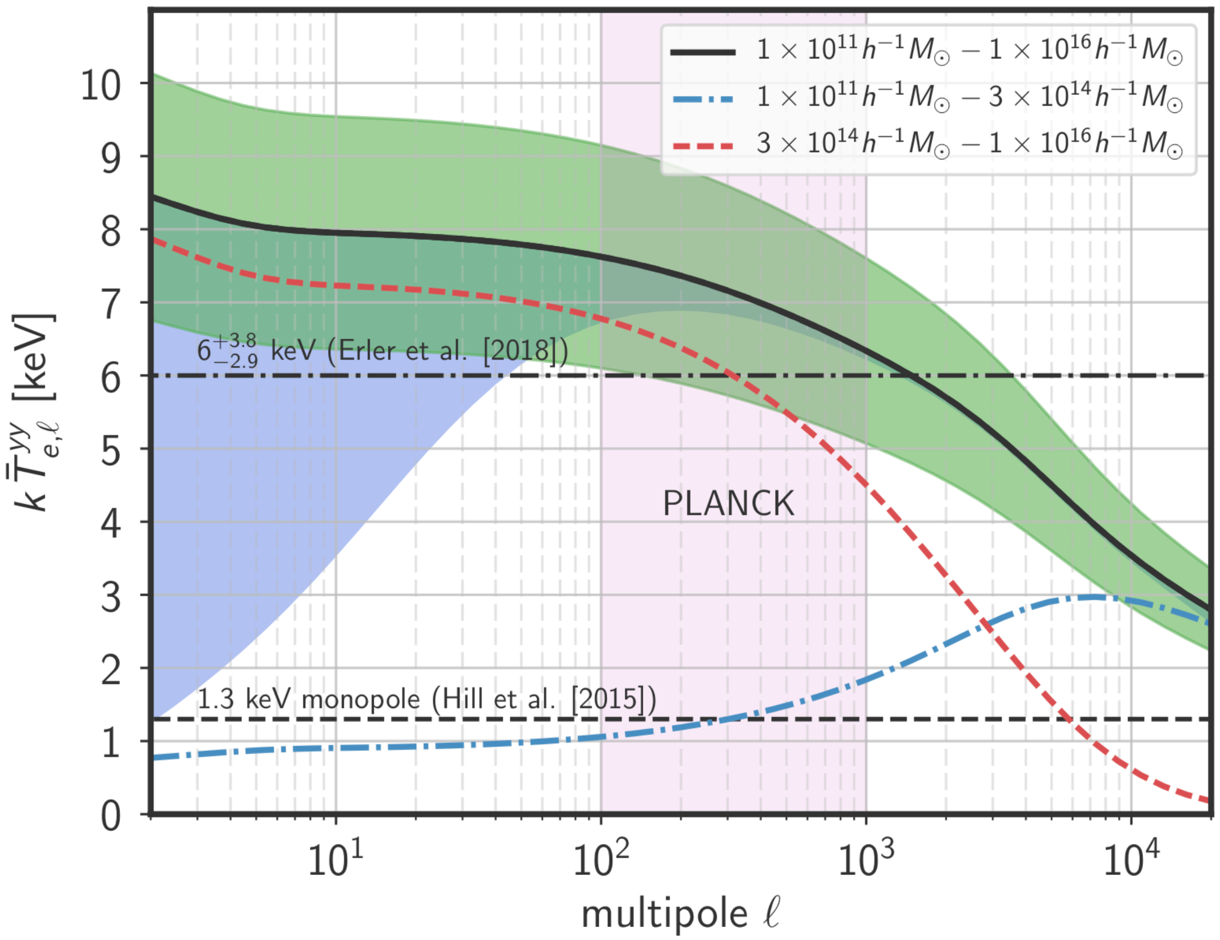
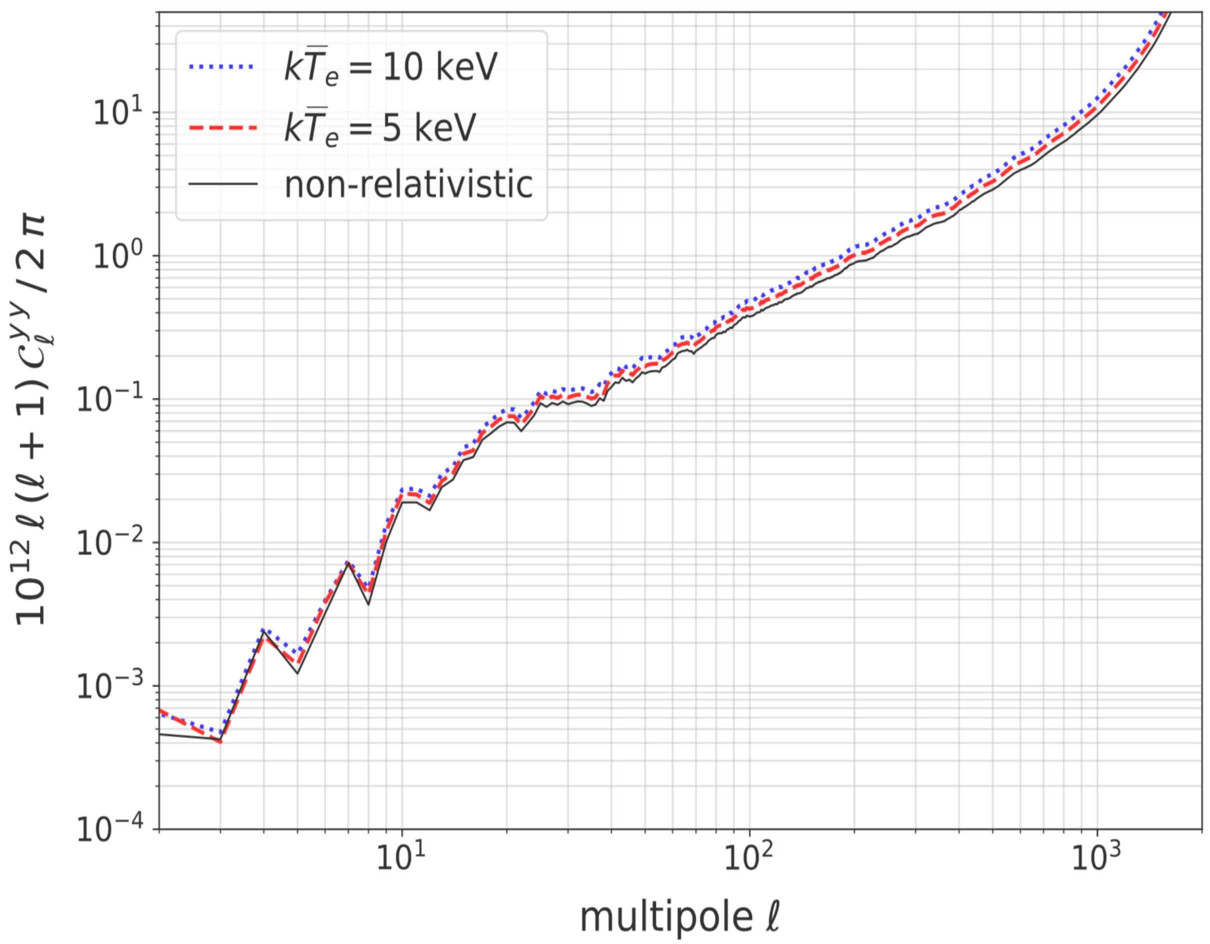
Can we neglect relativistic temperature corrections in the Planck SZ analysis?





Remazeilles, Bolliet, Rotti & JC, MNRAS, 483, 3459, 2019
Rotti, Bolliet, Remazeilles & JC, in preparation

MANCHESTER 1824
The University of Manchester

Jens Chluba

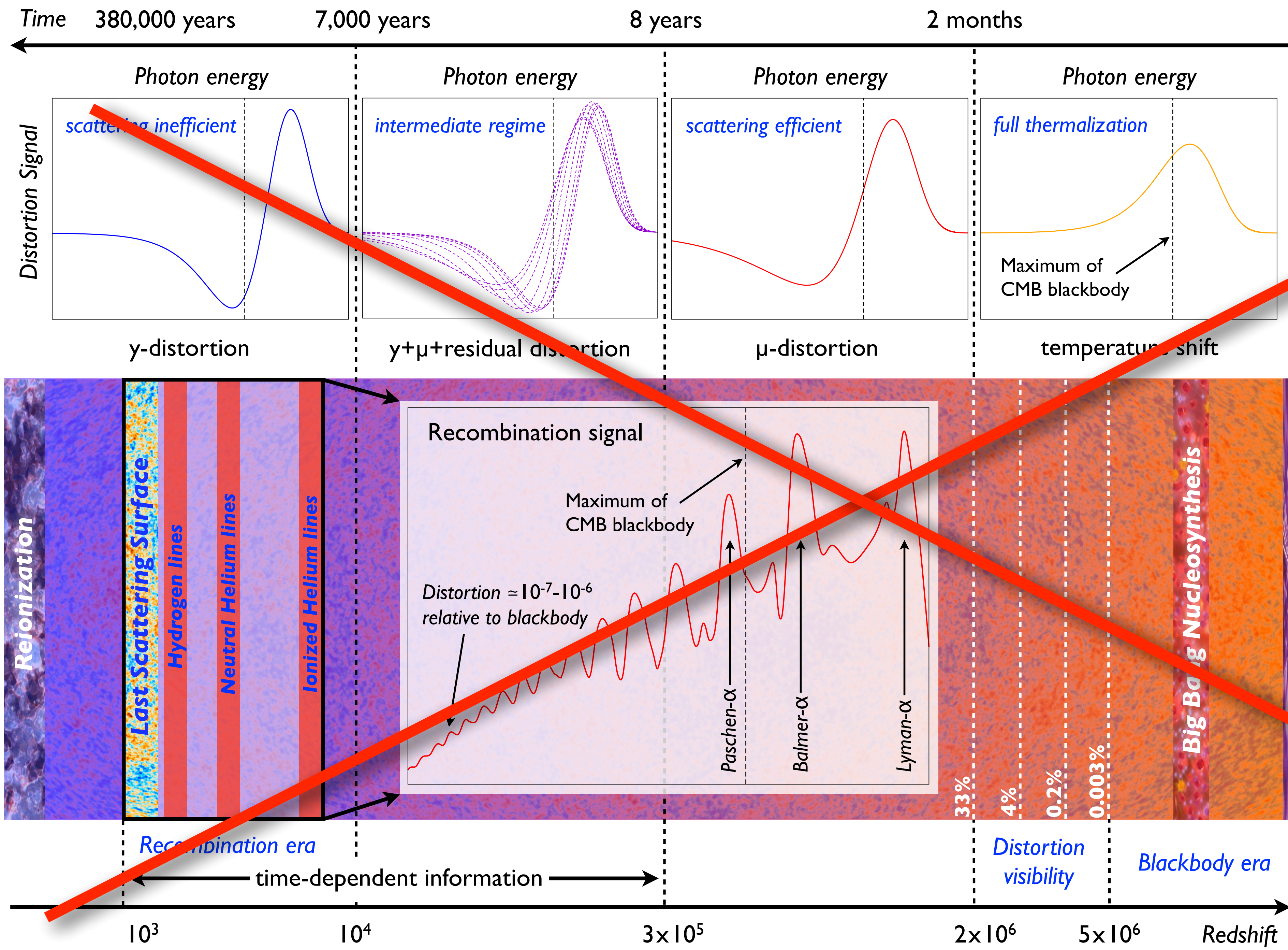
Cosmology - The Next Decade

ICTS, Bangalore, January 22nd - 25th, 2019

erc

THE ROYAL SOCIETY

Uniqueness of CMB Spectral Distortion Science



Guaranteed distortion signals in ΛCDM

New tests of inflation and particle/dark matter physics

Signals from the reionization and recombination eras

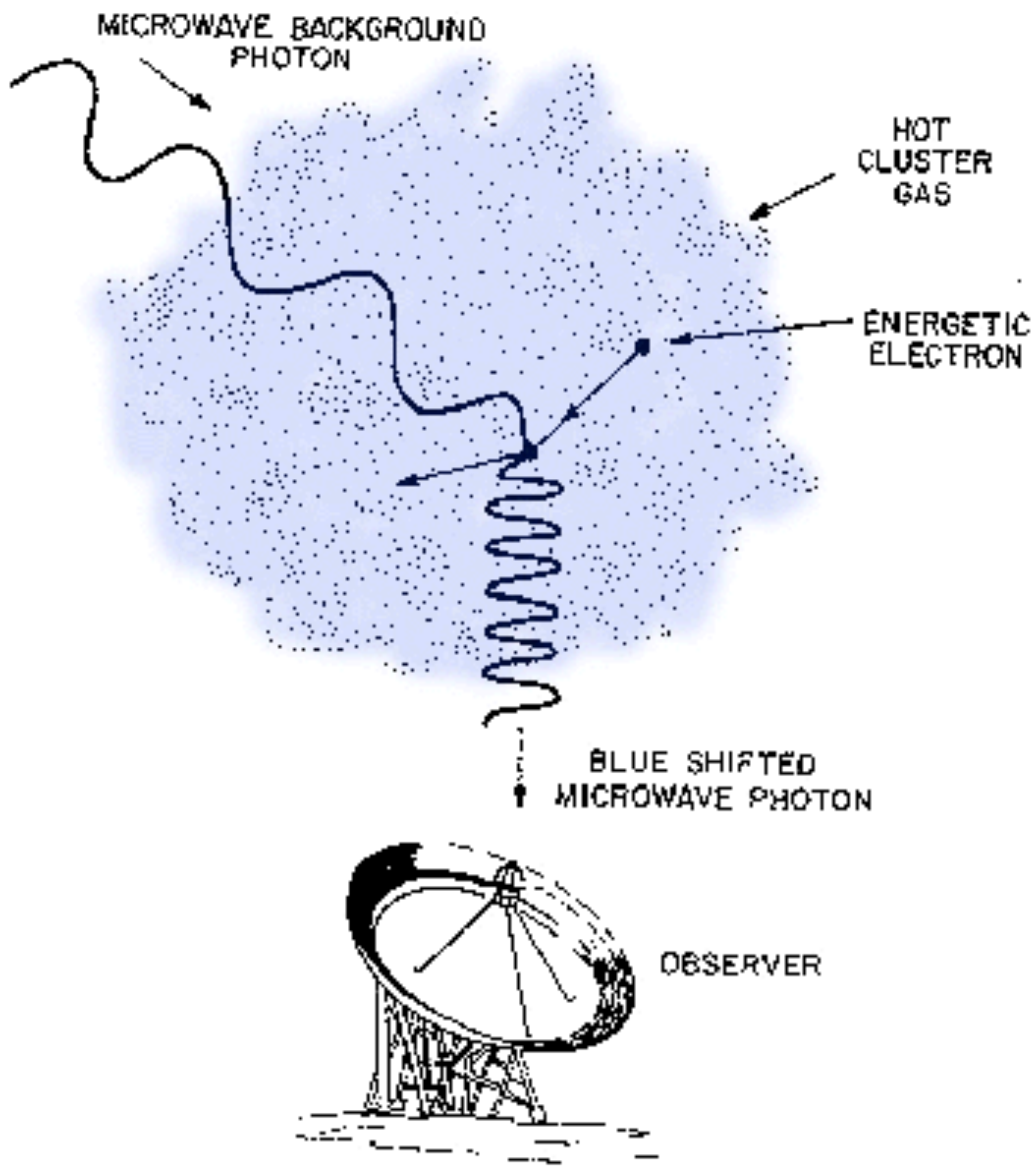
Huge discovery potential

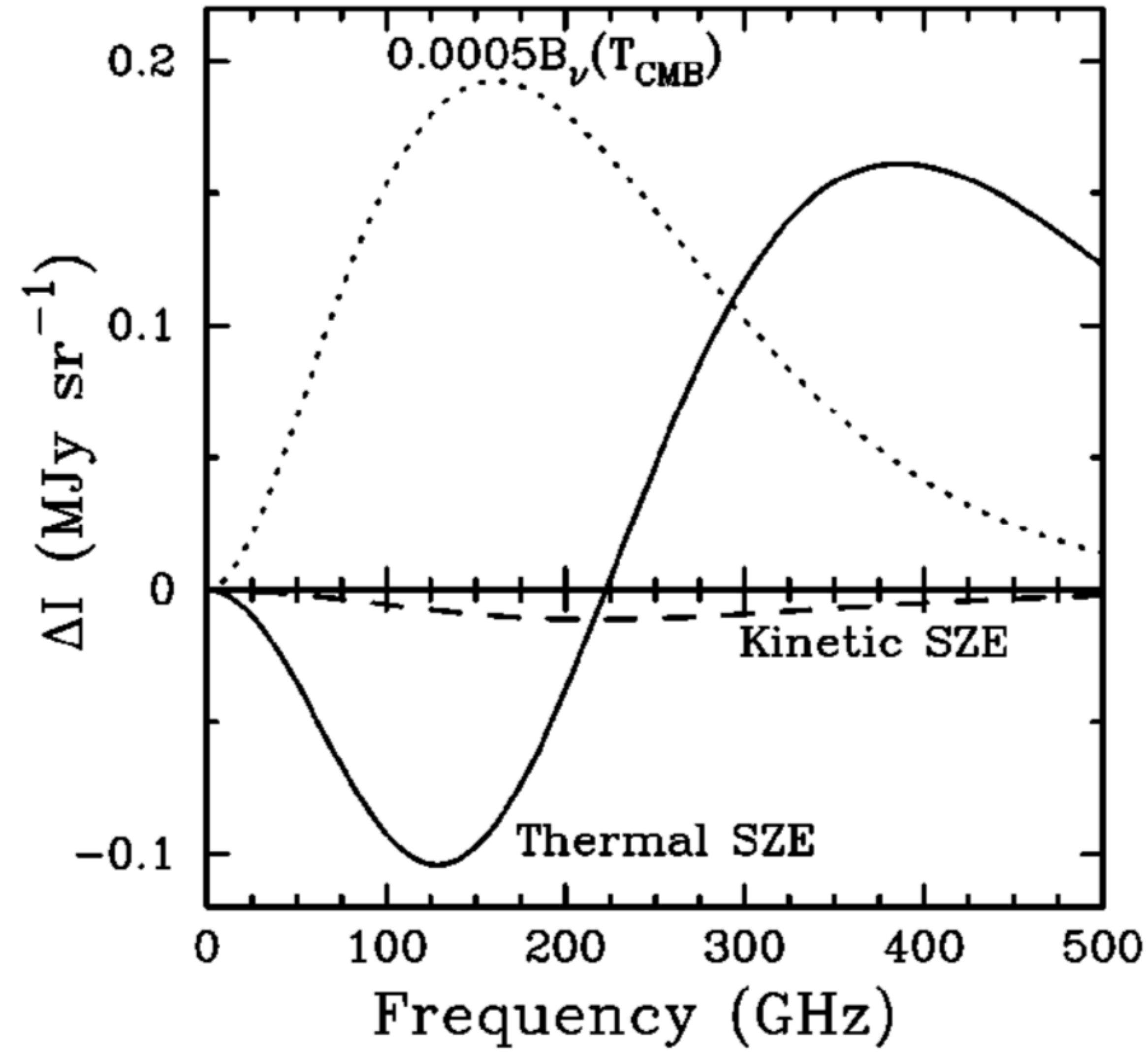
Complementarity and synergy with CMB anisotropy studies

Chluba & Sunyaev, MNRAS, 419, 2012
Chluba et al., MNRAS, 425, 2012
Silk & Chluba, Science, 2014
Chluba, MNRAS, 2016

PRISTINE
COSMO
CMB-Bharat

Classical SZ effects

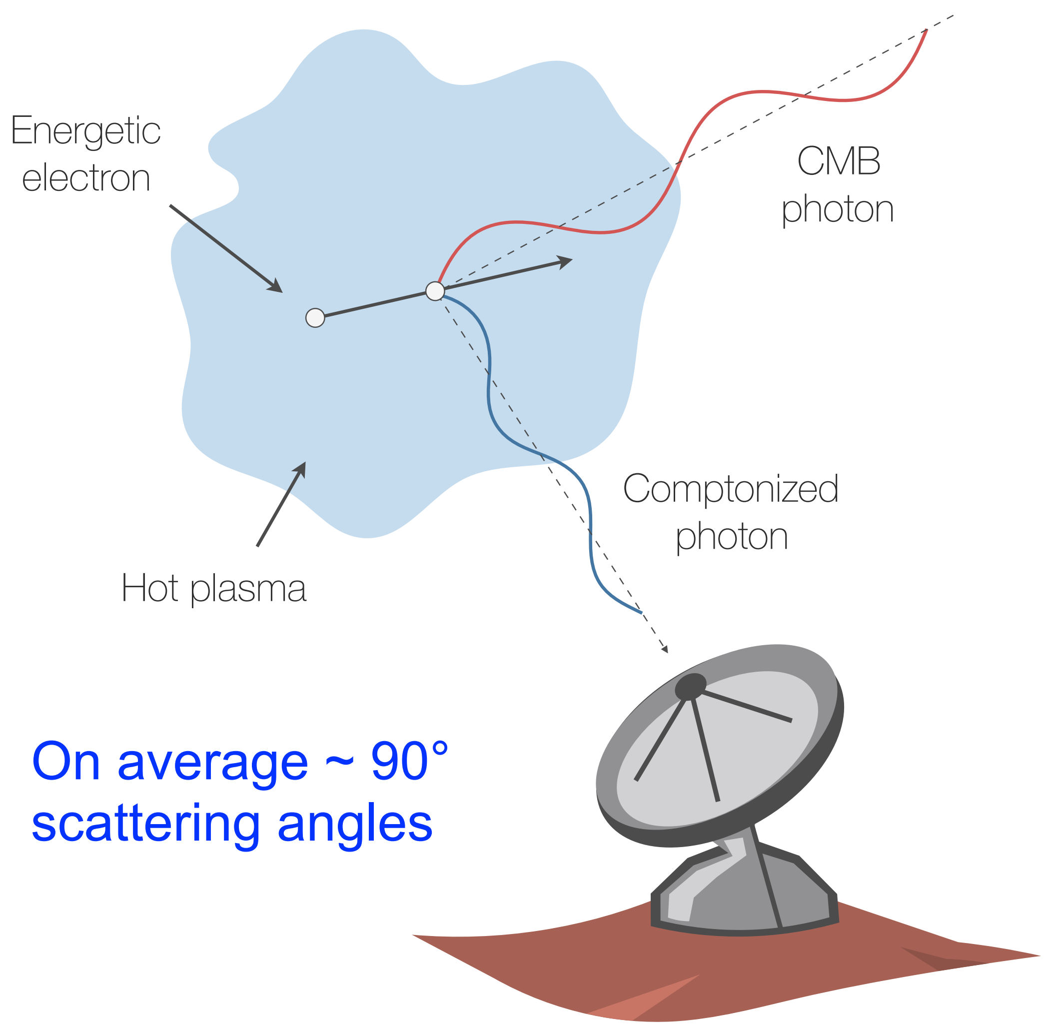




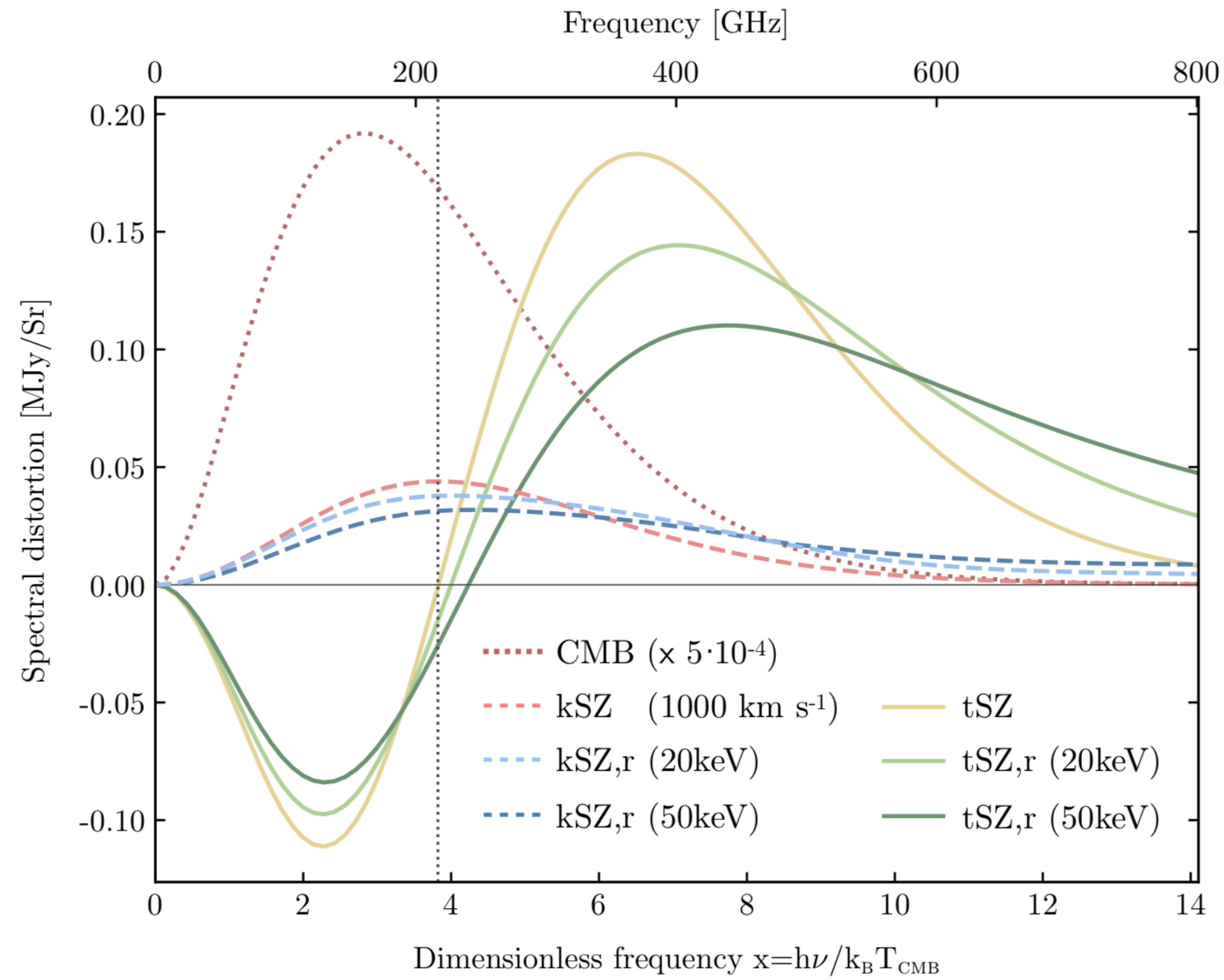
- SZ clusters are a great cosmological probe
- Many years of developments since its first prediction by Zeldovich & Sunyaev, 1969

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

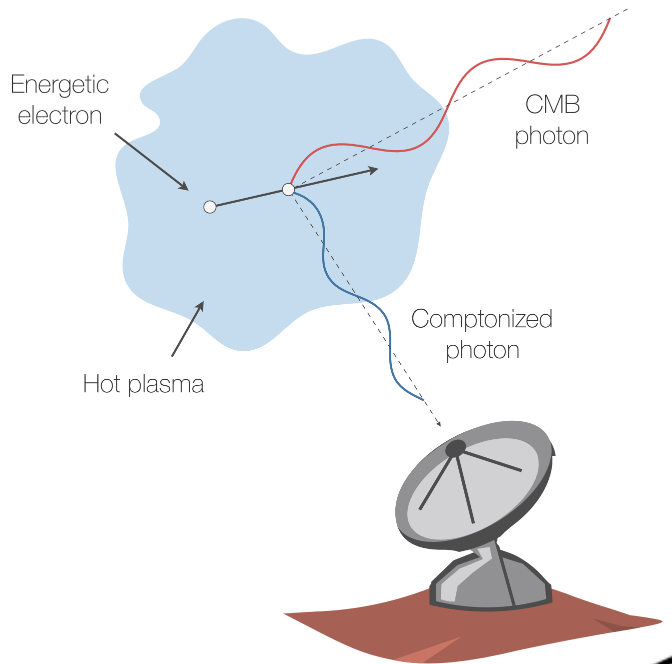
A Millimetre/Submillimetre Probe of the Warm and Hot Universe

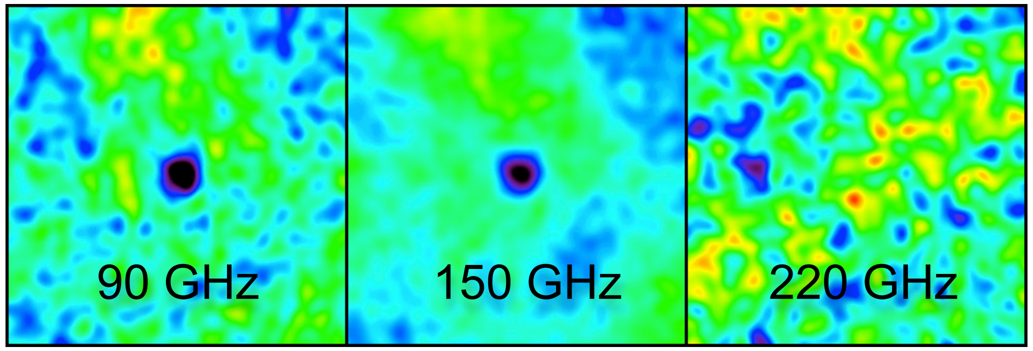
Tony Mroczkowski · Daisuke Nagai · Kaustuv Basu · Jens Chluba · Jack Sayers · Rémi Adam · Eugene Churazov · Abigail Crites · Luca Di Mascolo · Dominique Eckert · Juan Macias-Perez · Frédéric Mayet · Laurence Perotto · Etienne Pointecouteau · Charles Romero · Florian Ruppin · Evan Scannapieco · John ZuHone

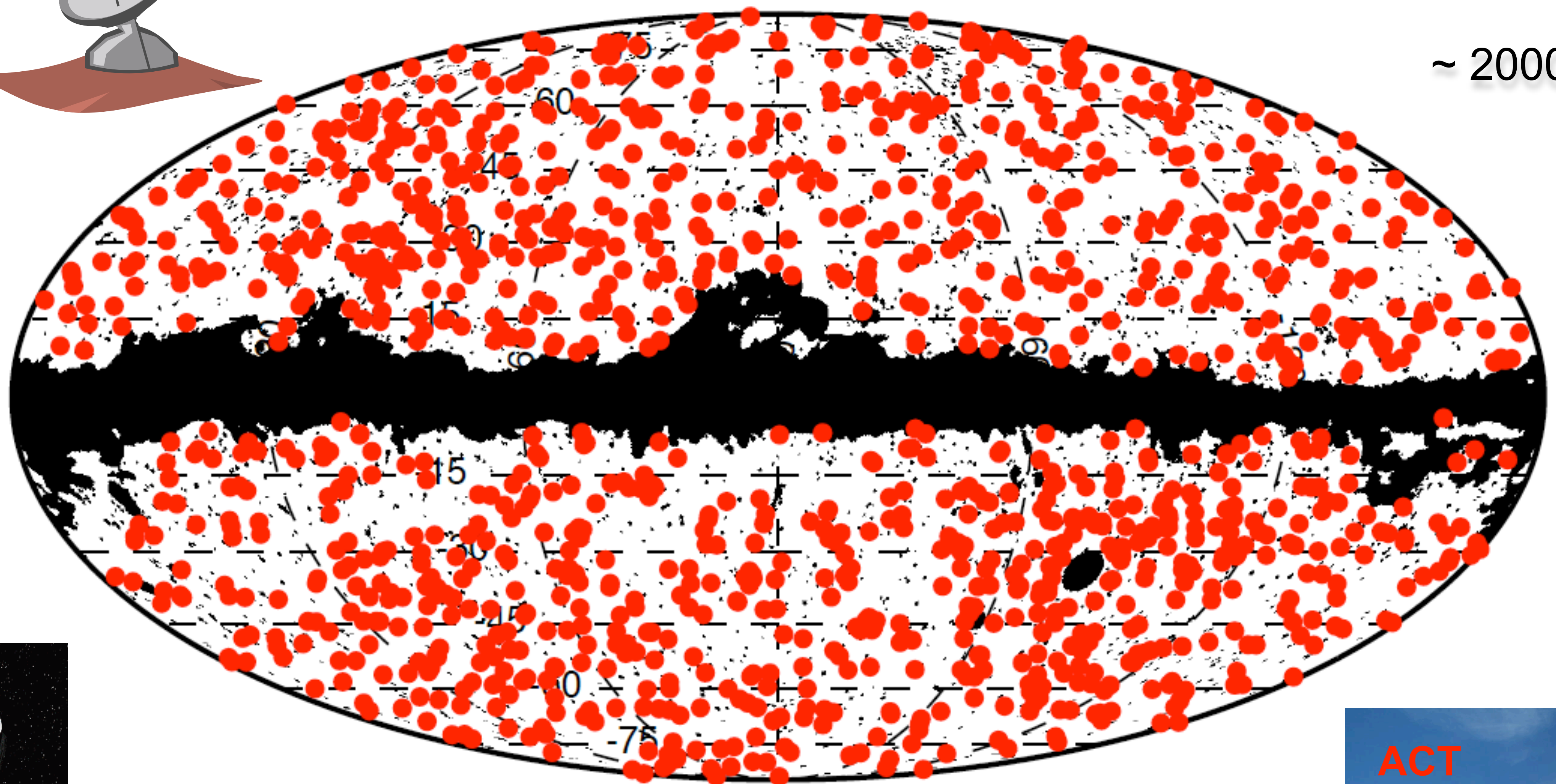
- Highlights high-resolution and high-sensitivity SZ
- Illuminates new directions
- Connection to simulations

See arXiv:1811.02310 → To appear as *Space Science Reviews*

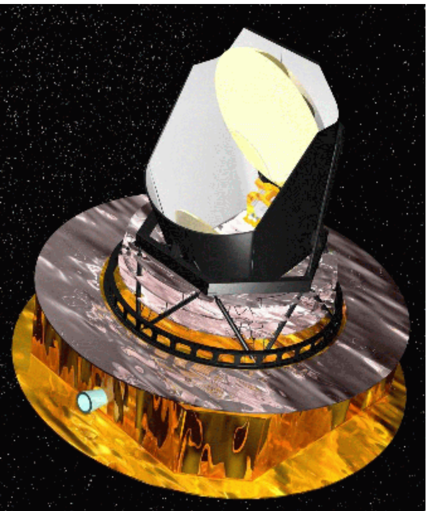
Thermal SZ effect is now routinely observed!







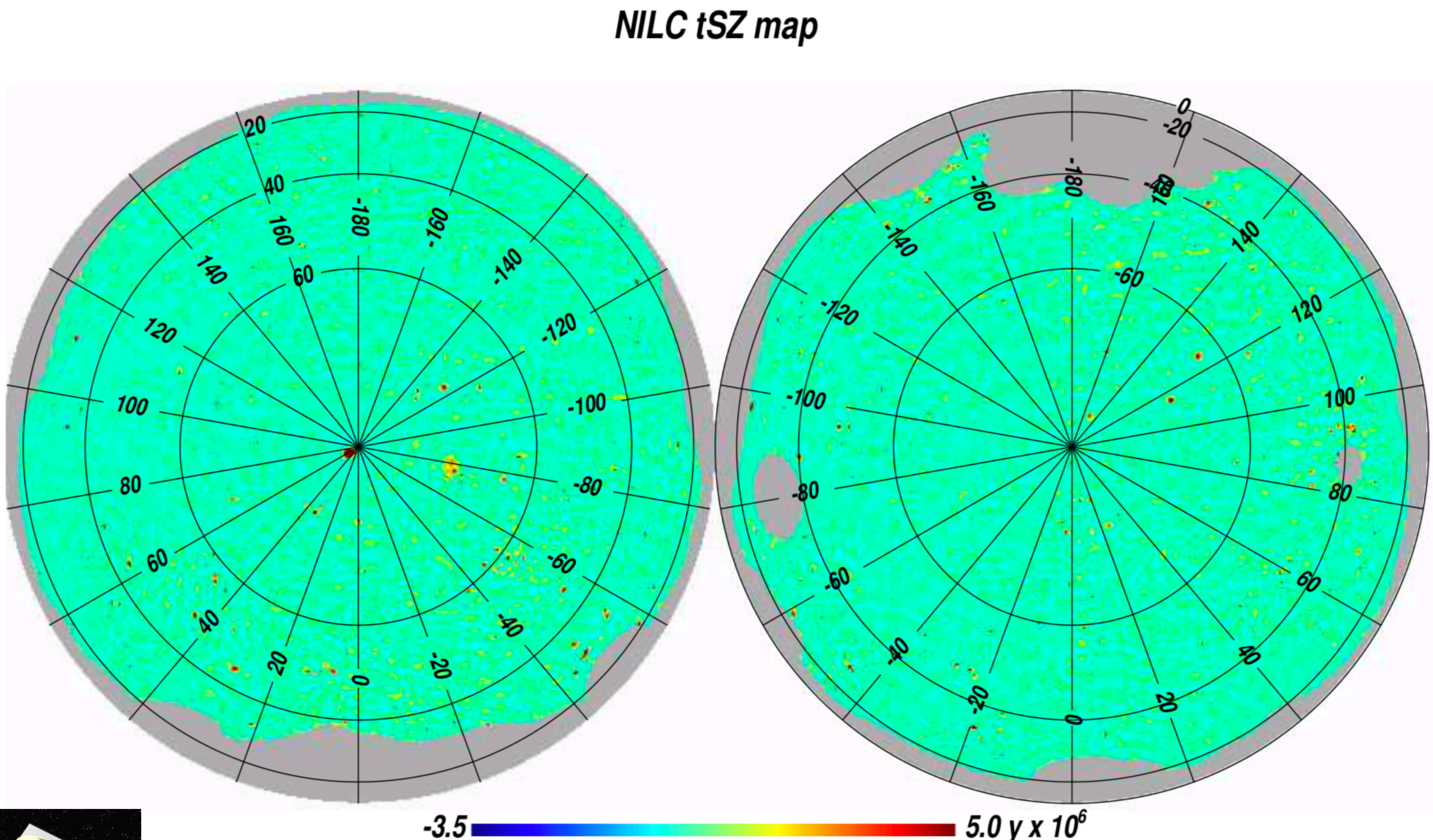
~ 2000 objects

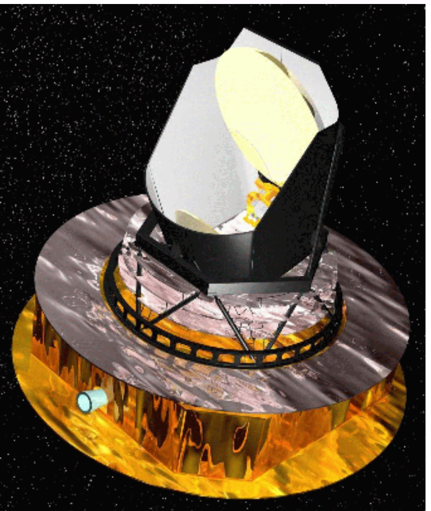


Planck Collaboration, 2013, paper XXIV

Planck Collaboration, 2015, paper XXIV

All-sky Compton *y*-map from Planck



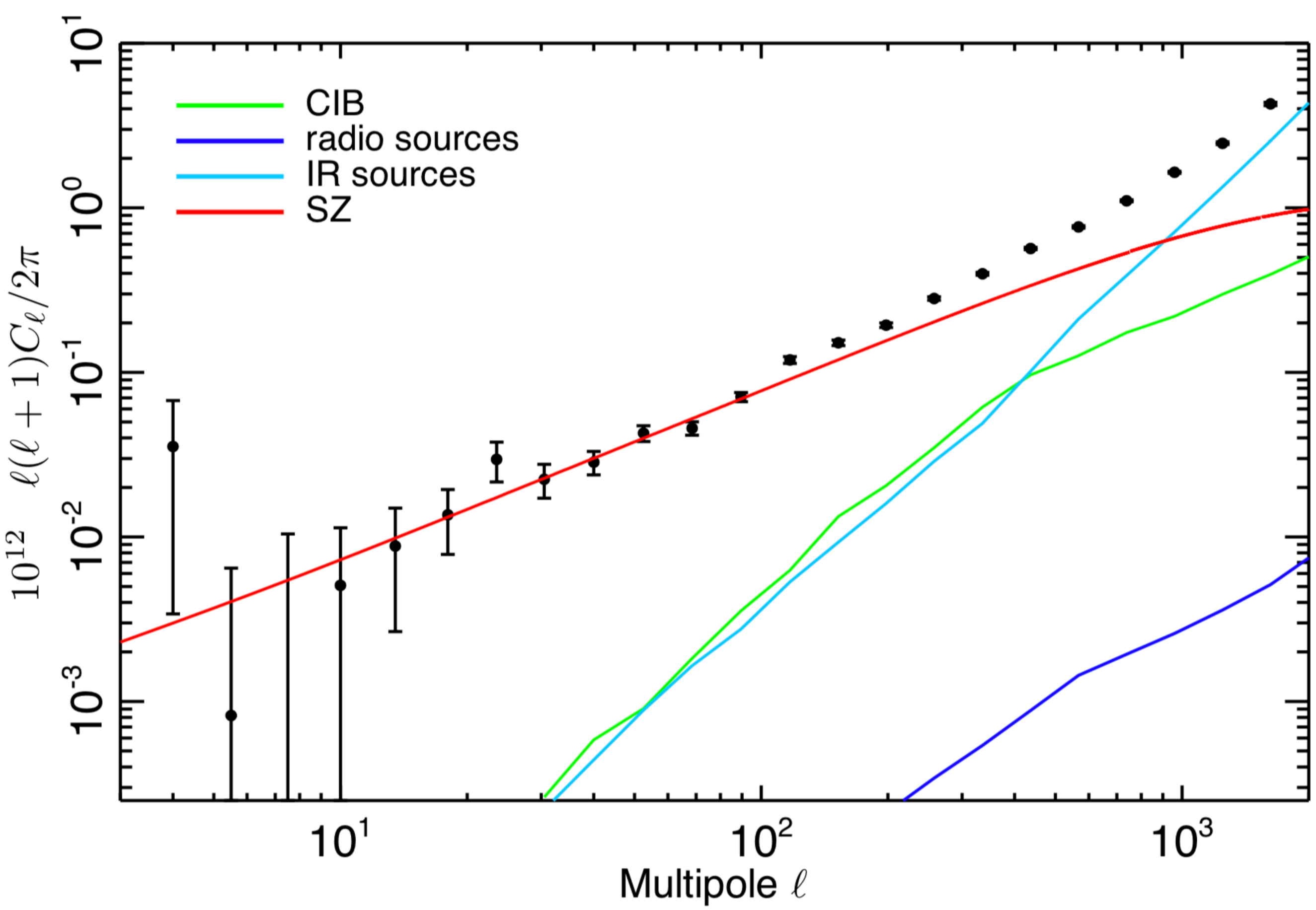


Planck Collaboration, 2013, paper XXI
Planck Collaboration, 2015, paper XXII

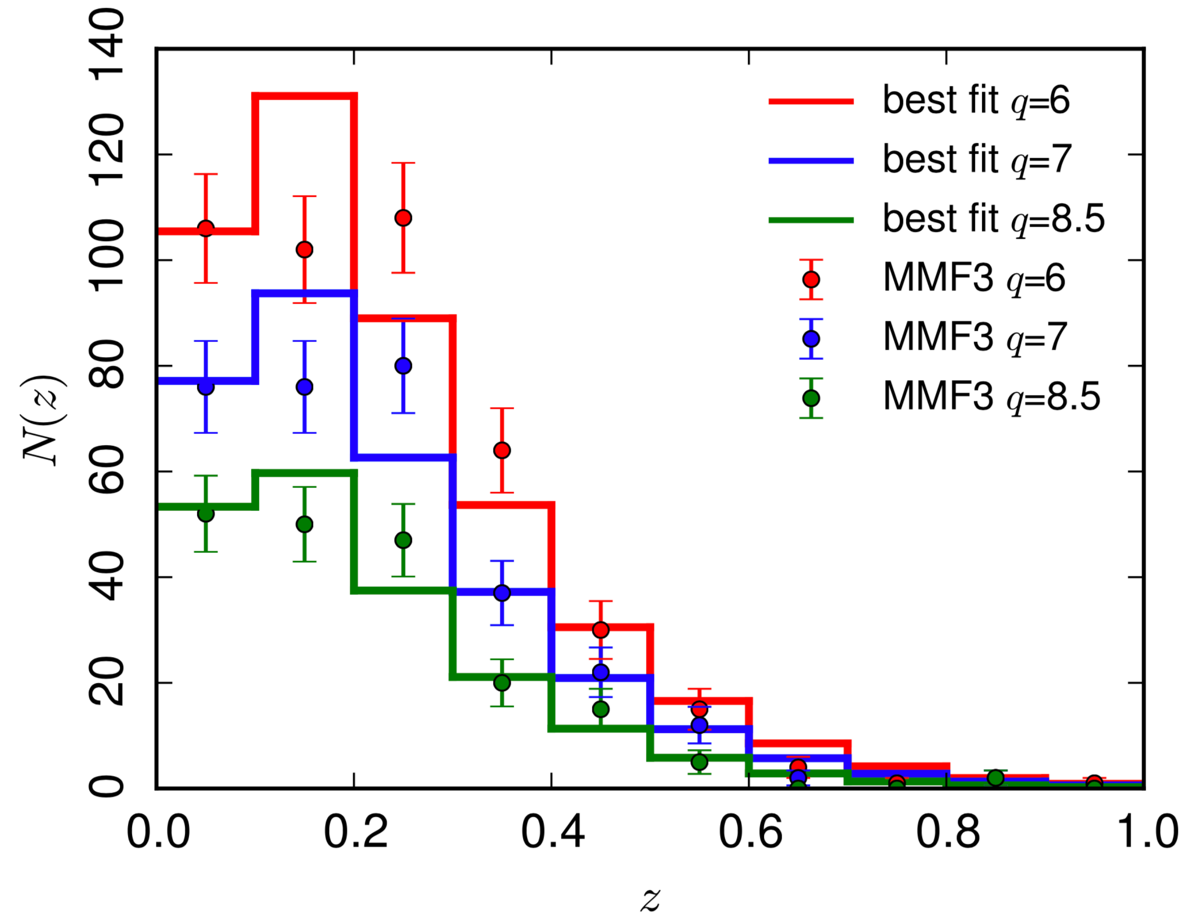
Map was produced by Mathieu Remazeilles

Planck SZ analysis

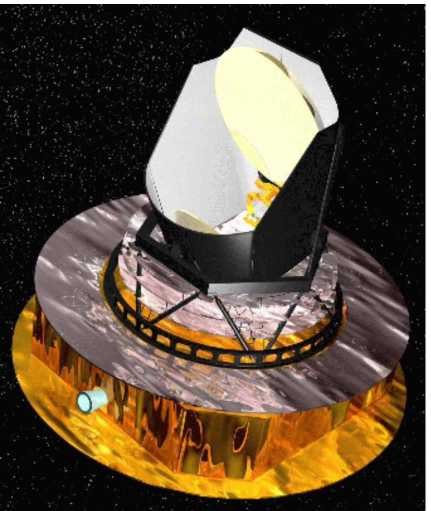
Power spectrum



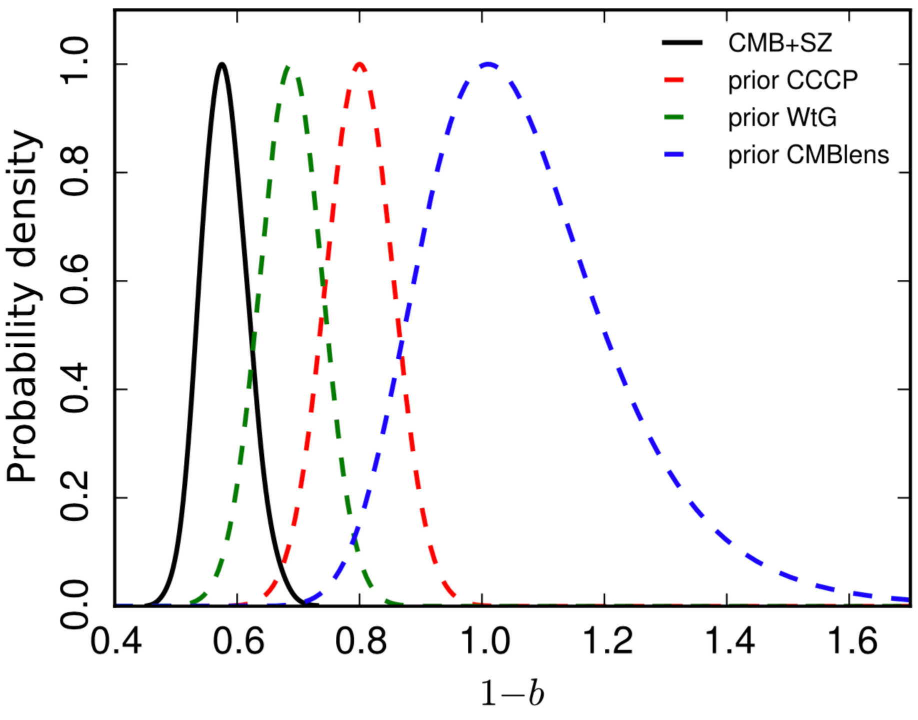
Number counts



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

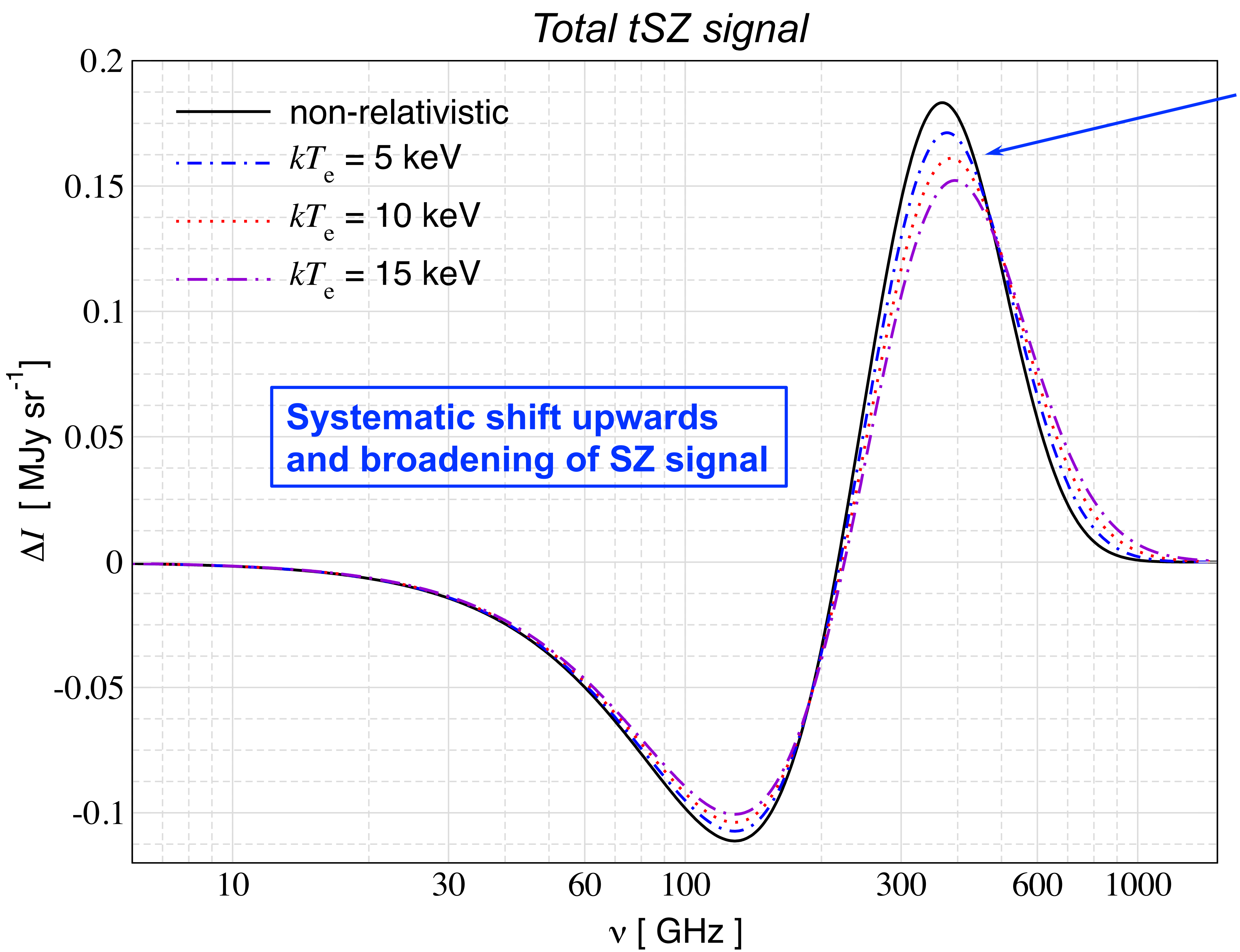


Planck Collaboration, 2015, paper XXIV
Planck Collaboration, 2015, paper XXII



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 ⇒

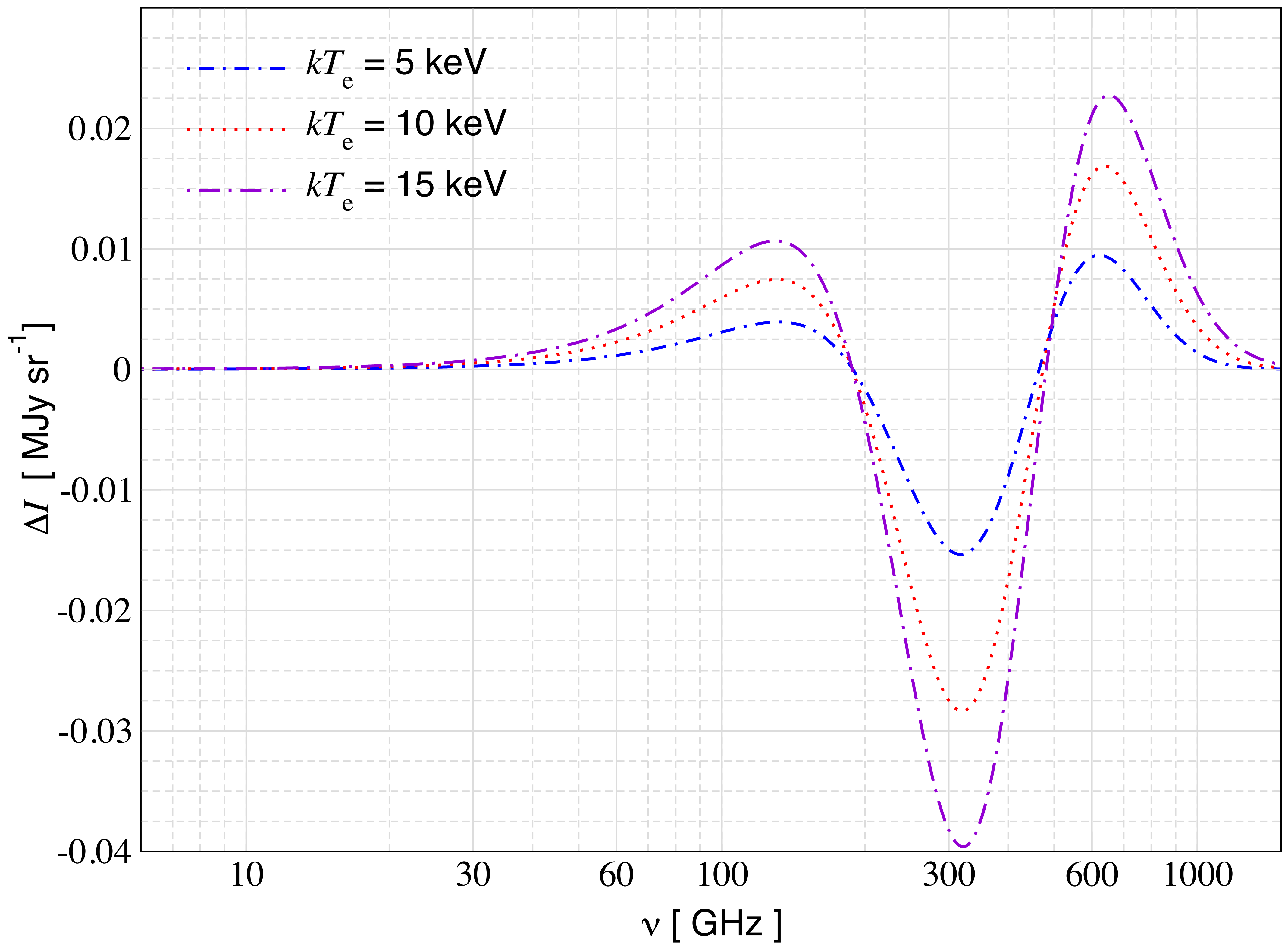
Relativistic electron velocities!

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

$y = 10^{-4}$

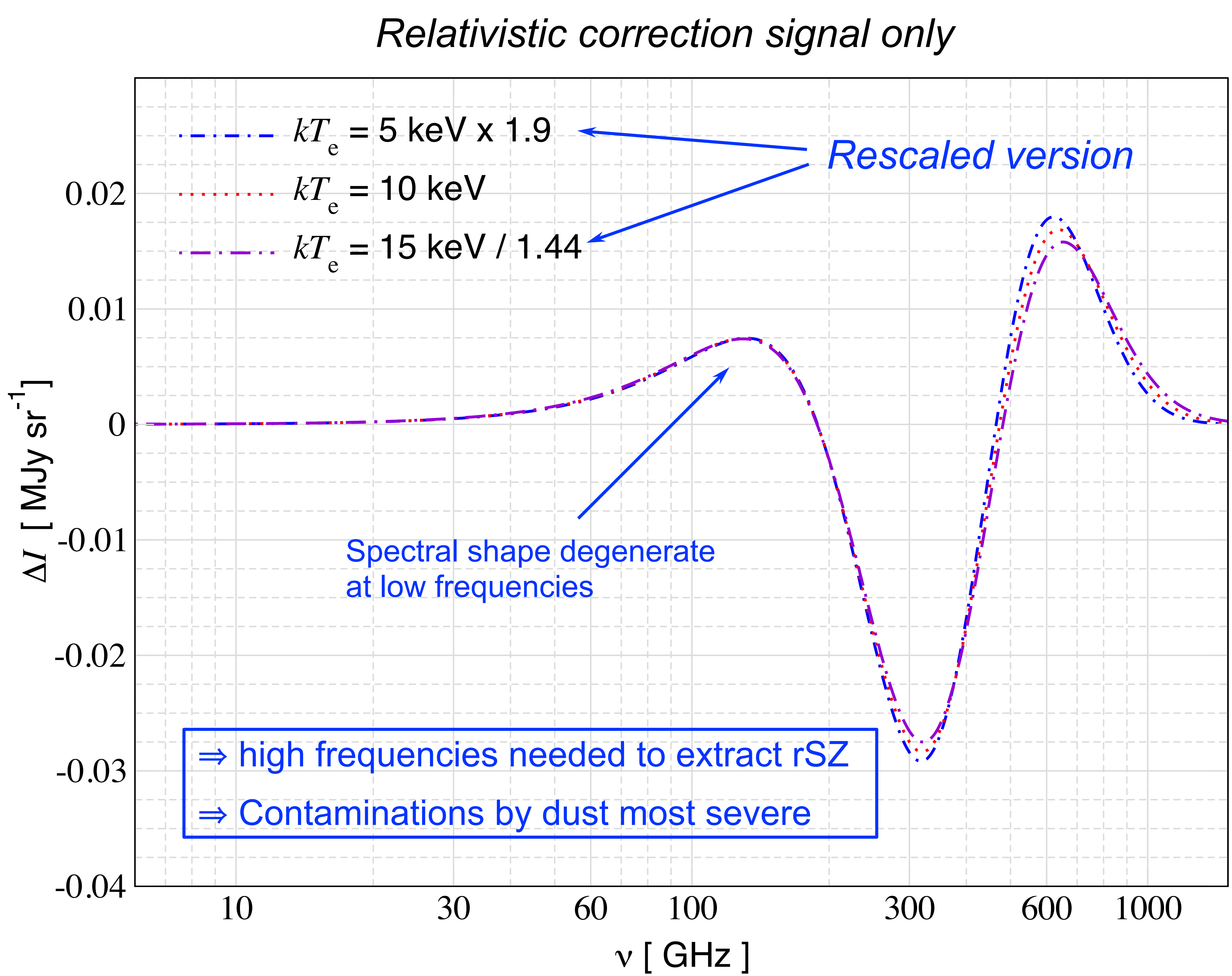
High frequencies are crucial for rSZ!

Relativistic correction signal only



$y = 10^{-4}$

High frequencies are crucial for rSZ!



$y = 10^{-4}$

High-frequency spectrum has to be computed carefully…

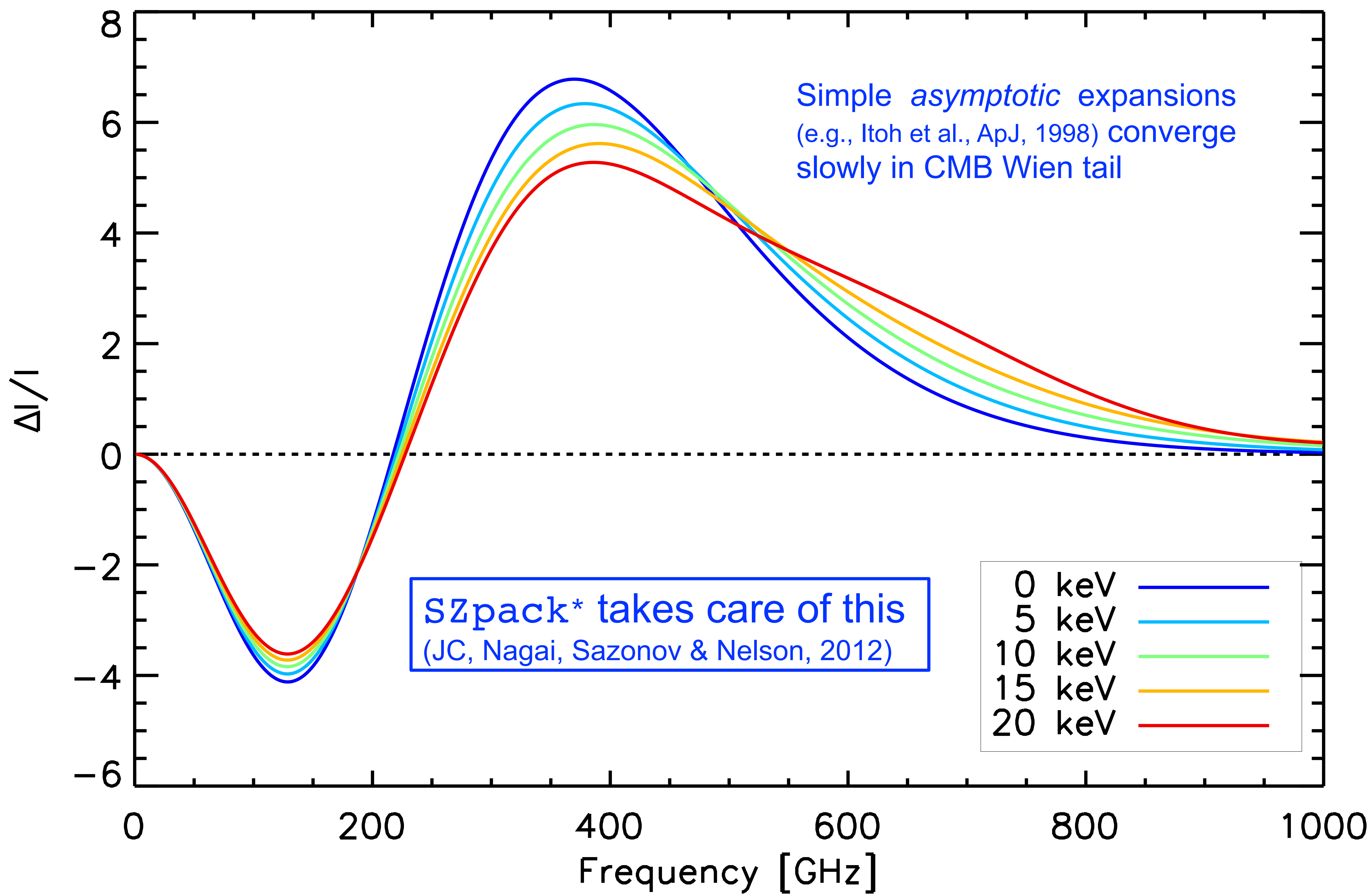
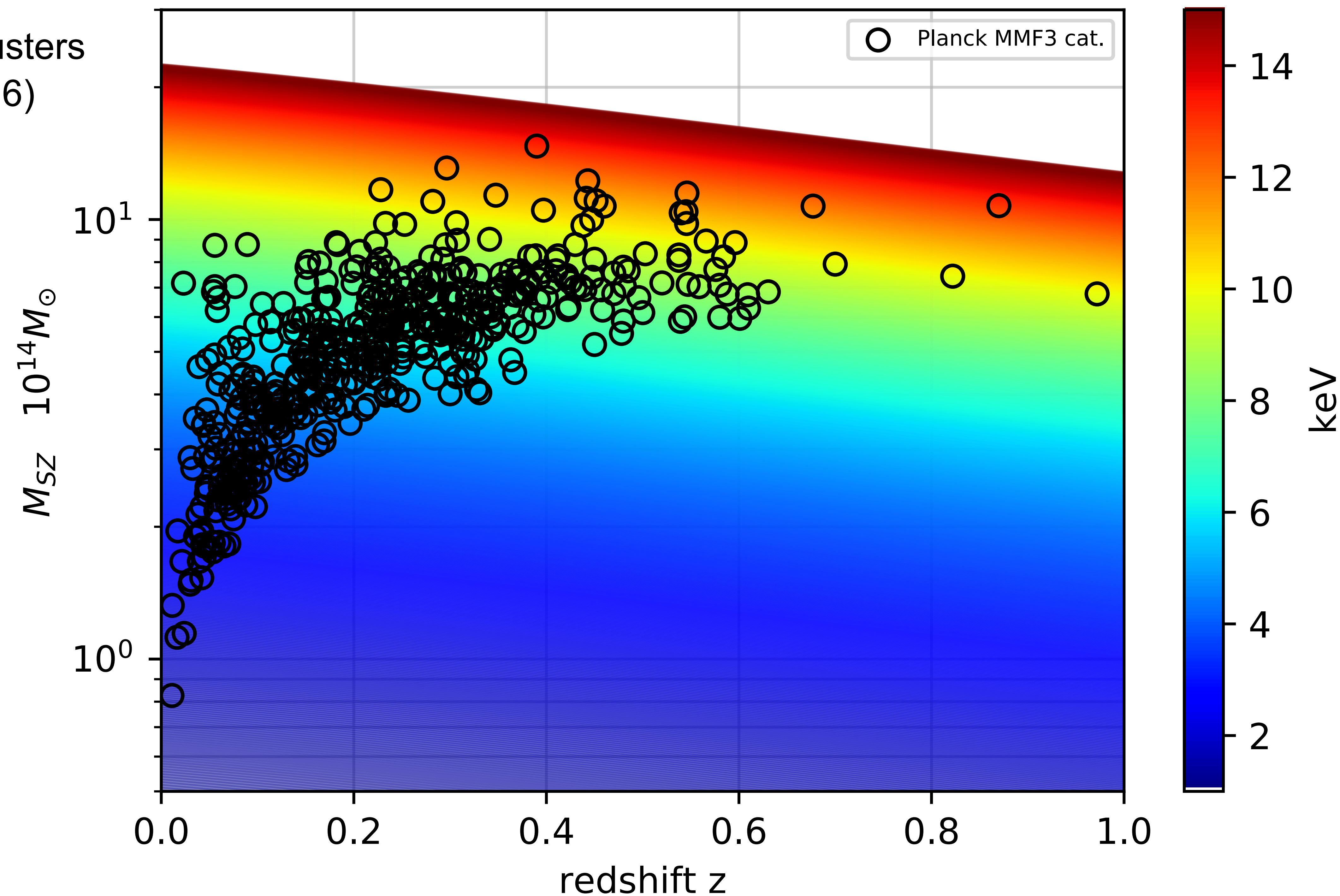


Figure from Hurier, 2016, ArXiv:1701.09020

*www.Chluba.de/SZpack

Clusters seen by Planck are pretty hot!

439 clusters
(S/N > 6)

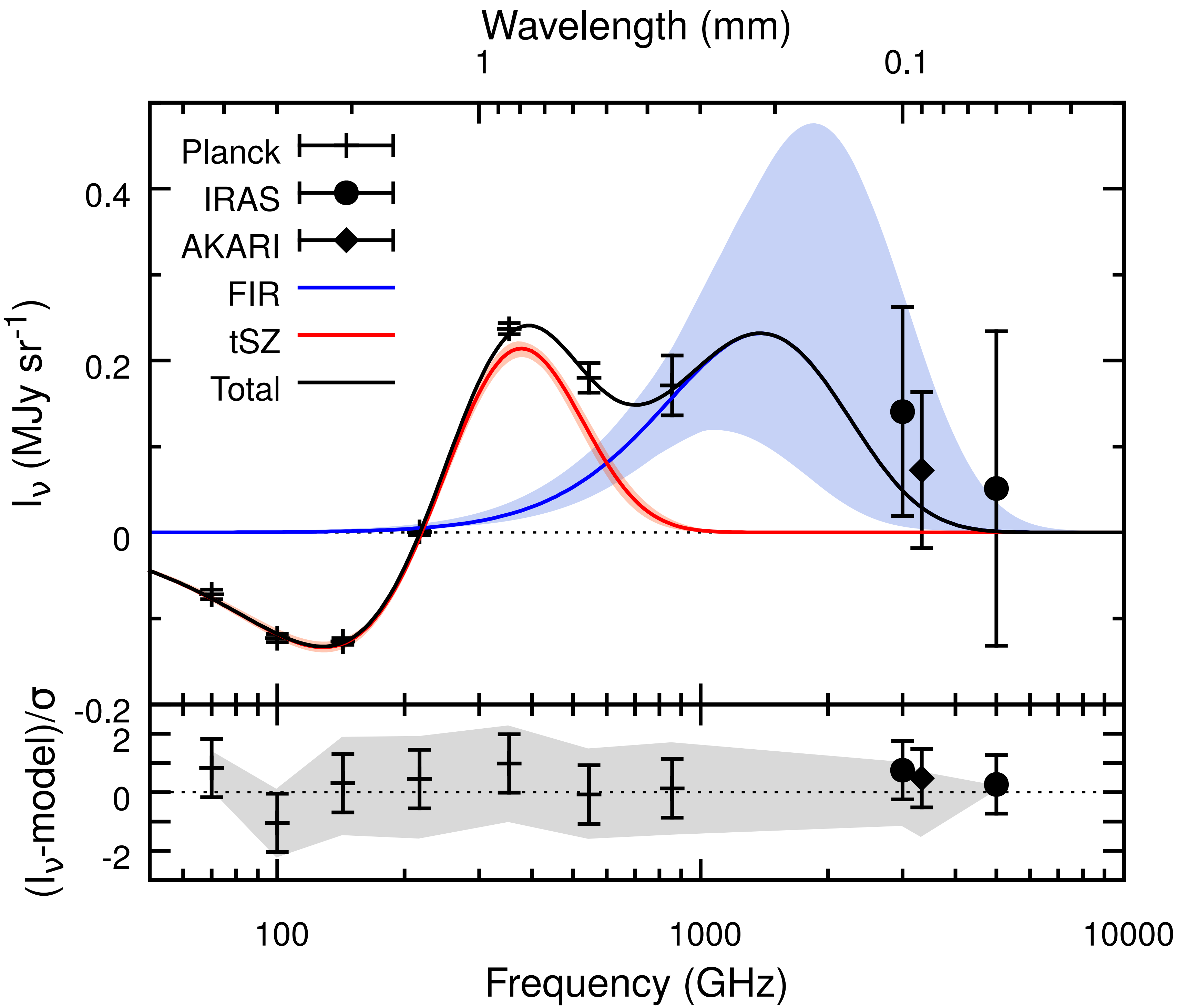


Standard (X-ray)
temperature mass-relation
(e.g., Arnaud et al., 2005, Erler et al. 2018)

$$kT_\mathrm{e} \simeq 5\,\mathrm{keV}\,\left[\frac{E(z)\,M_{500}}{3\times 10^{14} h^{-1}\,M_\odot}\right]^{2/3}$$

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:

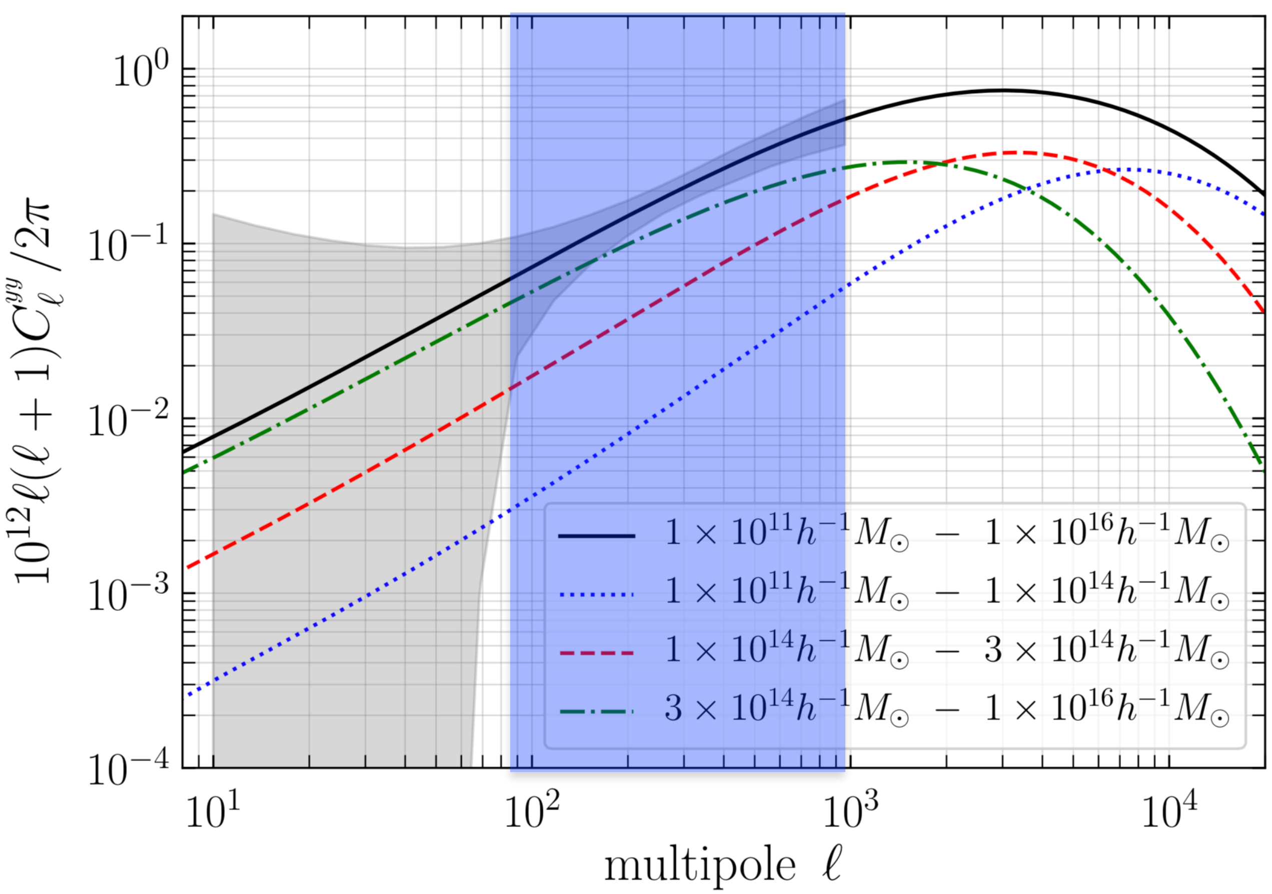
$$k_B T_{SZ} = 5.96^{+3.78}_{-2.93} \text{ keV}$$

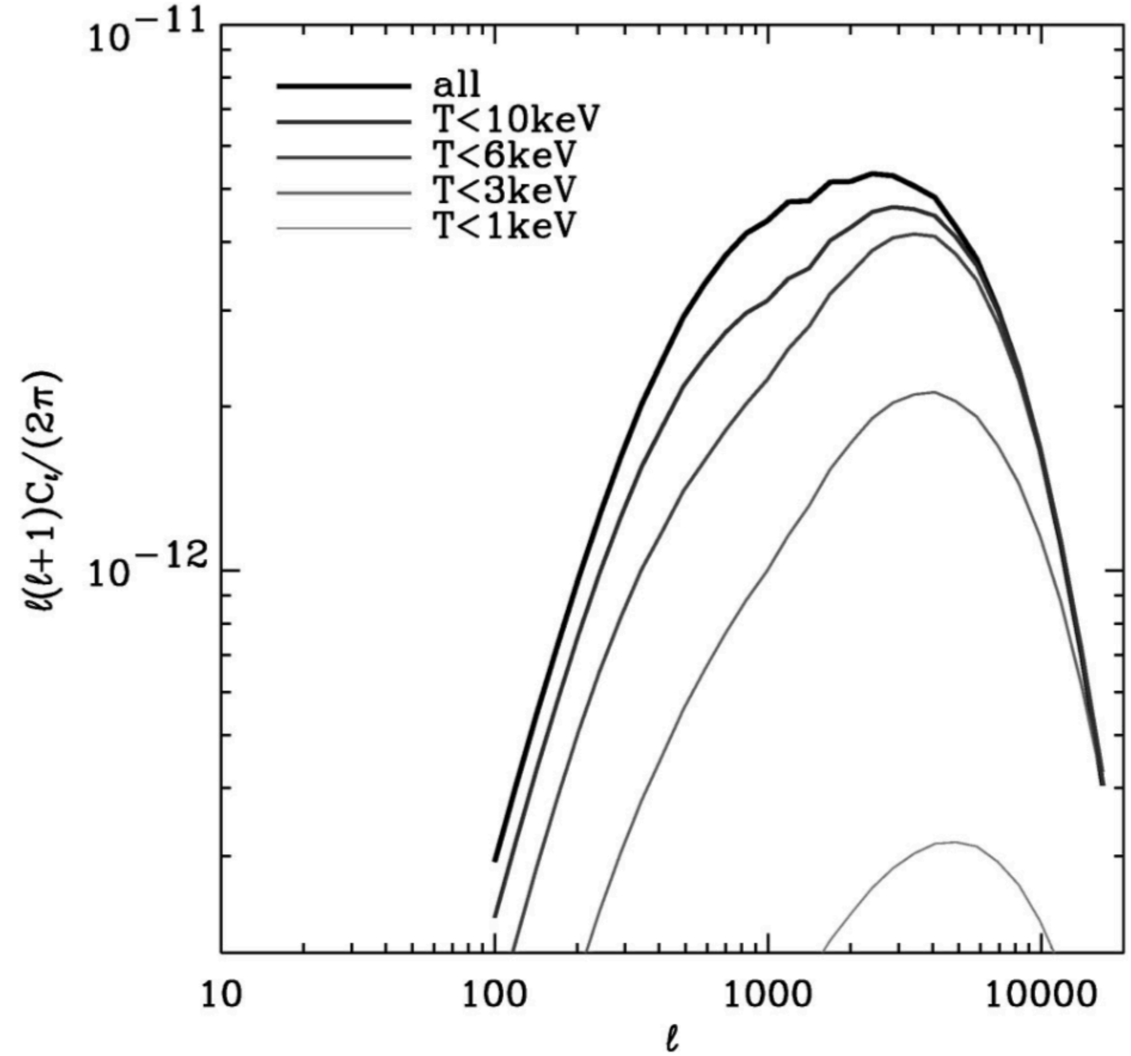
⇒ typical y-weighted temperature of ~ 4-7 keV quite reasonable

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

Theoretical SZ power spectrum computations

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





Refregier et al., 2000

From Komatsu & Seljak, 2002:

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

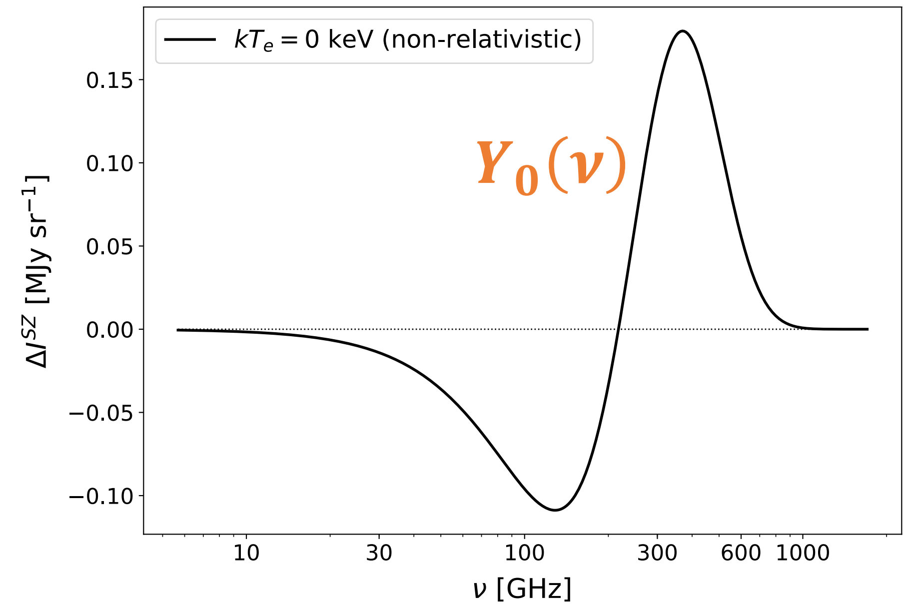
→ temperature of systems contributing to the multipole range relevant to *Planck*'s C_l analysis seems > 5 keV

Remazeilles, Bolliet, Rotti & JC, MNRAS, 2019

How is the y-map obtained?

SZ Compton-y signal reconstruction: ILC

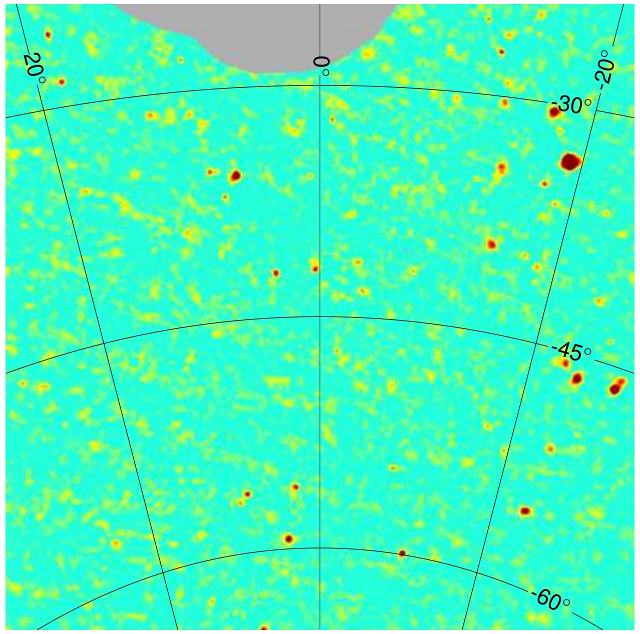
$$\underbrace{d(\nu,\vec{\theta})}_{\text{Planck frequency data}} = Y_0(\nu)\ \underbrace{y(\vec{\theta})}_{\text{signal of interest}} + \underbrace{N(\nu,\vec{\theta})}_{\text{foregrounds + noise}}$$



- ILC = weighted linear combination of frequency maps:

$$\hat{y}(\vec{\theta}) = \sum_\nu w(\nu)\, d(\nu,\vec{\theta})$$

$$\text{such that } \begin{cases} \langle \hat{y}^2 \rangle = w^t \langle d d^t \rangle\, w \text{ minimum} & (1) \\ \sum_\nu w(\nu)\, Y_0(\nu) = 1 & (2) \end{cases}$$



Planck 2015 results XXII

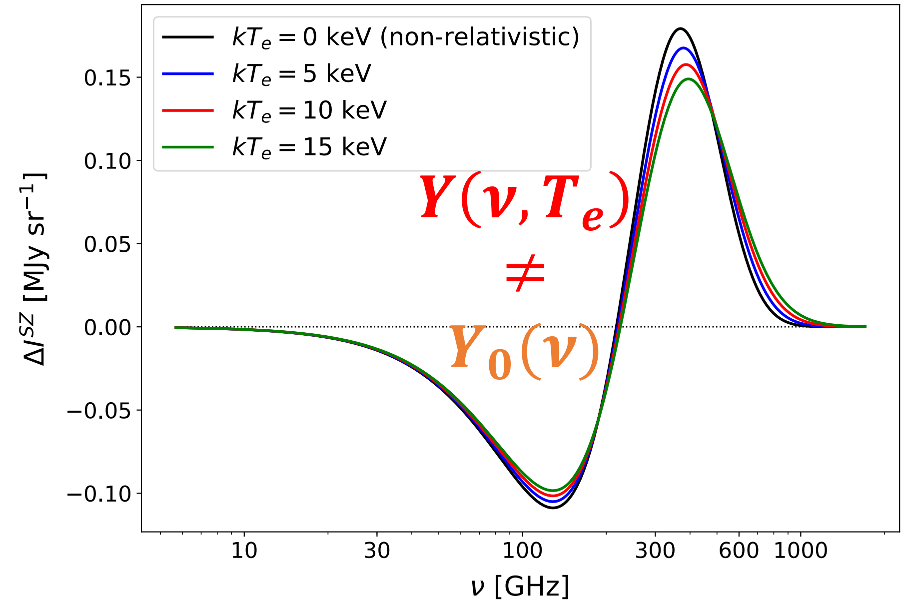
- ILC weights : $w^t = \dfrac{Y_0^t C^{-1}}{Y_0^t C^{-1} Y_0}$ $\quad (C \equiv \langle d d^t \rangle)$

$$\Longrightarrow \hat{y}(\vec{\theta}) = \underbrace{y(\vec{\theta})}_{\text{recovered signal (2)}} + \underbrace{w^t N}_{\text{minimized residuals by (1)}}$$

Courtesy Mathieu Remazeilles

Miscalibrated Compton-y signal reconstruction

$$\underbrace{d(\nu,\vec{\theta})}_{\text{Planck frequency data}} = Y(\nu, T_e)\ \underbrace{y(\vec{\theta})}_{\text{signal of interest}} + \underbrace{N(\nu,\vec{\theta})}_{\text{foregrounds + noise}}$$



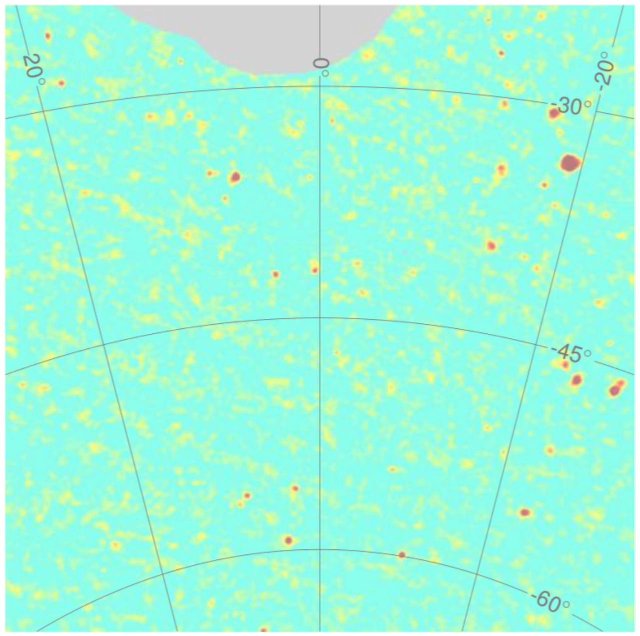
- ILC = weighted linear combination of frequency maps:

$$\hat{y}(\vec{\theta}) = \sum_\nu w(\nu)\, d(\nu,\vec{\theta})$$

$$\text{such that } \begin{cases} \langle \hat{y}^2 \rangle = w^t \langle dd^t \rangle w \text{ minimum} & (1) \\ \sum_\nu w(\nu)\, Y_0(\nu) = 1 & (2) \end{cases}$$

- ILC weights : $w^t = \dfrac{Y_0^t\, C^{-1}}{Y_0^t\, C^{-1}\, Y_0}$ $\quad (C \equiv \langle dd^t \rangle)$

$$\Longrightarrow\ \hat{y}(\vec{\theta}) = \underbrace{\frac{Y_0^t\, C^{-1}\, Y(T_e)}{Y_0^t\, C^{-1}\, Y_0}}_{\text{Bias} < 1} y(\vec{\theta}) + w^t N$$



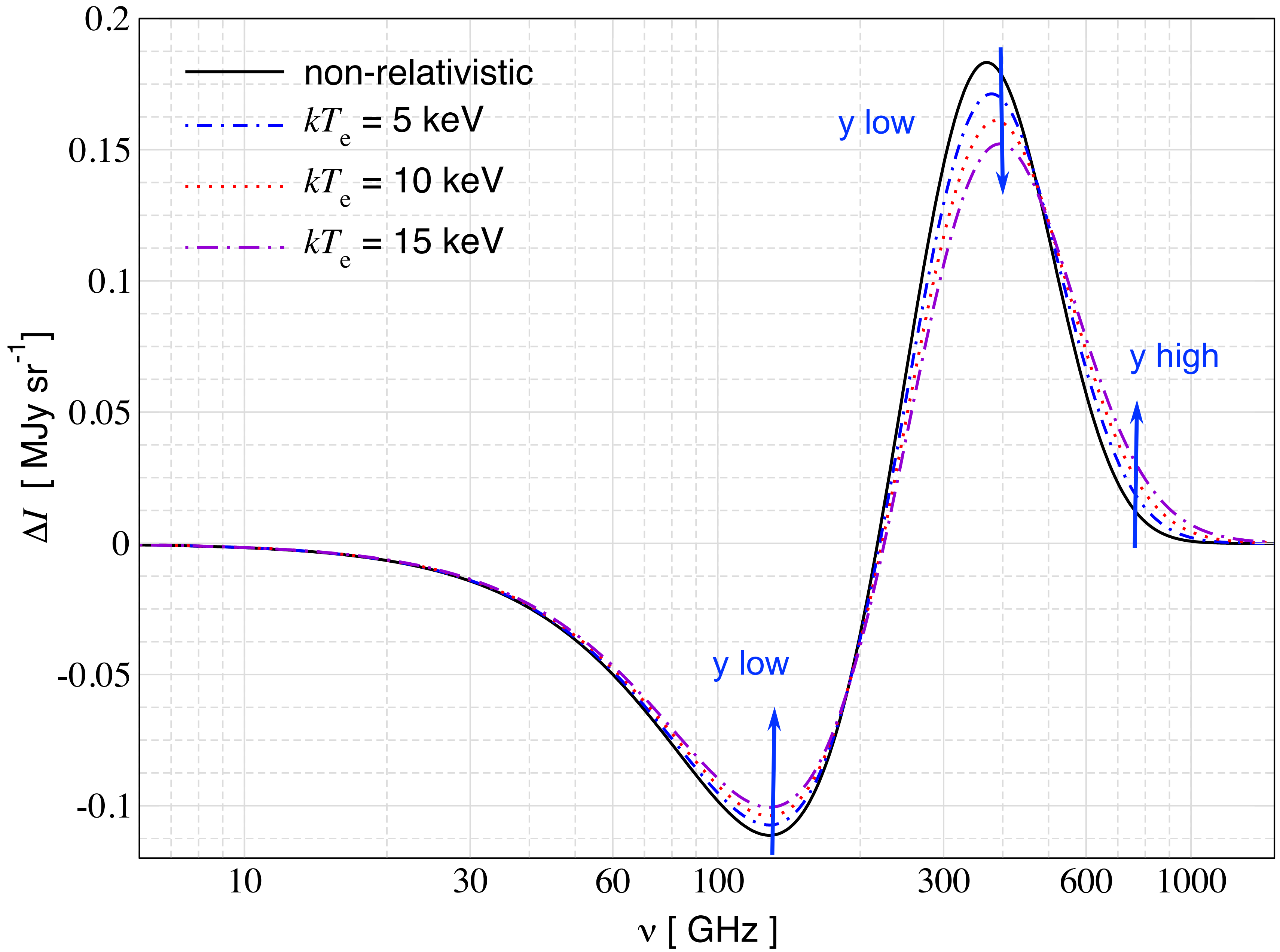
Planck 2015 results XXII

Underestimation of Compton-y signal !

Courtesy Mathieu Remazeilles

What is the net effect on the y-parameter?

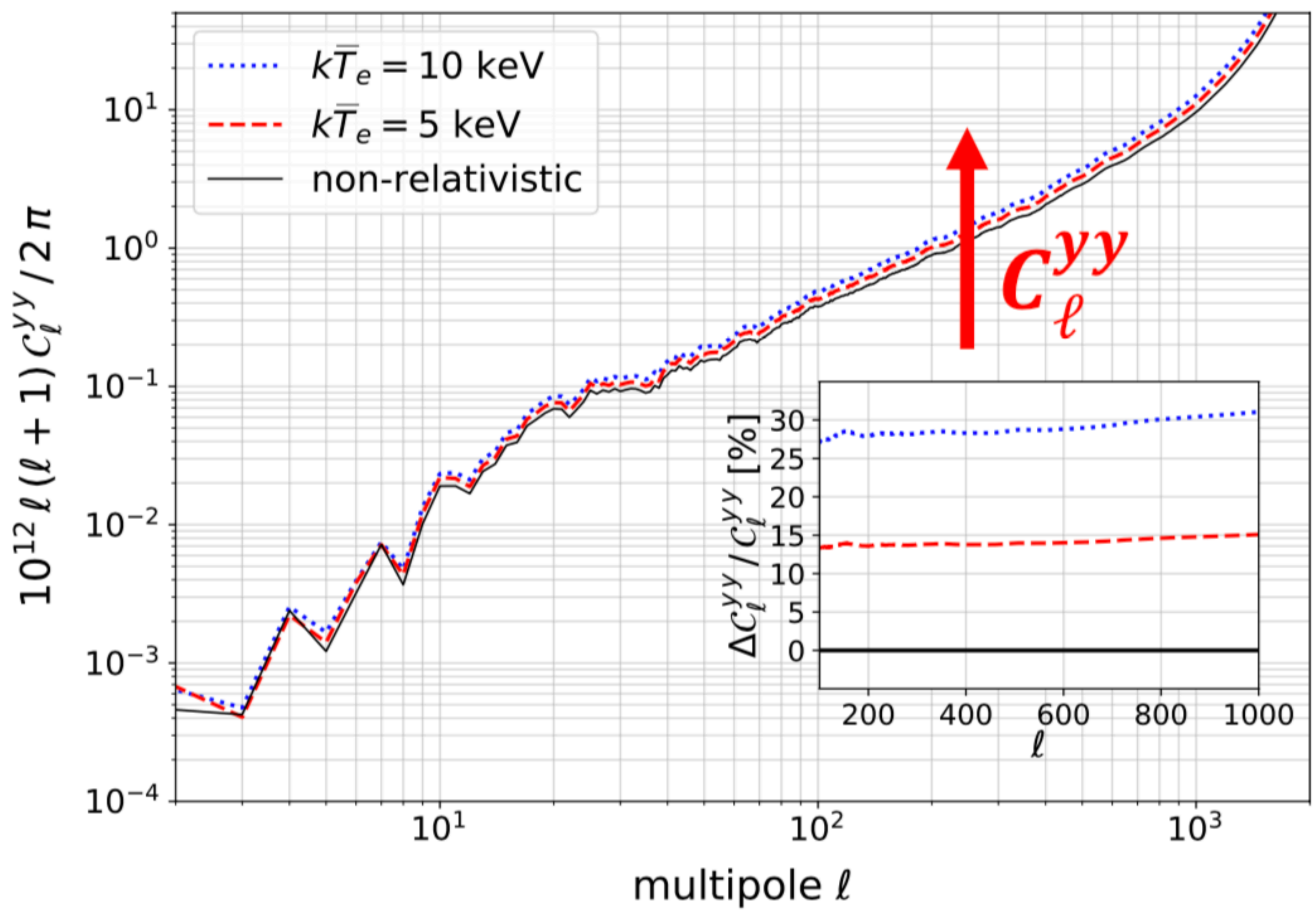
Total tSZ signal



- 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 $\bar{T}_e$

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

$\simeq 1\sigma$ *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

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

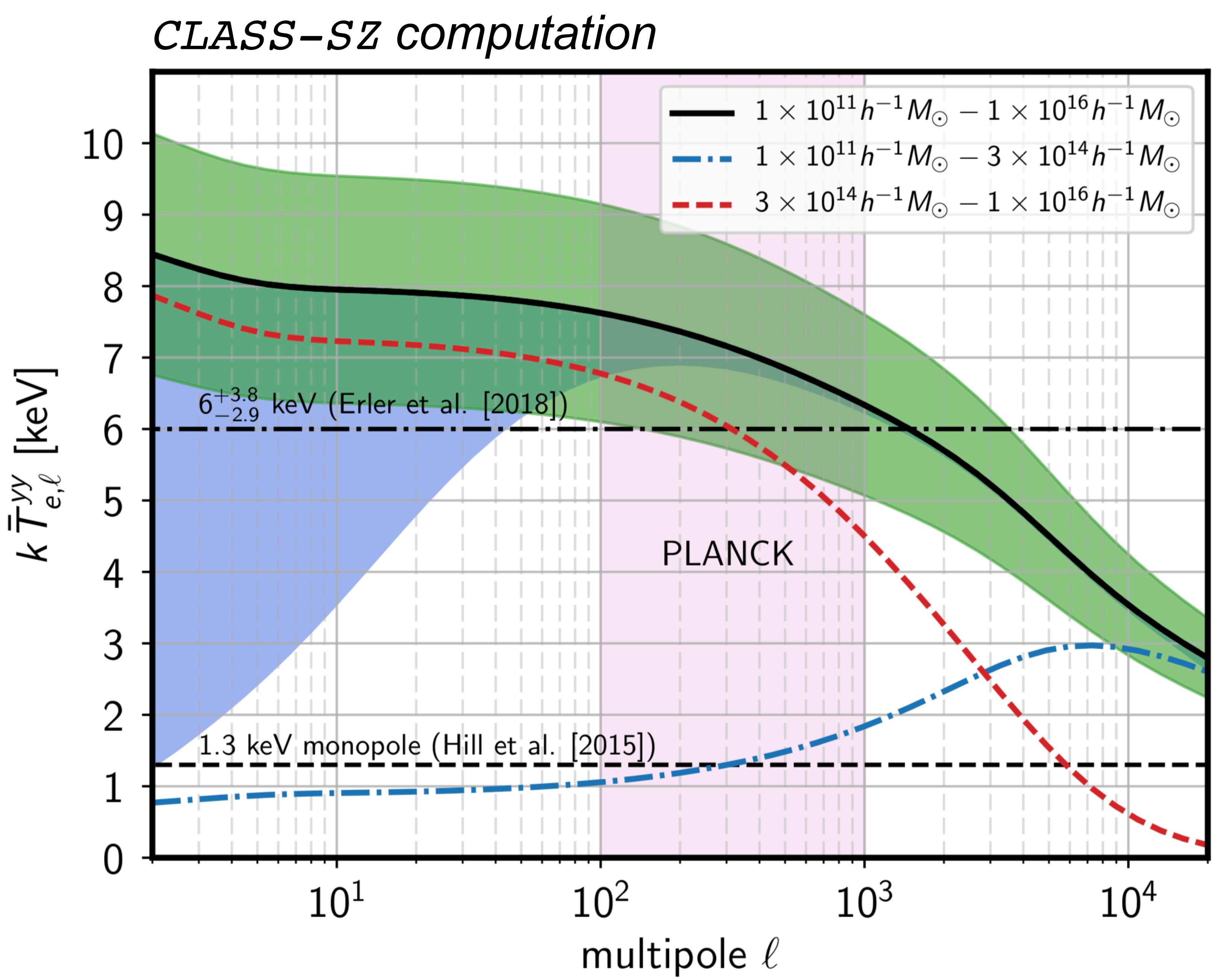
- SZ power spectrum analysis → y^2-weighted temperature is relevant

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

- 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

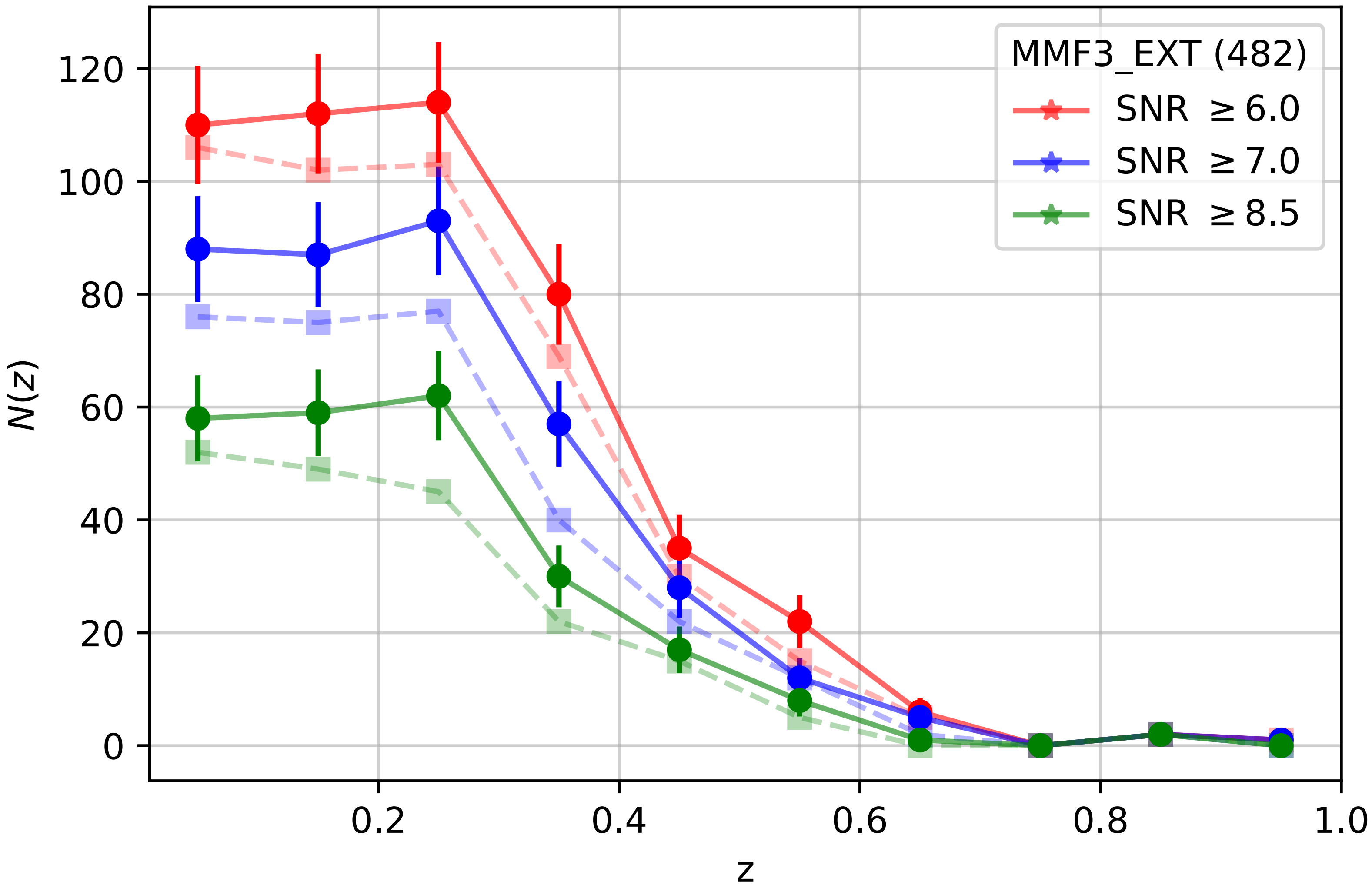


- Significant uncertainties…
- Contributions from diffuse y become important at large angular scales (e.g., Hansen et al., 2005)
- Assuming kT_e ~ 5 keV for *Planck* appears conservative
- Effective temperature is roughly constant for scales relevant to *Planck*

- 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

Effect of rSZ on cluster number counts



- Rescaled S/N increases
- Effect of rSZ pushes some systems 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.

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)

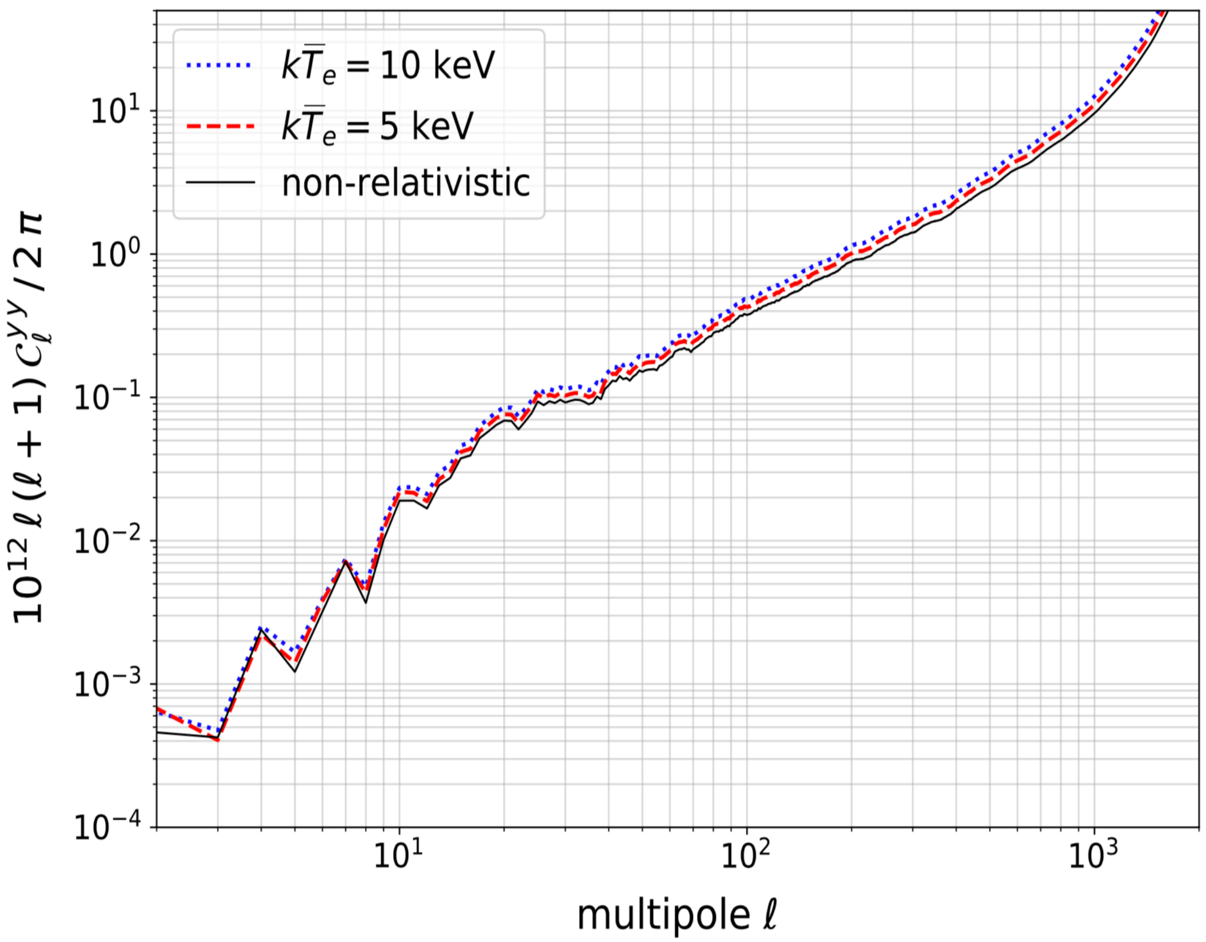
Statistical analysis

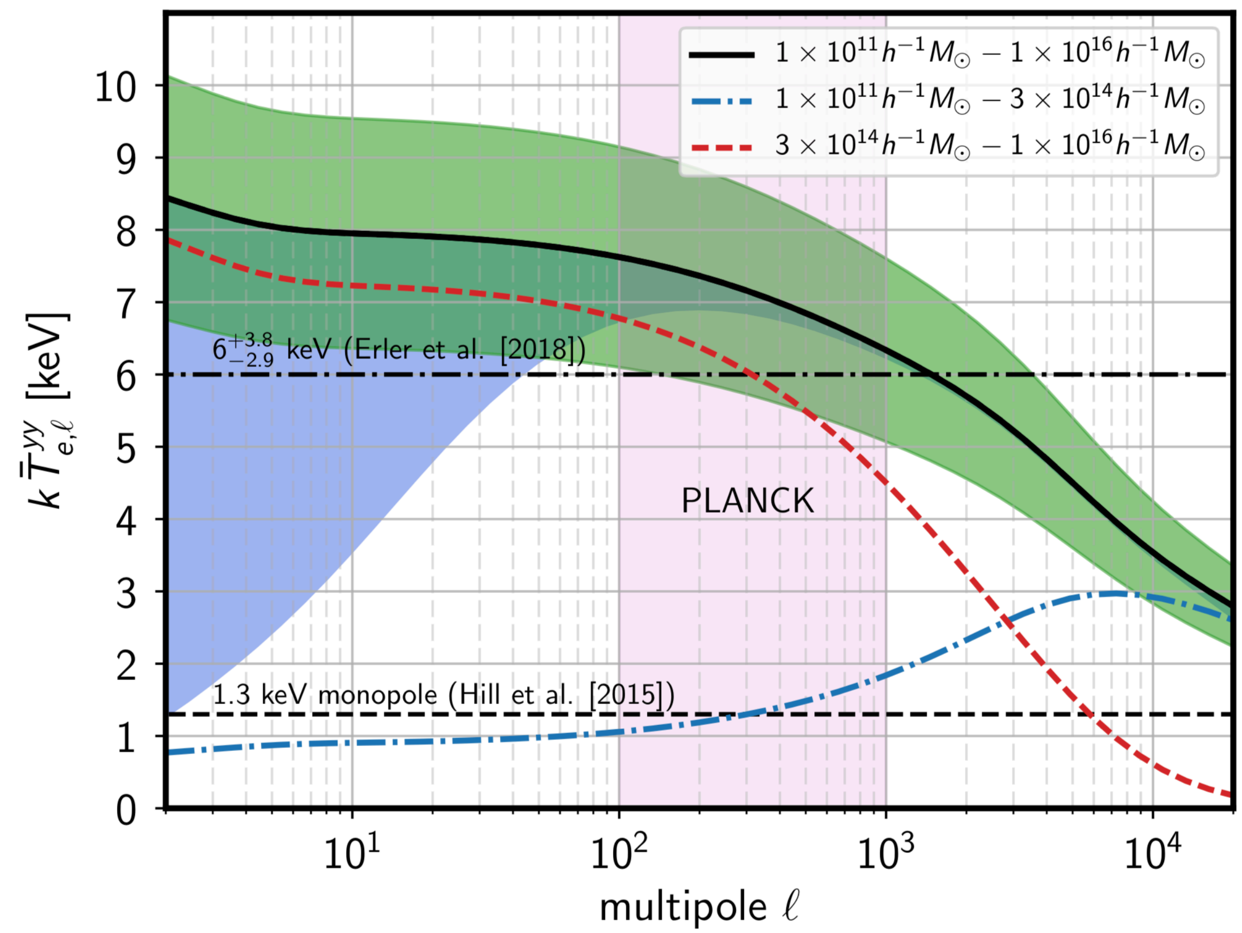
- rSZ power spectrum
- Cluster number counts in mass and redshift bins
- Higher order statistics
  (↔ non-Gaussianity)

Highly relevant when using SZ clusters as a cosmological tool
(↔ neutrino masses, σ_8, dark energy)

Conclusions

- rSZ still 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 plays a role in the σ_8 tension (shift upwards + increase of error)
- Careful analysis marginalizing over model uncertainties is required
- Net effect on SZ number counts still work in progress…





Remazeilles, Bolliet, Rotti & JC, MNRAS, 2019