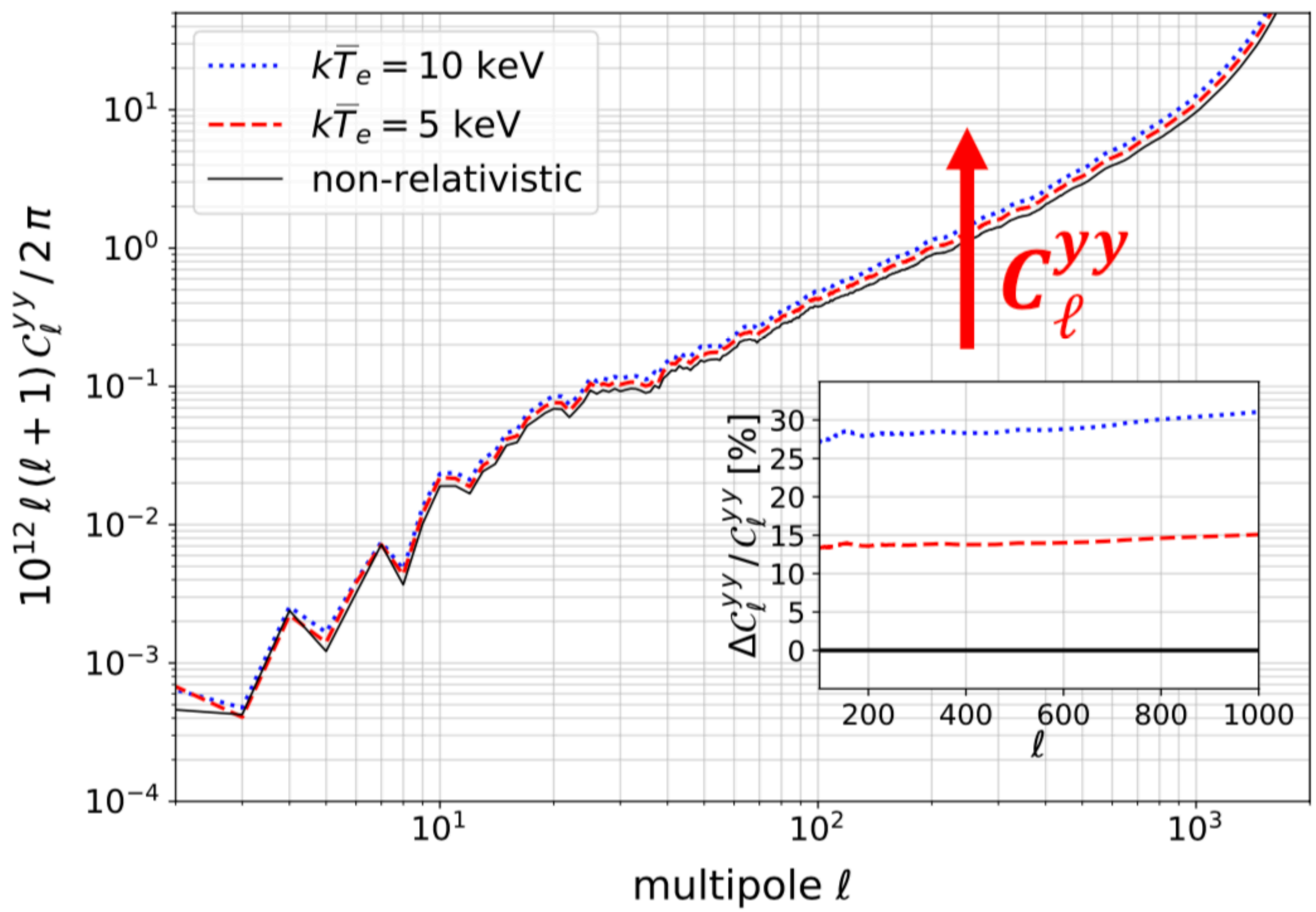
What is the net effect of rSZ on the y-parameter?



- Obtained *y*-parameter is underestimated by ~7% for kT_e ~ 5 keV for *Planck*
- This is consistent with 353 GHz channel driving the effect for *Planck* data
- Also consistent with Erler et al. 2018 ILC analysis
- Total effect generally depends on frequency configuration and ability to subtract foregrounds (Rotti et al., in prep.)

Remazeilles, Bolliet, Rotti & JC, MNRAS, 2019

Updating the *Planck* y-map power spectrum



Planck C_ℓ^{yy} increases with average cluster temperature $\bar{T}_e$

$$C_\ell^{yy} \propto \sigma_8^{8.1} \Longrightarrow \boxed{\frac{\Delta\sigma_8}{\sigma_8} \simeq 0.019\left(\frac{k\bar{T}_e}{5\text{ keV}}\right)}$$

$\simeq 1\sigma$ *increase*
for $\bar{T}_e \simeq 5$ *keV !*

Remazeilles, Bolliet, Rotti, Chluba (2018)

Courtesy Mathieu Remazeilles

Which effective electron temperature should be used?

- Single cluster / stacking → *y*-weighted temperature is relevant

$$kT_{\rm e}^{y} = \frac{\left\langle kT_{\rm e}\, y\right\rangle}{\left\langle y\right\rangle} = \frac{\int kT_{\rm e}^2 N_{\rm e}\,{\rm d}l}{\int T_{\rm e} N_{\rm e}\,{\rm d}l}$$

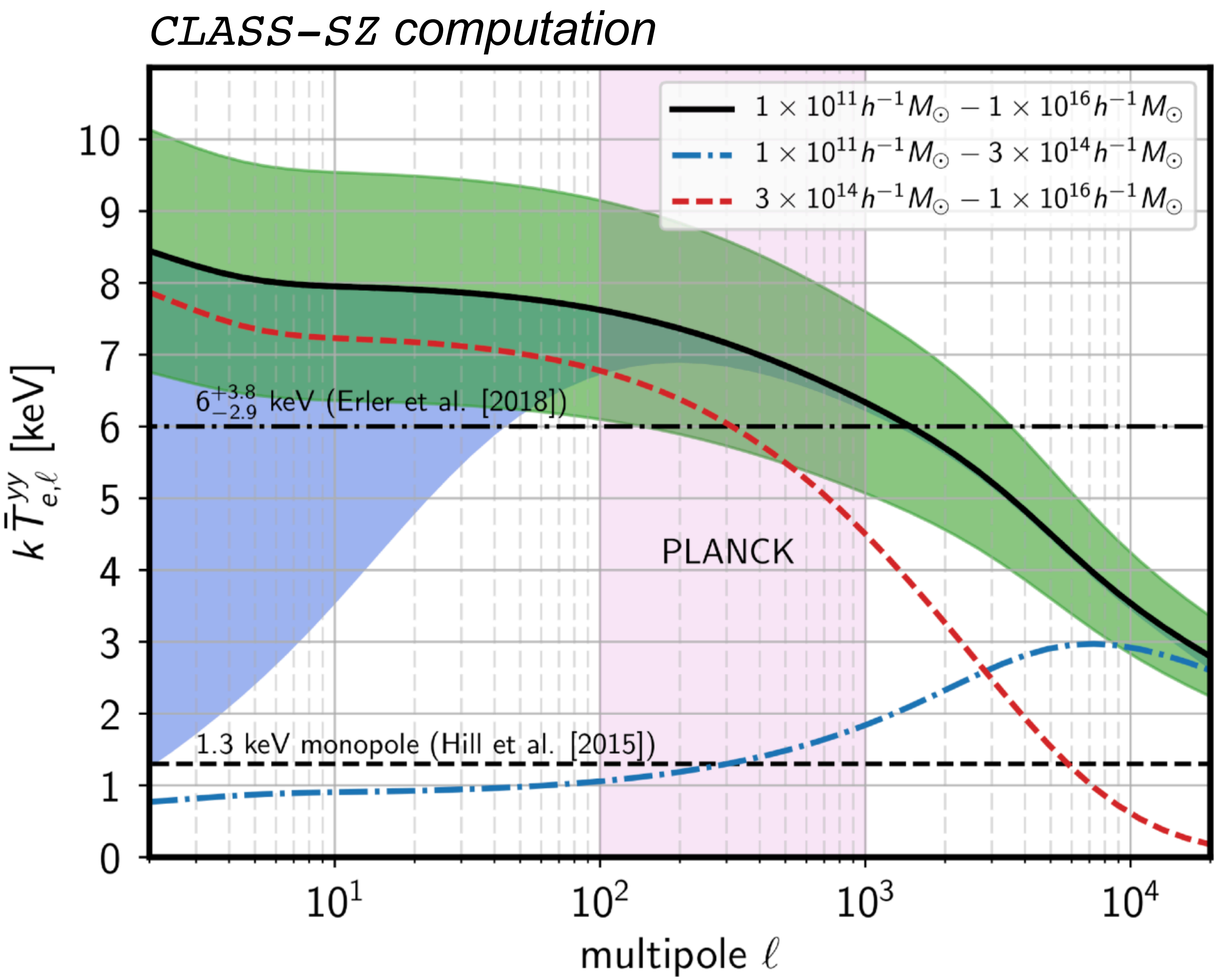
- SZ power spectrum analysis → y^2-weighted temperature is relevant

$$kT_{{\rm e},\ell}^{yy} = \frac{\left\langle kT_{\rm e}(M,z)\,|y_\ell|^2\right\rangle}{\left\langle |y_\ell|^2\right\rangle} \equiv \frac{C_\ell^{T_{\rm e},yy}}{C_\ell^{yy}}$$

- Can be efficiently computed based on the halo model using `CLASS-SZ`
- Higher mass systems are up-weighted → higher effective temperature expected
- Scale-dependent quantity (but fixed temperature captures leading order effect)!

Remazeilles, Bolliet, Rotti & JC, MNRAS, 2019

Theoretical estimate for the y^2-weighted temperature

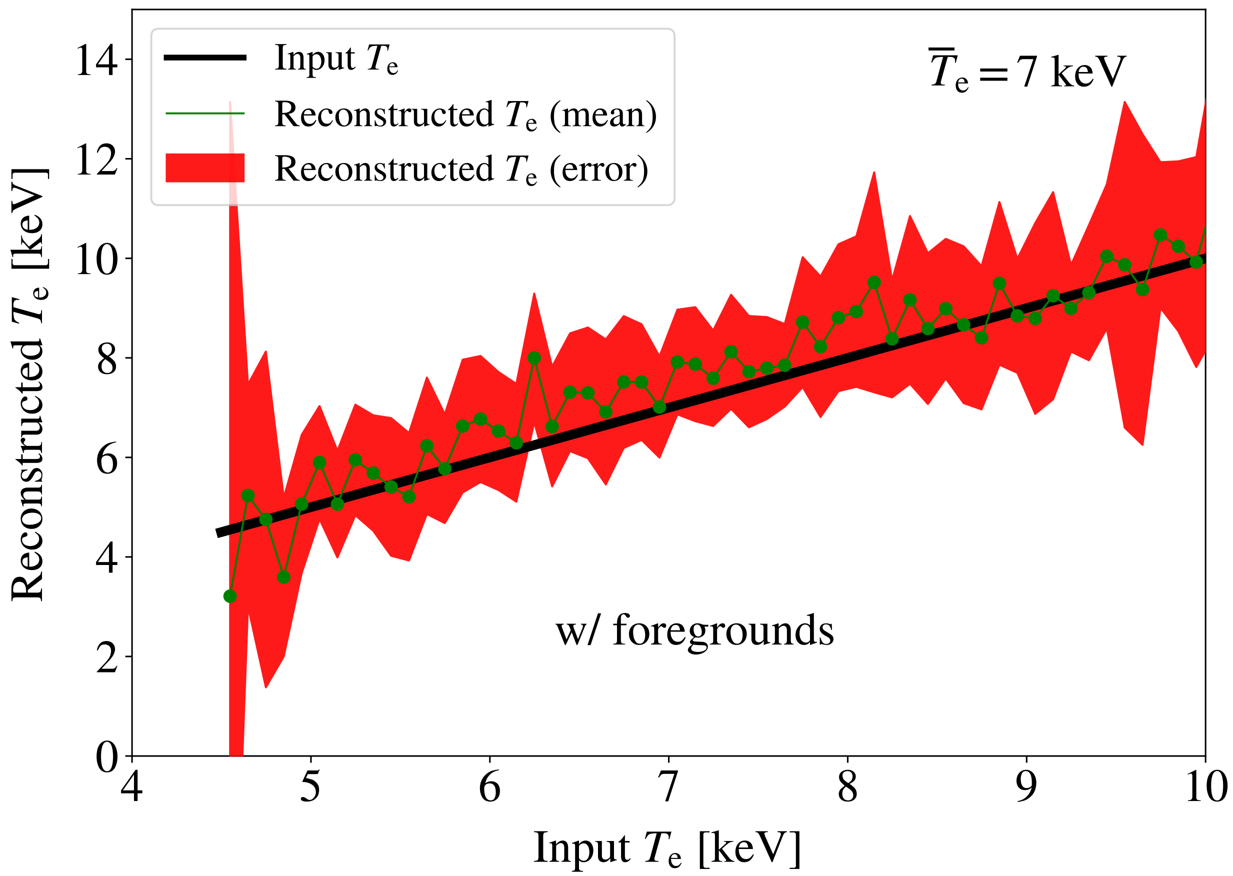


- Significant uncertainties…
- Contributions from diffuse y become important at large angular scales (e.g., Hansen et al., 2005)
- Assuming kT_e ~ 5 keV for *Planck* appears conservative
- Effective temperature is roughly constant for scales relevant to *Planck*

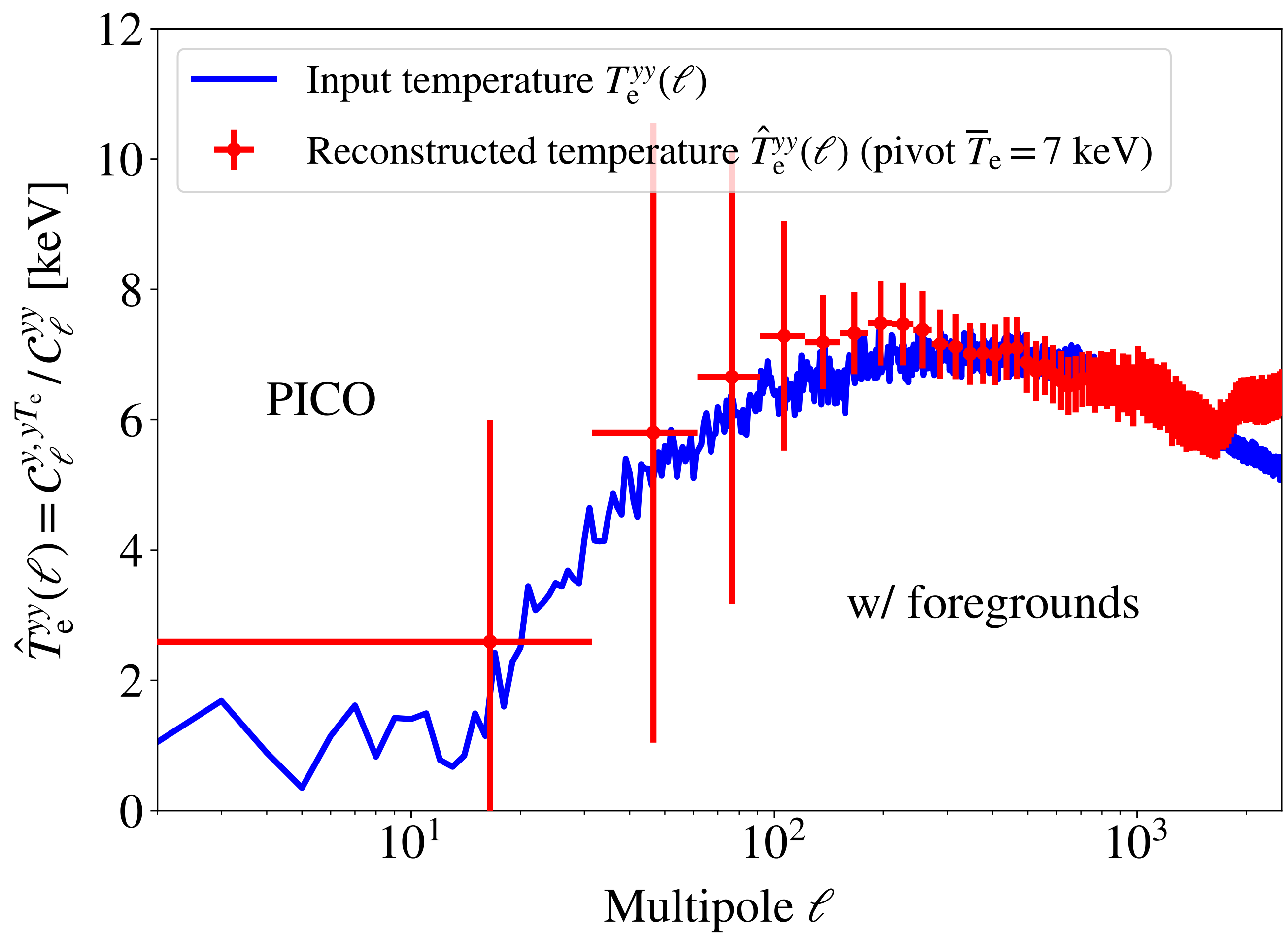
- rSZ plays a part in the σ_8 tension, alleviating it
- rSZ leads to systematic shift + increase of errors

Remazeilles, Bolliet, Rotti & JC, MNRAS, 2019

Future rSZ measurements with PICO-like experiments



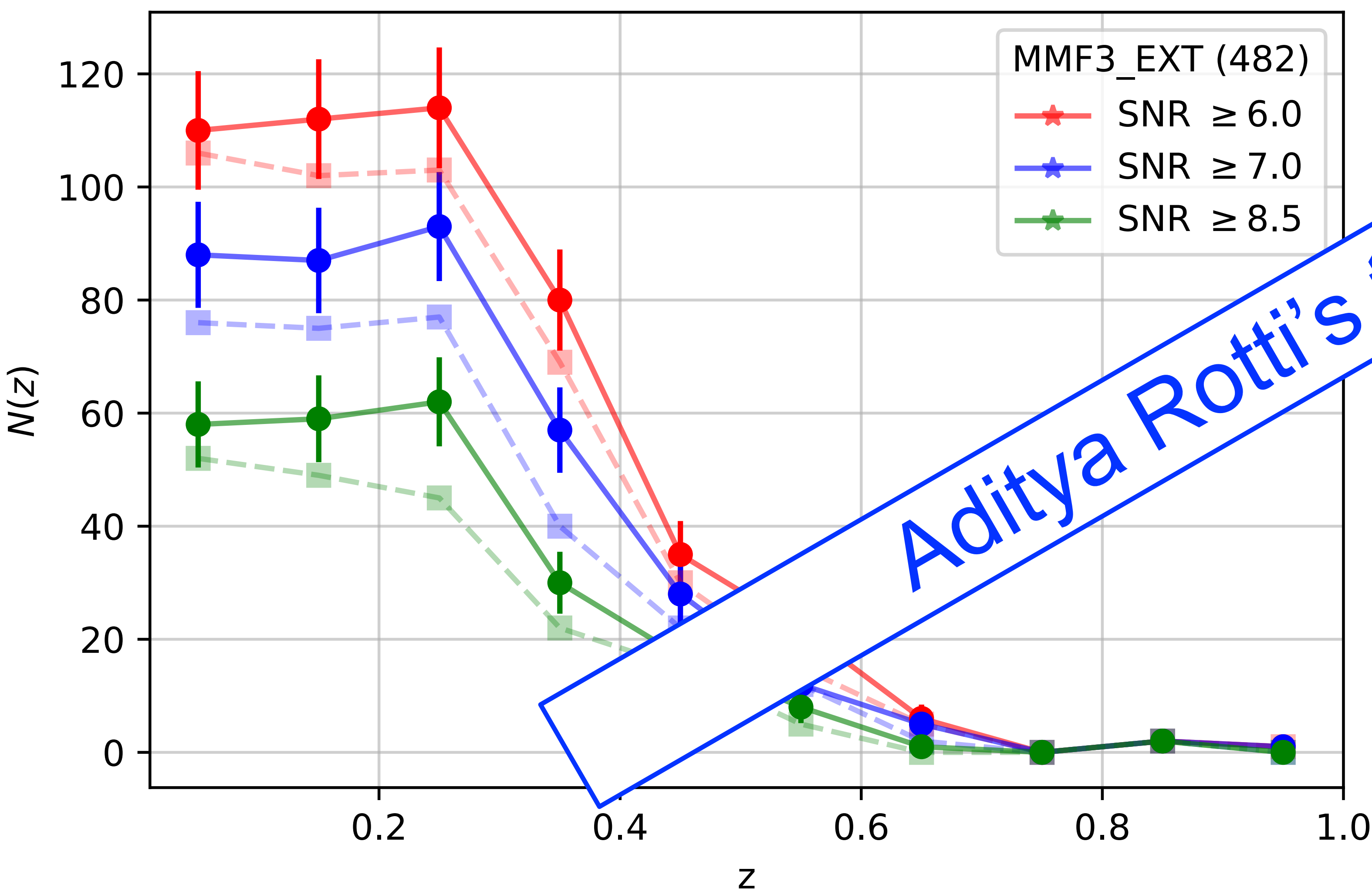
- Determination of cluster temperature using rSZ
- New mass proxy
- Self-calibration of scaling relations



- Map-based rSZ reconstruction!
- $\widehat{T}_e^{yy}(\ell)$ is new observable
- Learn about 'gastrophysics'

Remazeilles & JC, arXiv:1907.00916

Effect of rSZ on cluster number counts



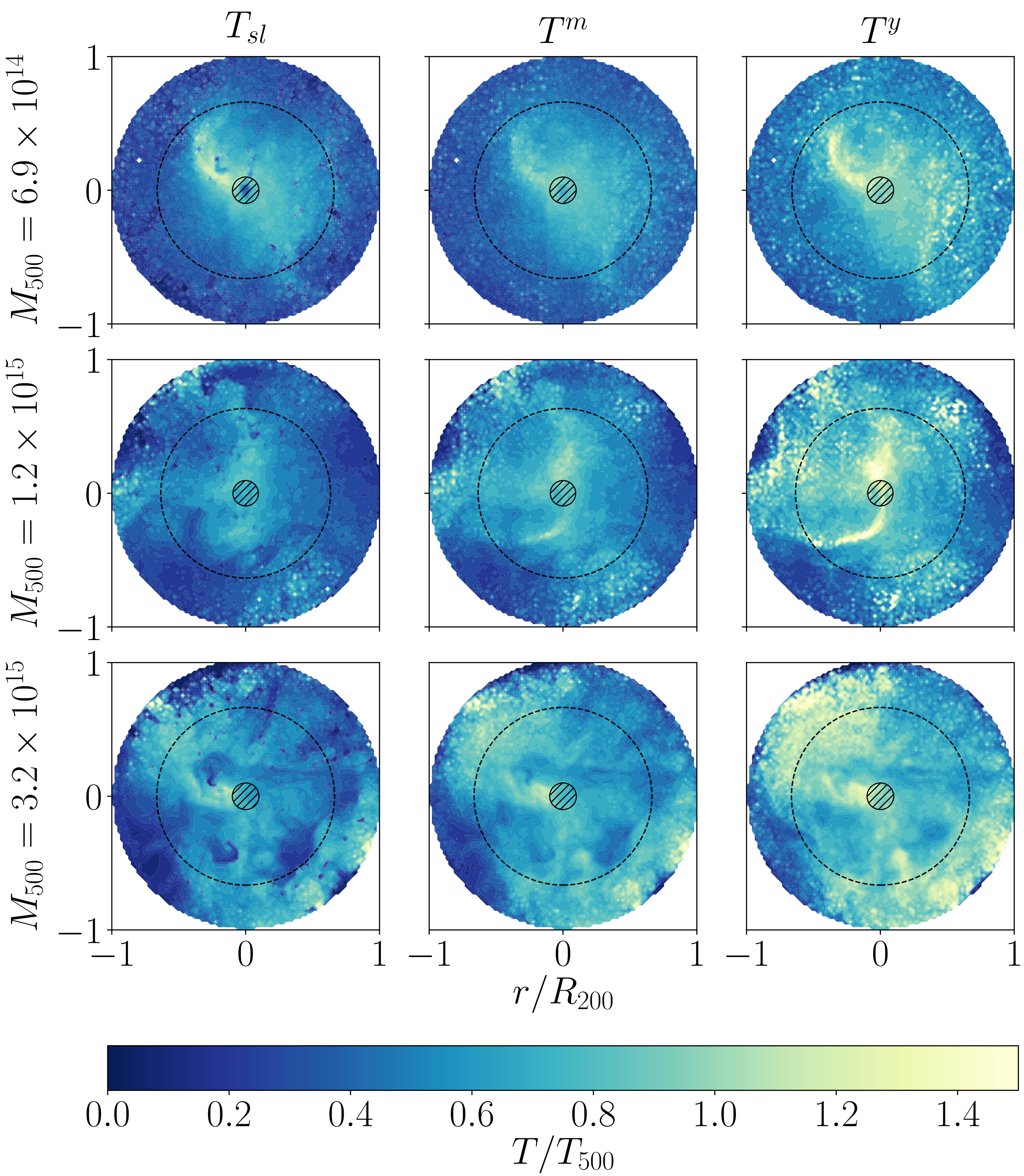
Aditya Rotti's talk

- Resc l increases
- r rSZ pushes some stems above S/N threshold
  → # of clusters increases
- Caveats regarding noise rescaling
  → filter scale also changed
- shape of *N*(*z*) seems better
- Still work in progress….

- rSZ again moves σ_8 into the right direction
- Preliminary effect found at ~1σ level

Rotti, Bolliet, Remazeilles & JC, in prep.

Temperature ≠ Temperature



- Temperature measure depends on observable
- Weighting matters
- Detailed analysis of *Bahamas* and *MACSIS* simulations:

$$T^y > T^m > T_{\rm sl}$$

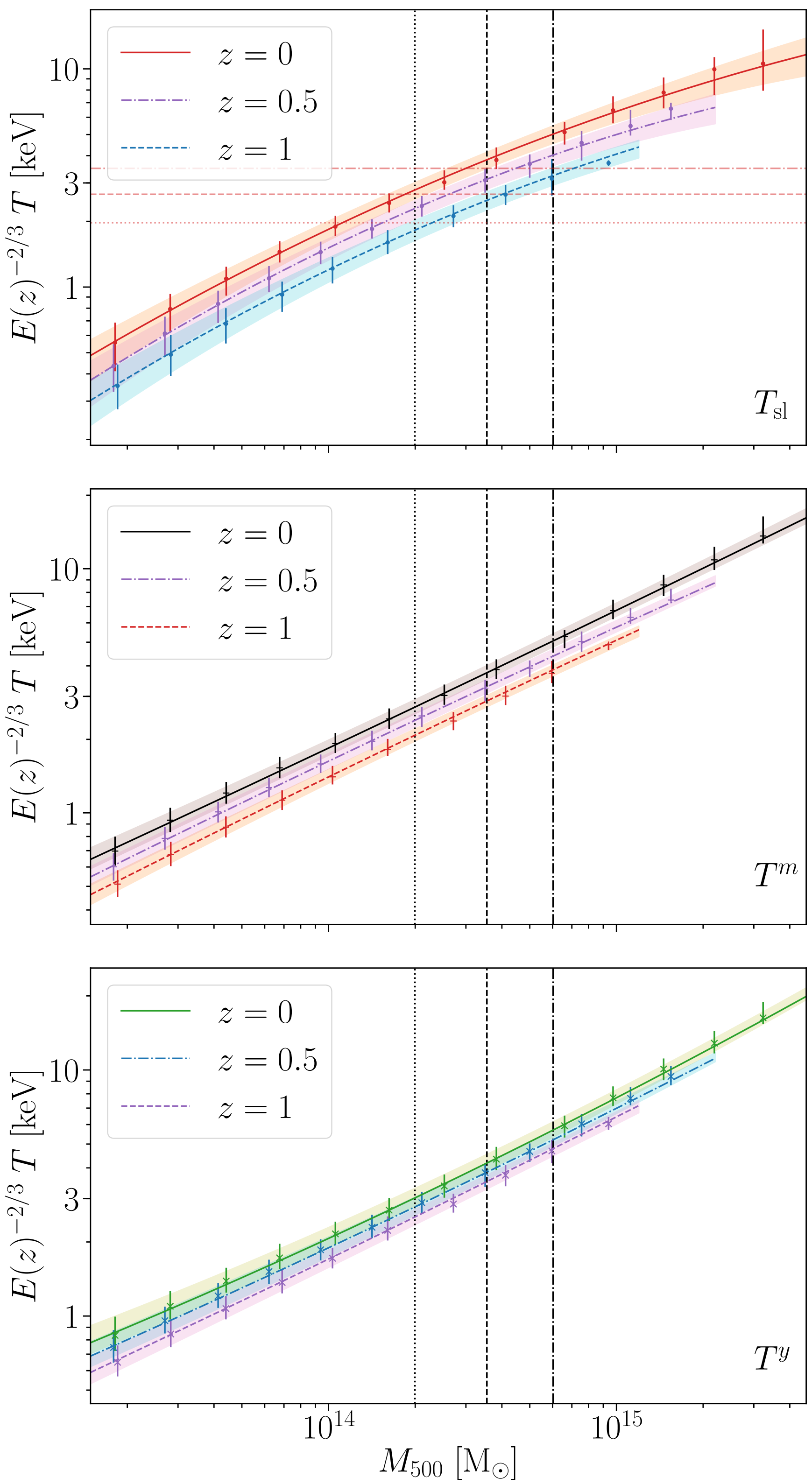
- Difference ~10%-40%

Elizabeth Lee

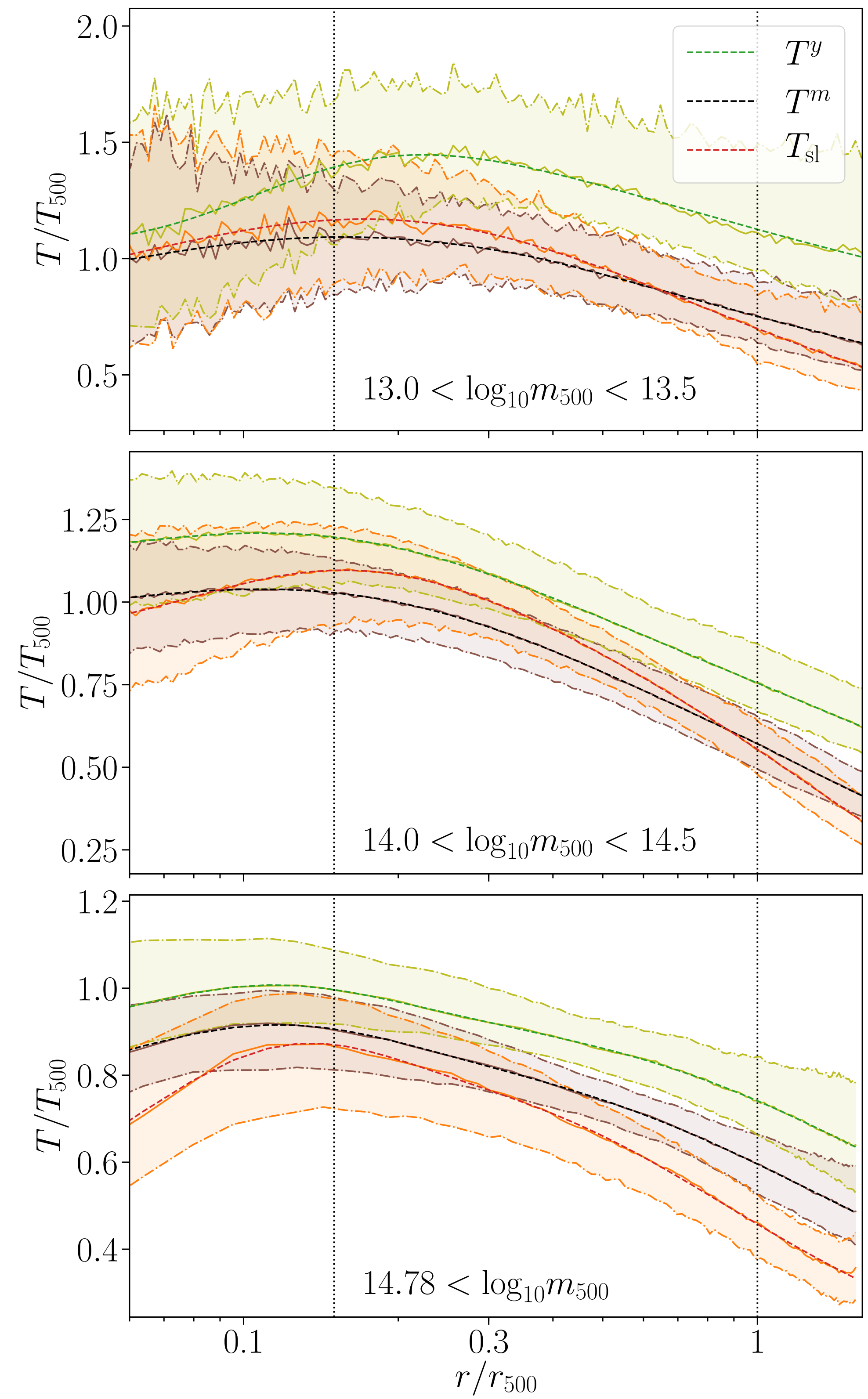
Lee, JC, Kay & Barnes, in prep.

New ingredients for accurate modeling of rSZ!

T-M scaling relations



Temperature profiles



Lee, JC, Kay & Barnes, in prep.

Conclusions

- rSZ currently hard to see for individual clusters or in stacking analysis (e.g., Erler et al., 2017)
- rSZ causes an underestimation of the *y*-parameter for *Planck*
- rSZ may play a role in the σ_8 tension and hence in cosmology
- rSZ delivers new information about the hot gas inside clusters
- Many opportunities ahead with future CMB imagers and spectrometers