Relativistic SZ maps and electron temperature spectroscopy

Mathieu Remazeilles

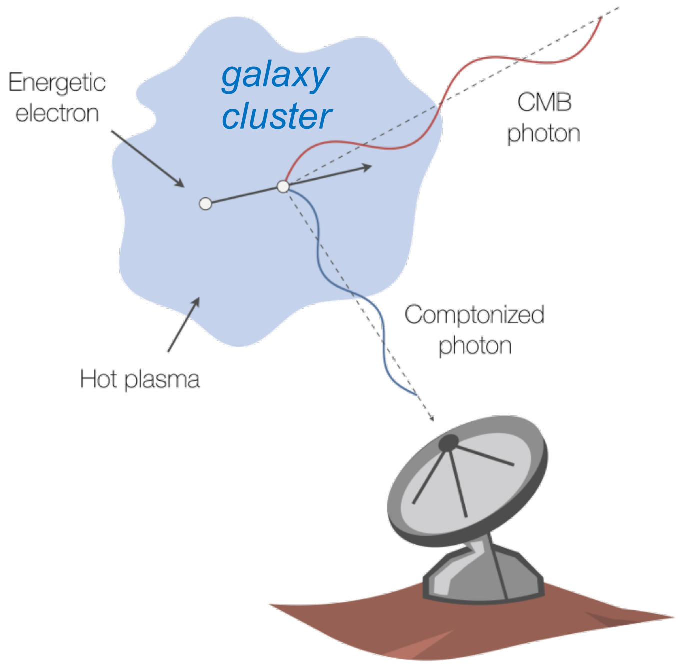
The University of Manchester

Remazeilles & Chluba, MNRAS (2020)
Remazeilles, Bolliet, Rotti, Chluba, MNRAS (2019)

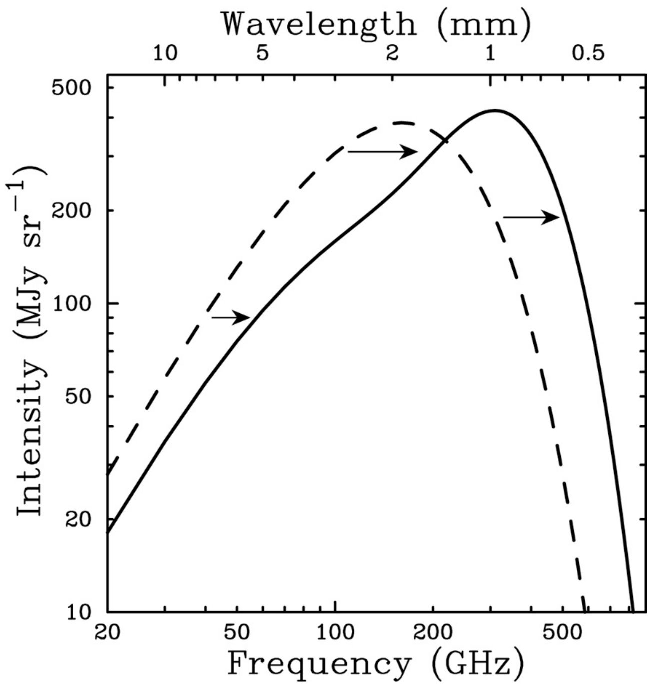
2nd mm Universe @ NIKA2
Rome, 28 June – 2 July 2021

Thermal Sunyaev-Zeldovich (SZ) Effect

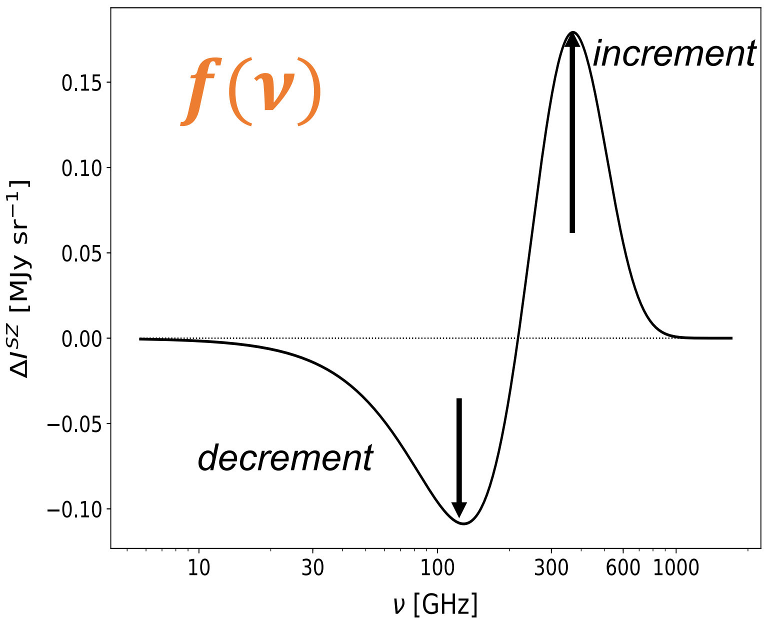
Zeldovich & Sunyaev 1969



Inverse Compton scattering of CMB photons by hot gas of electrons in galaxy clusters



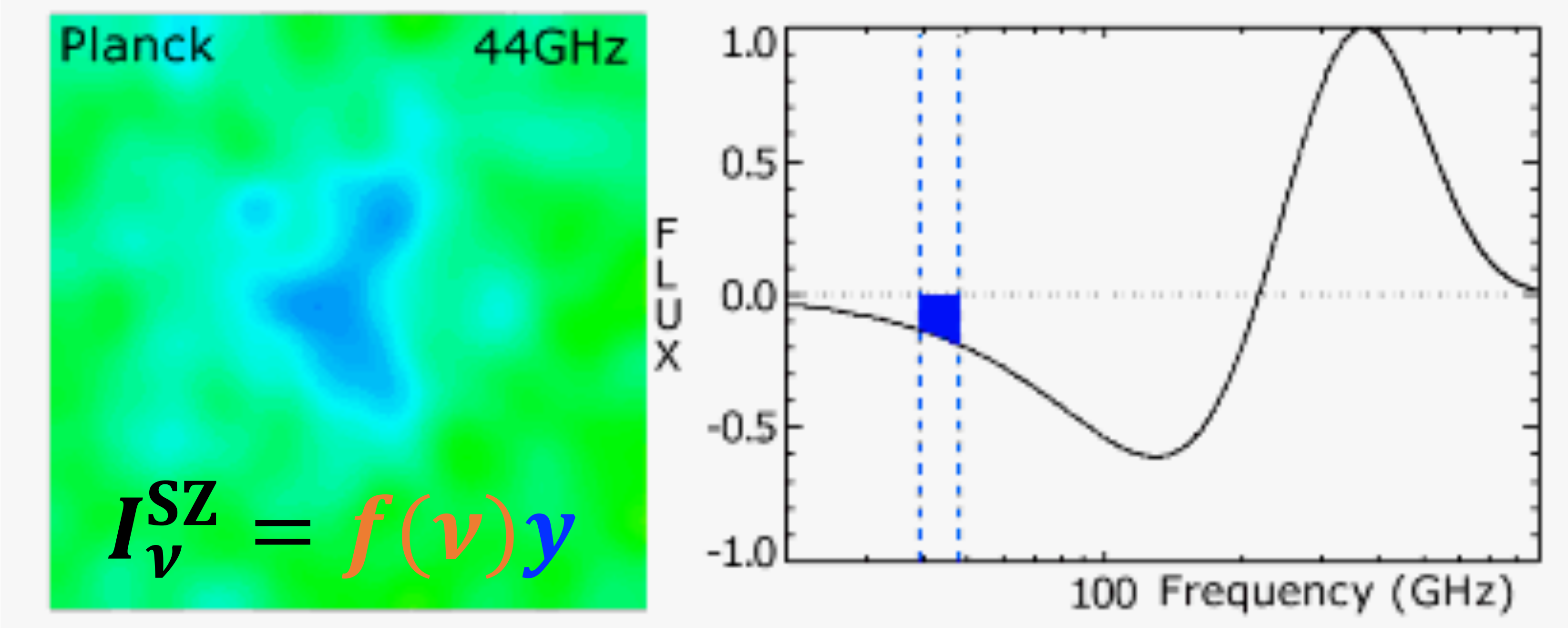
***y**-type spectral distortion of CMB blackbody radiation*

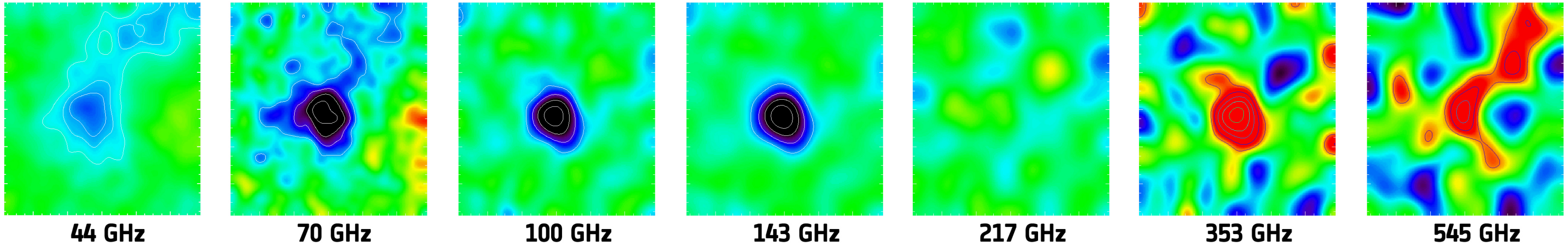


Spectral signature

$$I_\nu^{SZ} \equiv \frac{\Delta I_\nu^{\mathrm{CMB}}}{I_\nu^{\mathrm{CMB}}} = f(\nu)\,\frac{\sigma_T}{m_e c^2}\int P_{\mathrm{e}}(l)\,dl = f(\nu)\,y$$

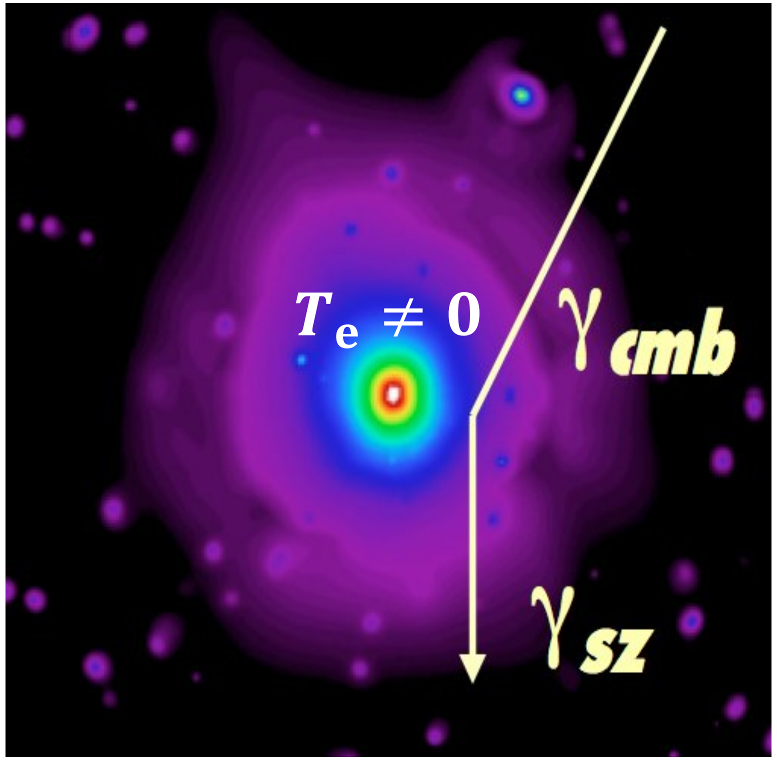
Spectroscopy of clusters across frequencies





Credit: ESA/Planck Collaboration

Relativistic SZ effect (rSZ): Temperature corrections to thermal SZ effect



- Galaxy clusters are massive, so they are hot

Arnaud et al, A&A 2005

$$kT_e \simeq 5\ \mathrm{keV}\left[\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}\,\frac{M_{500}}{3\times10^{14}\ h^{-1}M_\odot}\right]^{2/3}$$

- Thermal velocities of electrons approach the speed of light

$$v_e^{th} = \sqrt{2kT_e/m_e} \gtrsim 0.1c$$

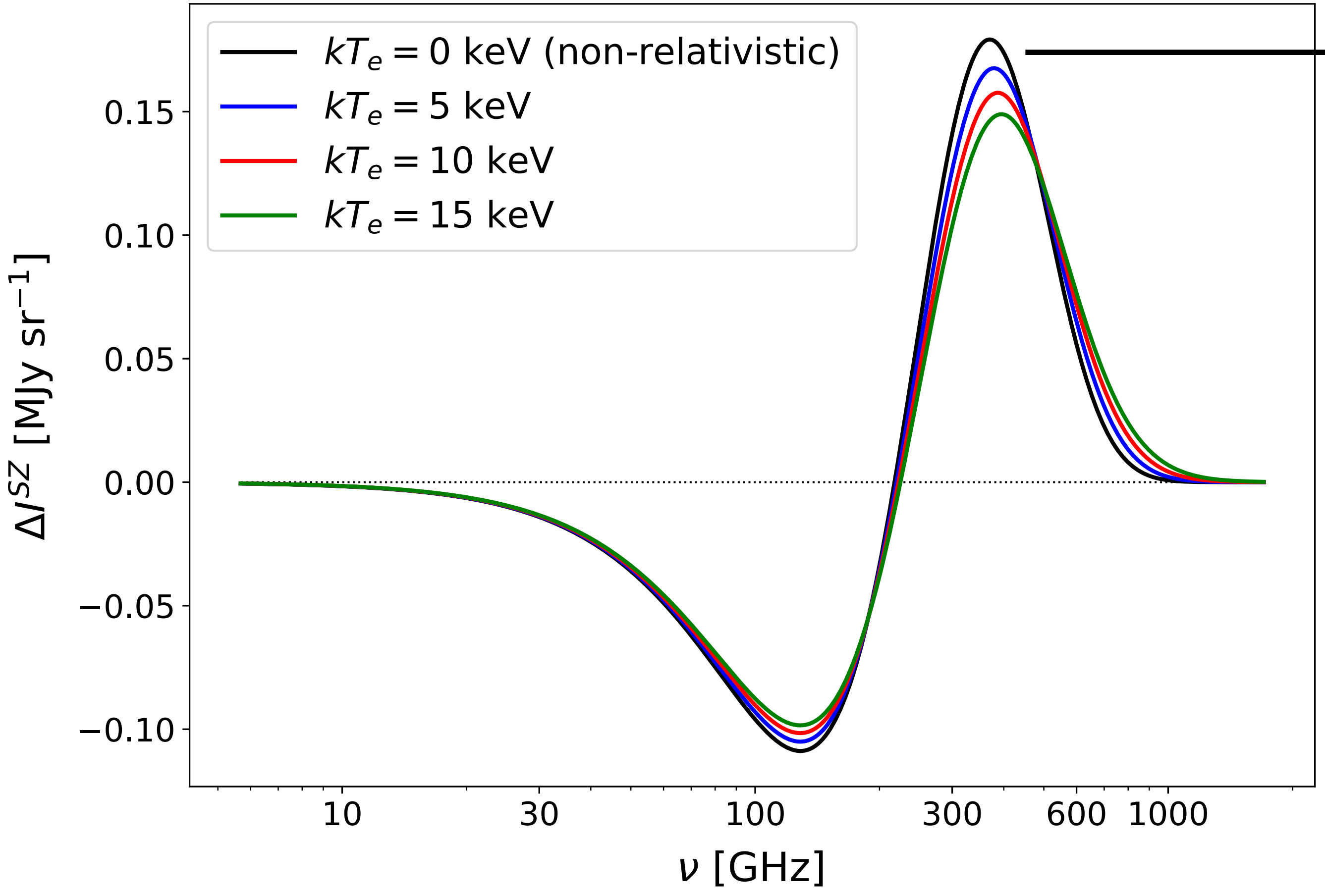
- Relativistic temperature corrections to the thermal SZ effect should be accounted for

$$I^{SZ}(\nu,\vec{n}) = f\,(\nu, T_e(\vec{n}))\ y(\vec{n})$$

The spectral signature of SZ emission from galaxy clusters changes with the local electron gas temperature

Relativistic SZ temperature corrections

$$I_\nu^{SZ} = f(\nu, T_e(\vec{n}))\, y(\vec{n})$$



Planck's assumption: $T_e \simeq 0$ keV

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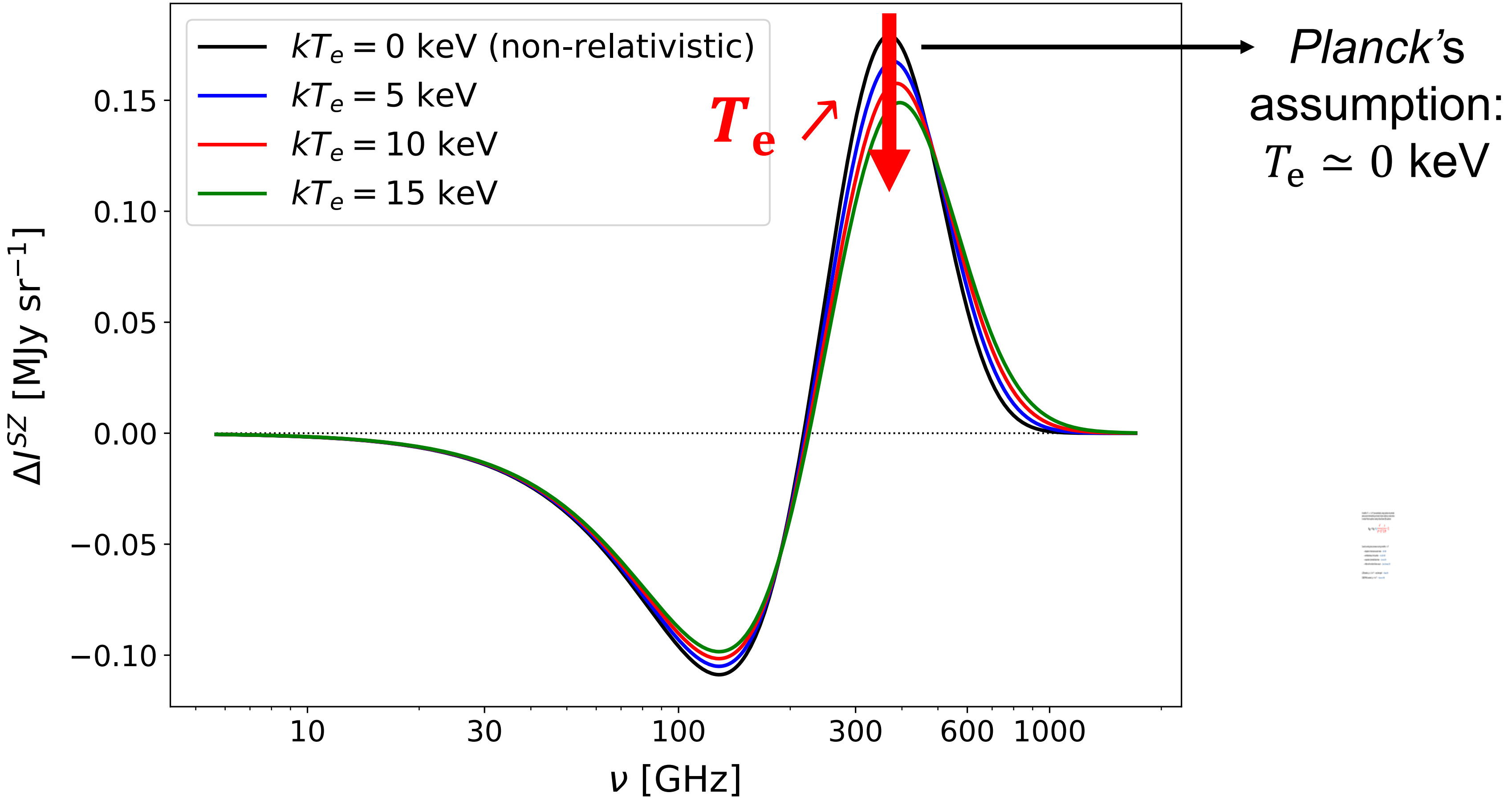
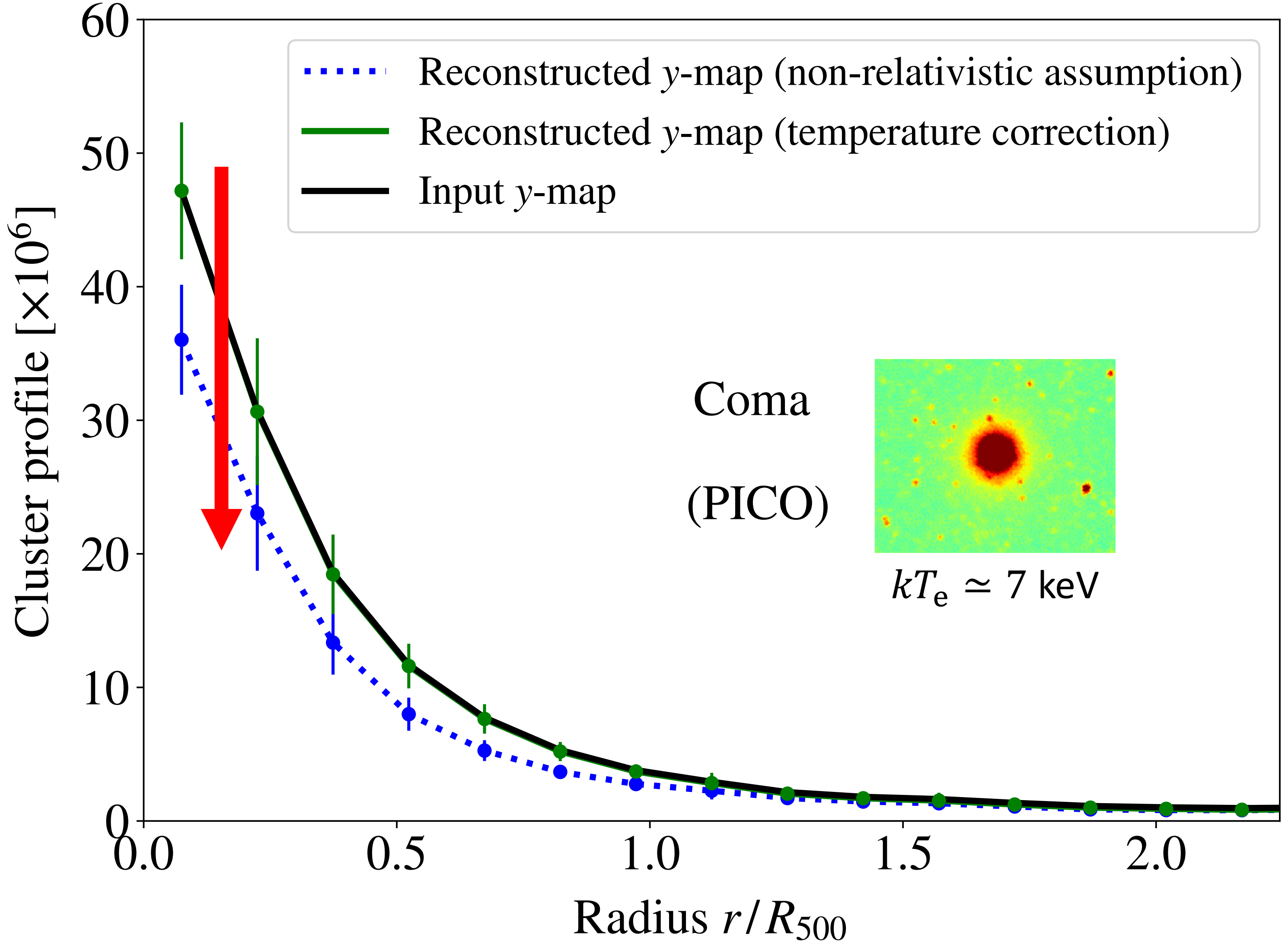


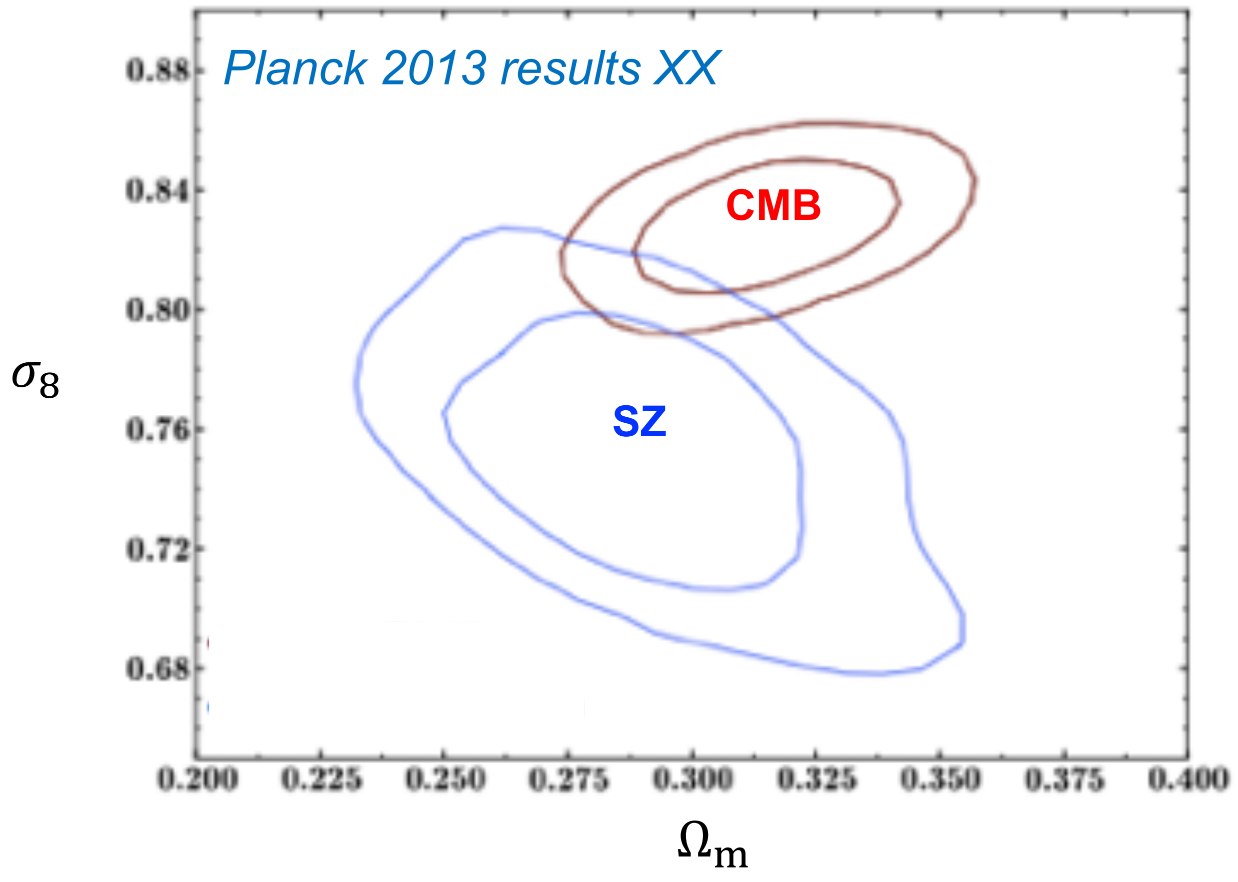
- Relativistic temperature corrections reduce the overall SZ intensity at fixed Compton-y parameter
- Assuming the non-relativistic SED $f(\nu, T_e = 0)$ underestimates the Compton-y parameter

Impact on cluster pressure profiles of neglecting relativistic SZ corrections



Remazeilles & Chluba, MNRAS 2020

Planck tension on σ_8 between CMB and SZ



- Incompleteness of ΛCDM model?

  Evidence for massive neutrinos?

- Incorrect mass-bias in the Y-M relation?

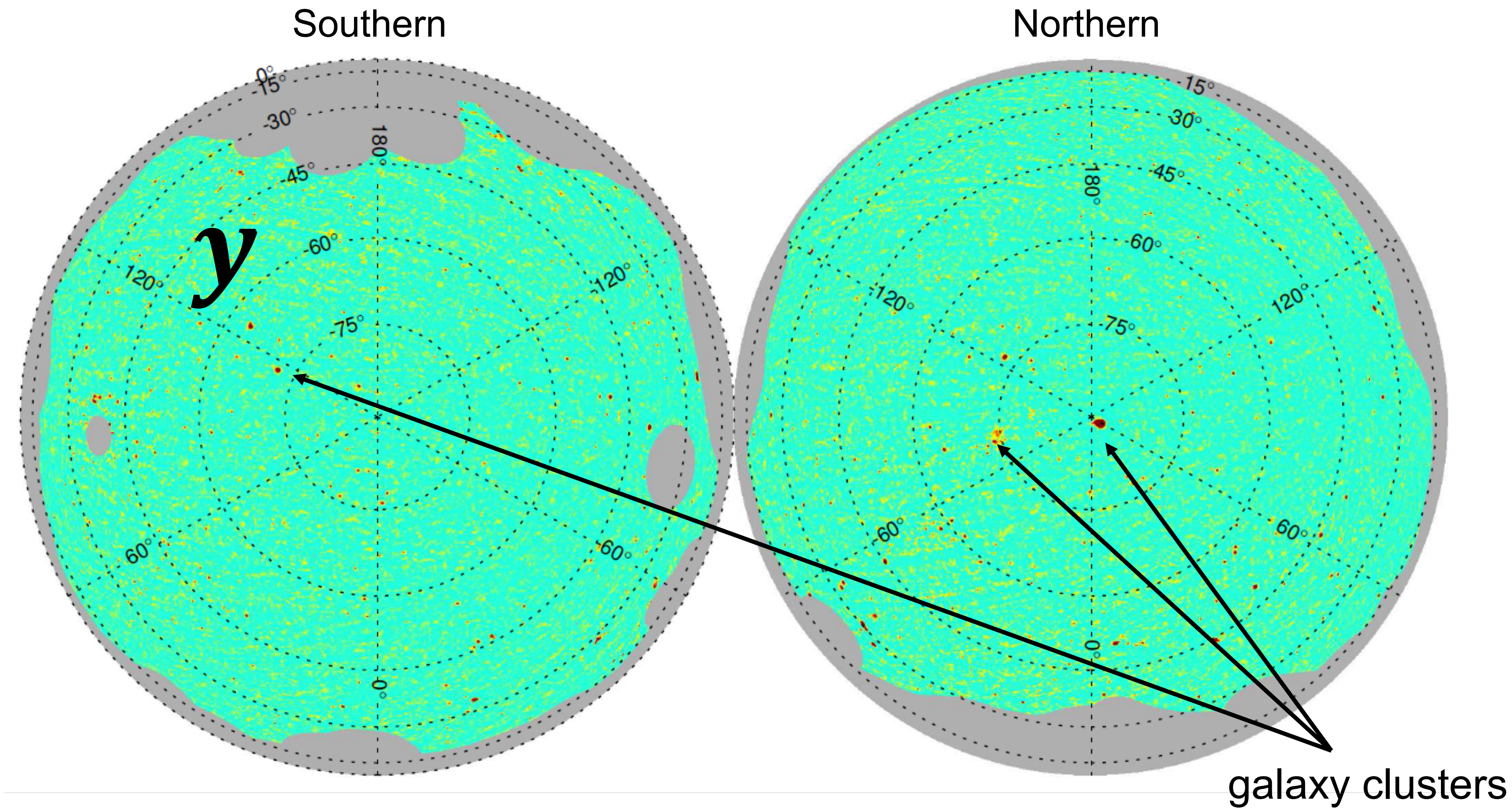
  Hydrodynamical simulations predict $M_{SZ}/M_{\text{dark matter}} = (1-b) \simeq 0.8$

- Miscalibrated Planck SZ analysis because of neglecting relativistic corrections?

  Remazeilles, Bolliet, Rotti, Chluba, MNRAS (2019)

The *Planck* SZ Compton y-map

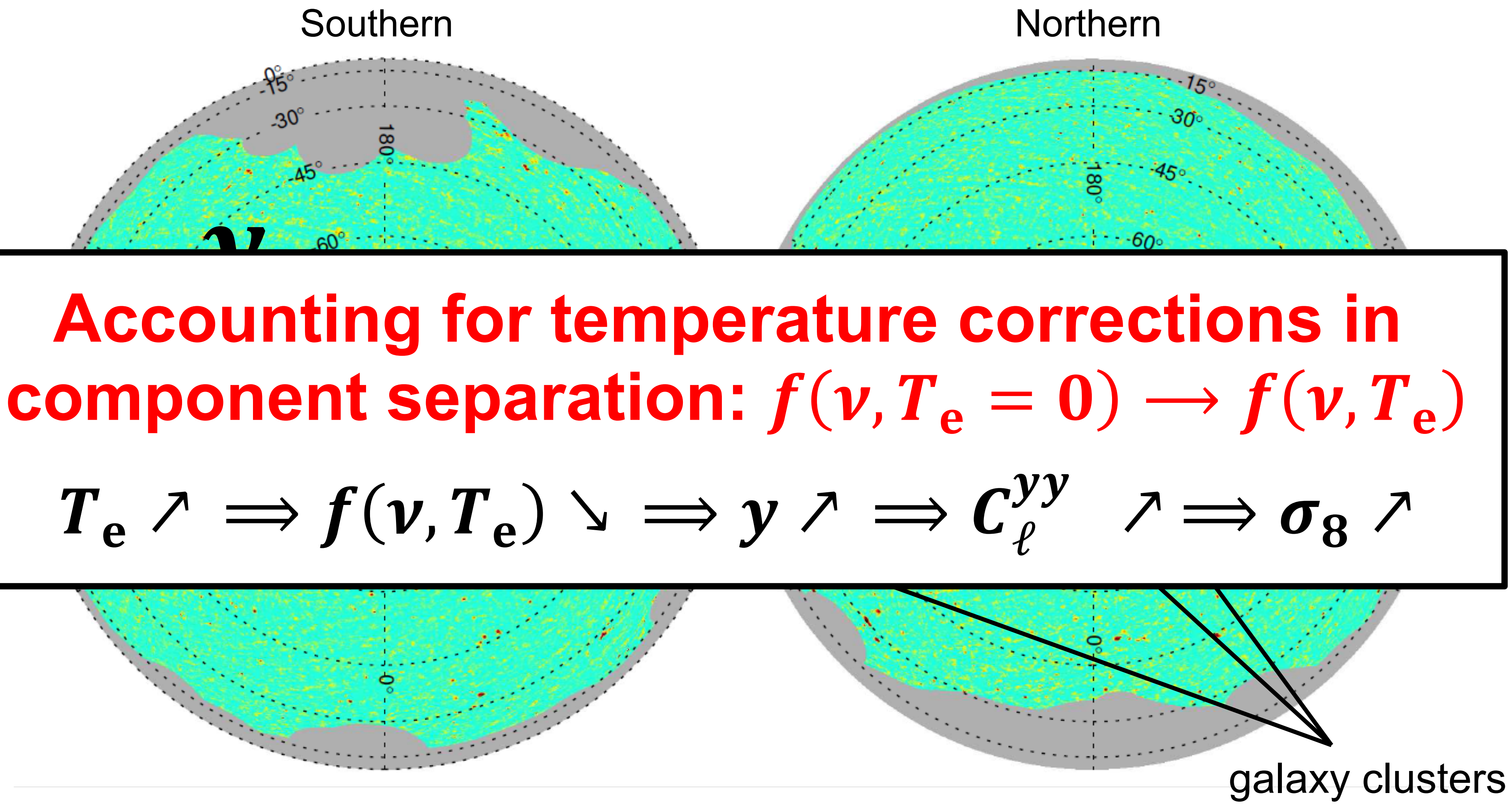
Non-relativistic approximation $f(\nu, T_e = 0)$ for component separation



Planck 2015 results XXII, A&A (2016)

Revisiting the *Planck* SZ Compton y-map

Remazeilles, Bolliet, Rotti, Chluba, MNRAS (2019)

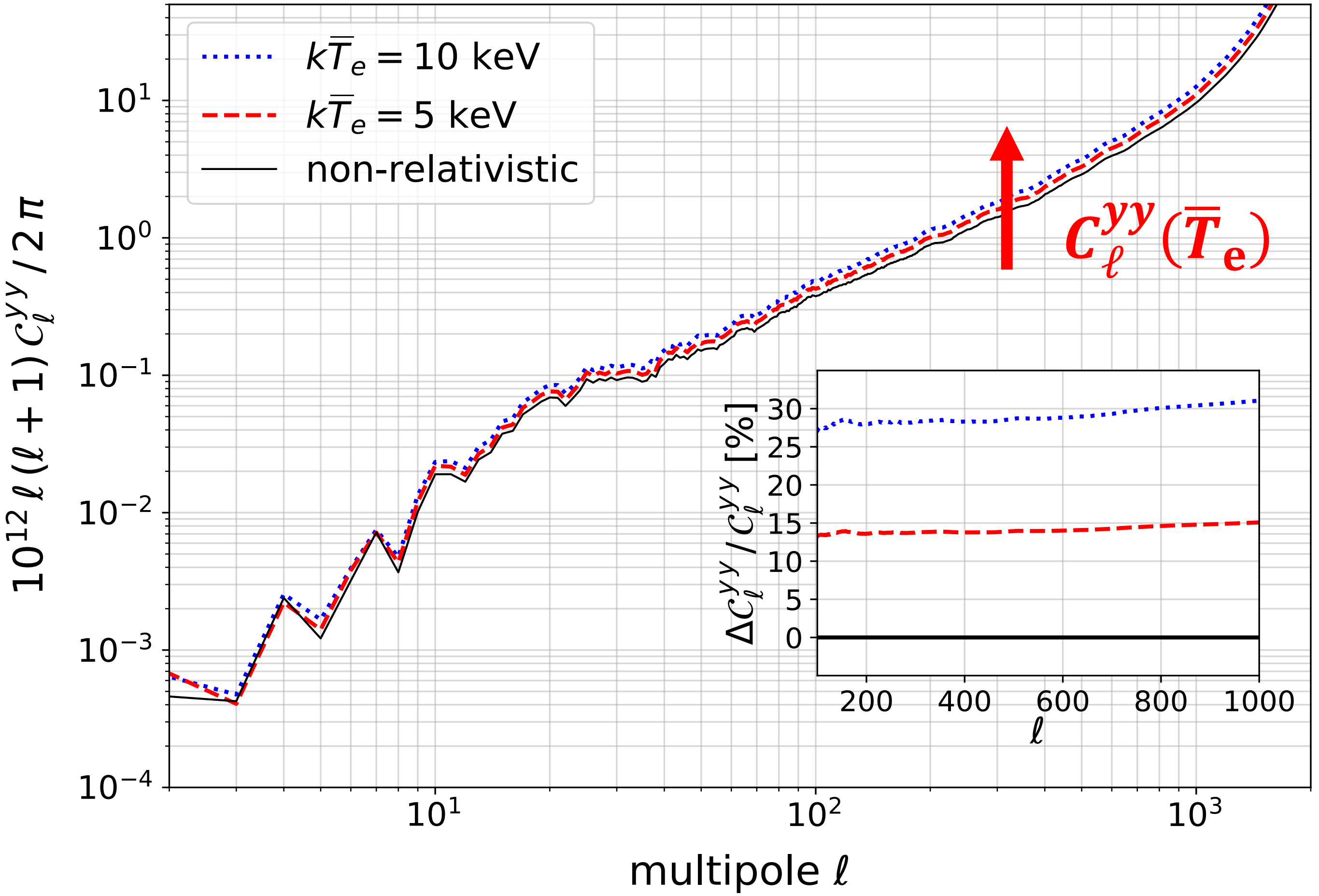


Accounting for temperature corrections in component separation: $f(\nu, T_{\rm e} = 0) \longrightarrow f(\nu, T_{\rm e})$

$$T_{\rm e} \nearrow \;\Longrightarrow f(\nu, T_{\rm e}) \searrow \;\Longrightarrow y \nearrow \;\Longrightarrow C_\ell^{yy} \nearrow \;\Longrightarrow \sigma_8 \nearrow$$

Relativistic temperature corrections to the Planck SZ power spectrum

Remazeilles, Bolliet, Rotti, Chluba, MNRAS 2019



C_ℓ^{yy} increases with the average temperature $\bar{T}_\mathrm{e}$

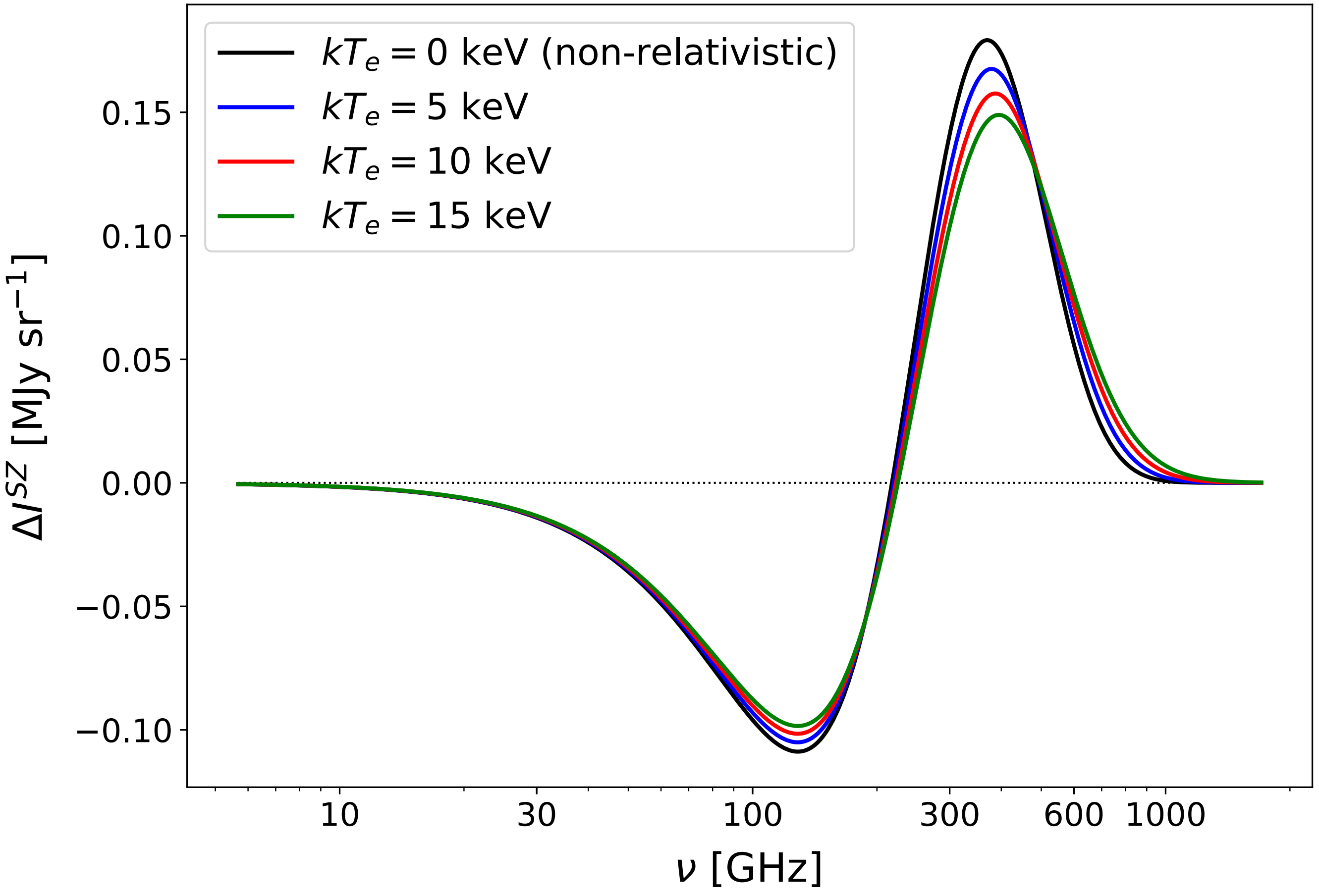
$$C_\ell^{yy} \sim \sigma_8^{8.1} \implies \frac{\Delta\sigma_8}{\sigma_8} \simeq 0.019\left(\frac{k\bar{T}_\mathrm{e}}{5\ \mathrm{keV}}\right)$$

$k\bar{T}_\mathrm{e} \simeq 5$ keV alleviates *Planck*'s tension by 1σ

Mapping relativistic electron temperatures?

Relativistic SZ temperature corrections

$$I_\nu^{SZ} = f\,(\nu, T_e(\vec{n}))\; y(\vec{n})$$

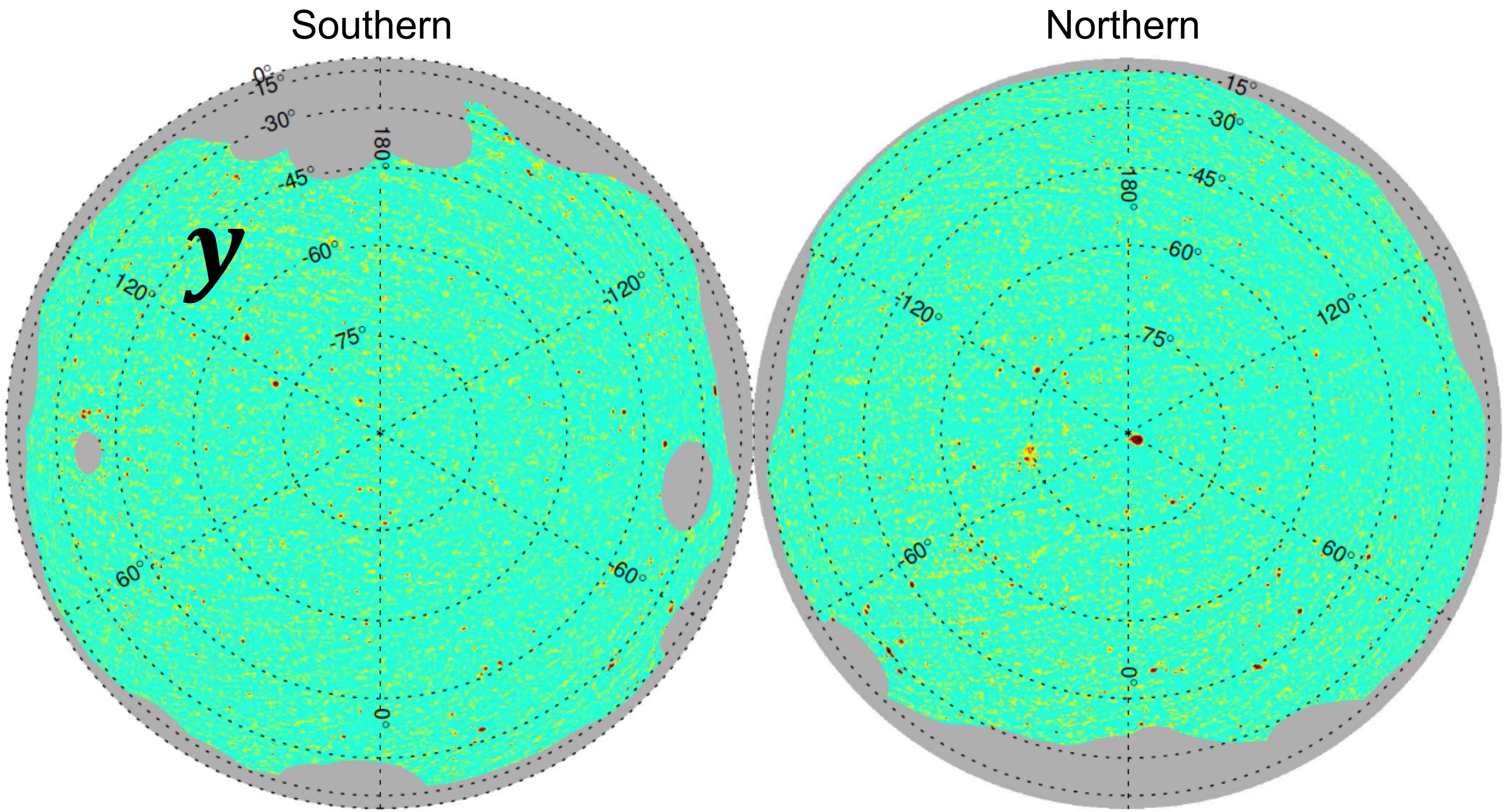


Relativistic electron temperatures distort the shape of the SZ spectrum

Two complementary observables

$$y(\vec{n})\ ,\ T_e(\vec{n})$$

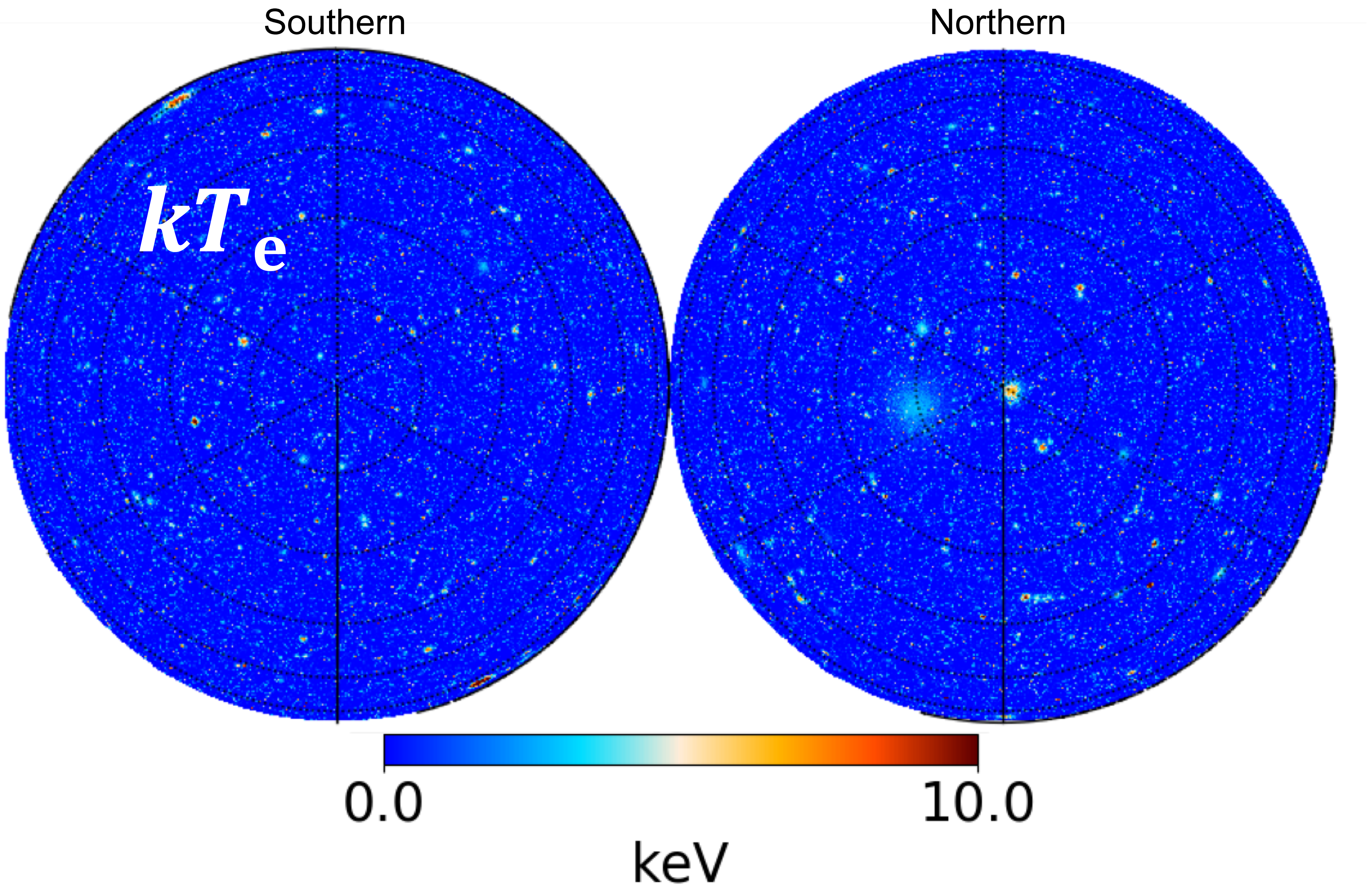
"First SZ revolution":
The *Planck* Compton y-map



Planck 2015 results XXII, A&A (2016)

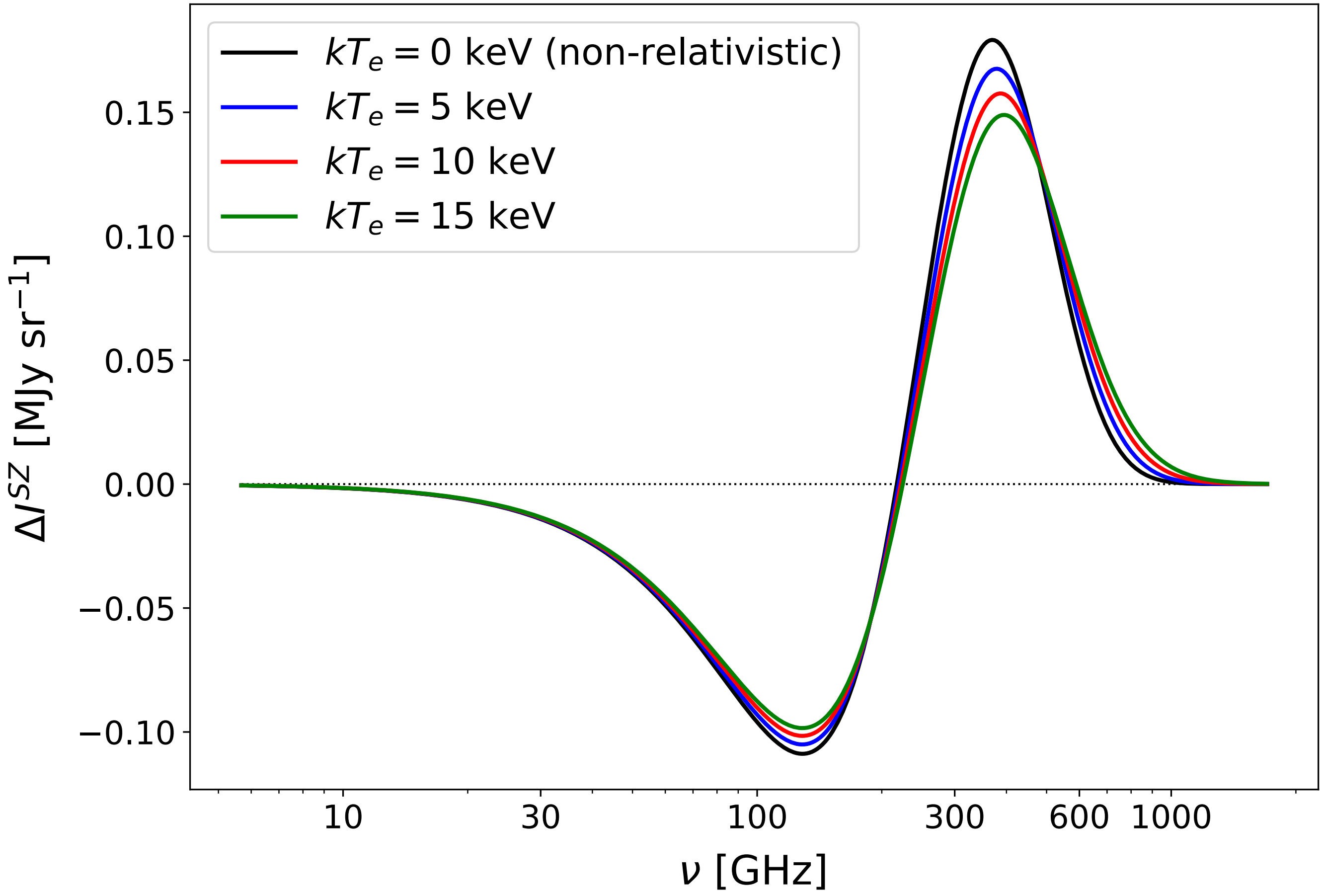
“Second SZ revolution”:

The electron temperature T_e-map ?



Relativistic SZ temperature corrections

$$I_\nu^{\mathrm{SZ}} = f(\nu, T_\mathrm{e}(\vec{n}))\, y(\vec{n})$$



The spectral signature of SZ emission from galaxy clusters changes with the local electron gas temperature

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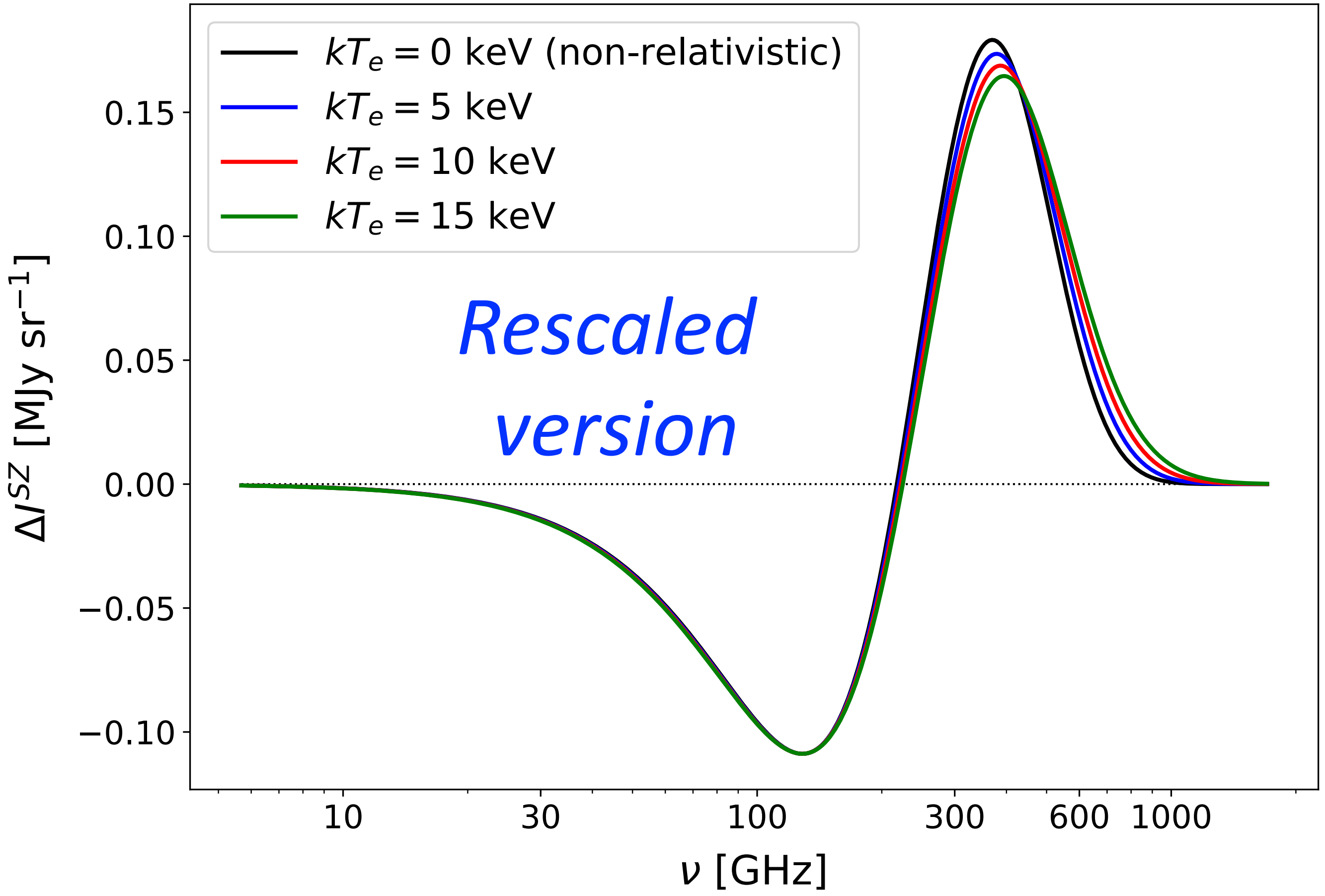
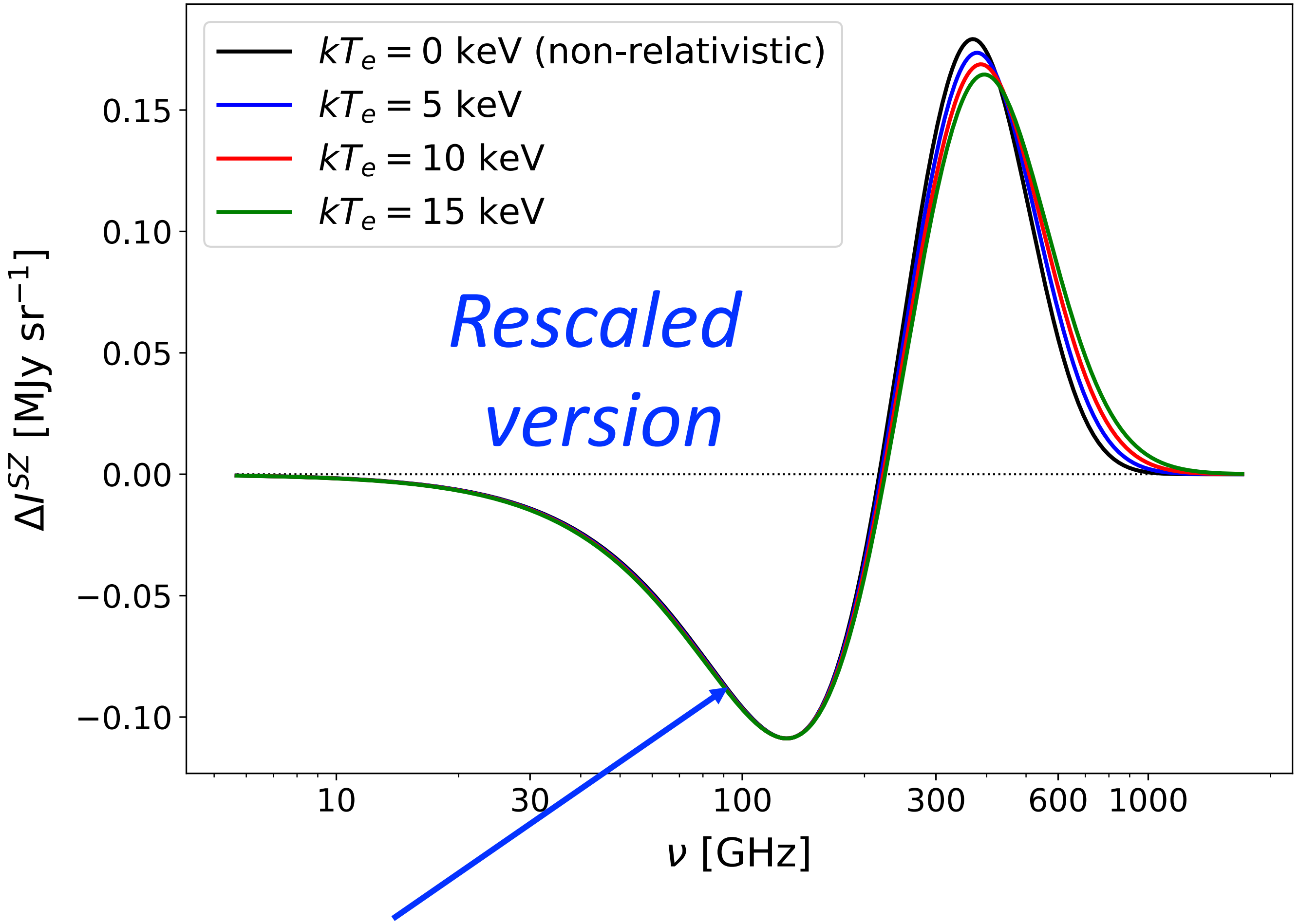


The spectral signature of SZ emission from galaxy clusters changes with the local electron gas temperature

The y-T_e degeneracy at low frequency

$$I_\nu^{SZ} = f(\nu, T_e(\vec{n}))\, y(\vec{n})$$



Spectral shapes are degenerate at low frequency

(impossible to disentangle $\boldsymbol{y}$ and $\boldsymbol{T}_e$)

The y-T_e degeneracy at low frequency

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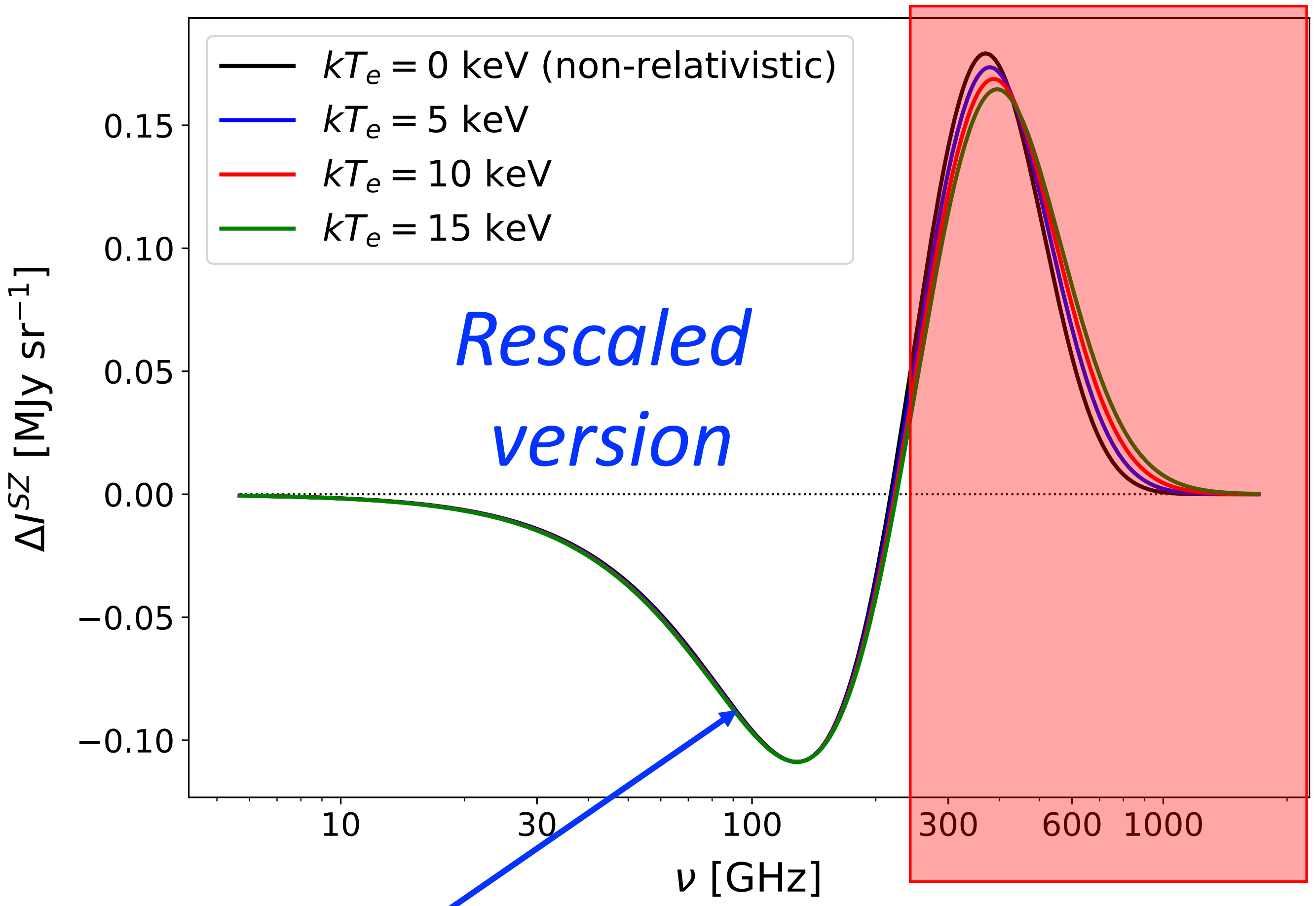


High frequencies are essential to extract rSZ

Spectral shapes are degenerate at low frequency

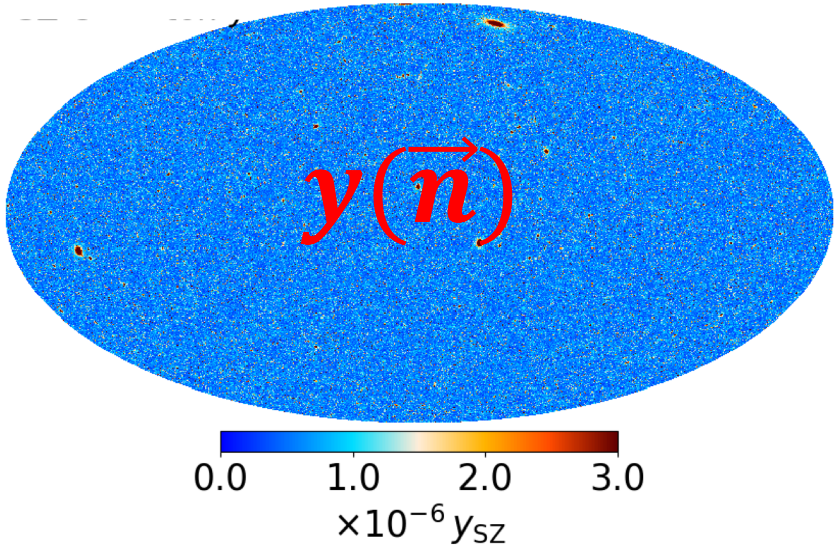
(impossible to disentangle $\boldsymbol{y}$ and $\boldsymbol{T}_\mathbf{e}$)

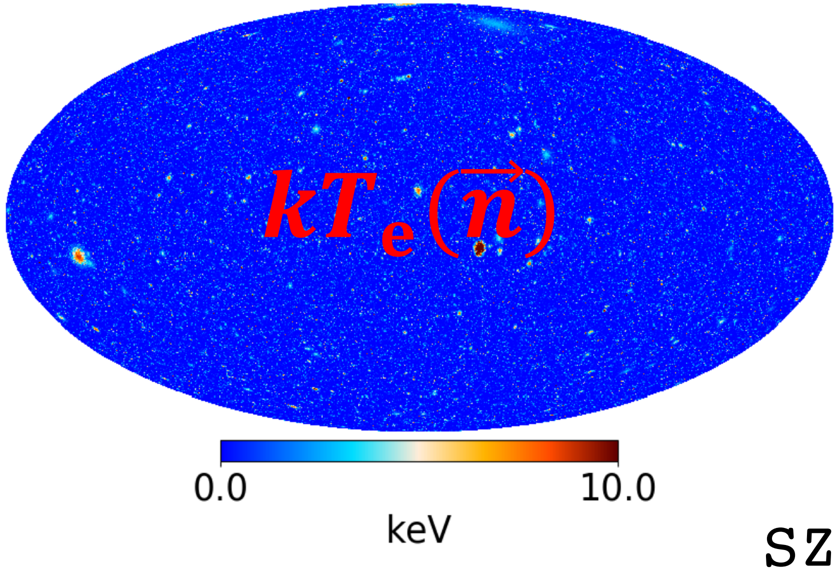
PICO in Brief

arXiv:1902.10541

- Millimeter/submillimeter-wave, polarimetric survey of the entire sky
- 21 bands between 20 GHz and 800 GHz
- 1.4 m aperture telescope
- Diffraction limited resolution: 38' to 1'
- 13,000 transition edge sensor bolometers
- 5 year survey from L2
- 0.87 uK*arcmin requirement; 0.61 uK*arcmin goal (=CBE)

Foreground-obscured sky simulations

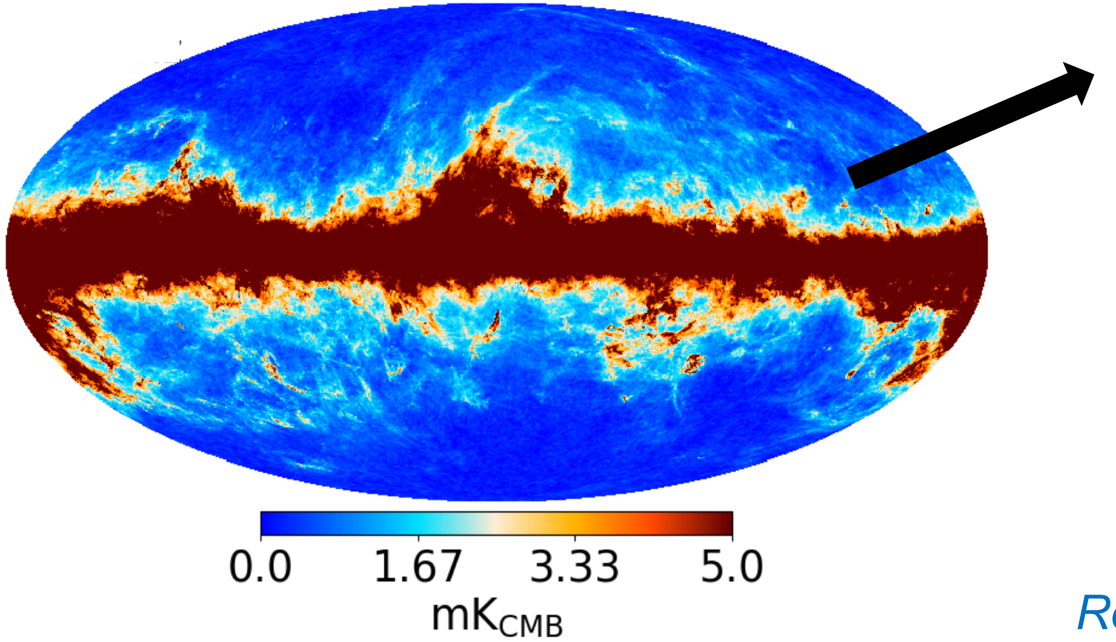




SZpack
Chluba, Nagai, Sazonov, Nelson, MNRAS 2012

rSZ maps (20 - 800 GHz): $I_\nu^{\mathrm{rSZ}}(\vec{n}) = f\left(\nu, T_e(\vec{n})\right) y(\vec{n})$

PICO sky maps 20 - 800 GHz



rSZ, kSZ, CMB, CIB, Galactic foregrounds (dust, synchrotron, AME, free-free), noise

Remazeilles & Chluba, MNRAS 2020

Component Separation

How to disentangle the $\boldsymbol{y}$ and $\boldsymbol{T_{\mathrm{e}}}$ observables of the rSZ effect in sky observations?

SZ temperature moment expansion

$$\boldsymbol{I_\nu^{\mathrm{SZ}}(\vec{n}) = f(\nu, T_{\mathrm{e}}(\vec{n}))\, y(\vec{n})}$$

Remazeilles & Chluba, MNRAS (2020)

SZ temperature moment expansion

$$I_\nu^{SZ}(\vec{n}) = f(\nu, T_e(\vec{n}))\, y(\vec{n})$$

Taylor expansion around pivot temperature $\bar{T}_e$

$$I_\nu^{SZ}(\vec{n}) = f(\nu, \bar{T}_e)\; y(\vec{n}) + \frac{\partial f(\nu, \bar{T}_e)}{\partial T_e}\; (T_e(\vec{n}) - \bar{T}_e) y(\vec{n}) + \mathcal{O}(T_e^2)$$

Remazeilles & Chluba, MNRAS (2020)

SZ temperature moment expansion

$$I_\nu^{SZ}(\vec{n}) = f(\nu, T_e(\vec{n}))\, y(\vec{n})$$

Taylor expansion around pivot temperature $\bar{T}_e$

$$I_\nu^{SZ}(\vec{n}) = \underbrace{f(\nu, \bar{T}_e)}_{\text{Spectrum of } y} \underbrace{y(\vec{n})}_{y \text{ component}} + \underbrace{\frac{\partial f(\nu, \bar{T}_e)}{\partial T_e}}_{\text{Spectrum of } yT_e} \underbrace{(T_e(\vec{n}) - \bar{T}_e) y(\vec{n})}_{y\Delta T_e \text{ component}} + \mathcal{O}(T_e^2)$$

Remazeilles & Chluba, MNRAS (2020)

SZ temperature moment expansion

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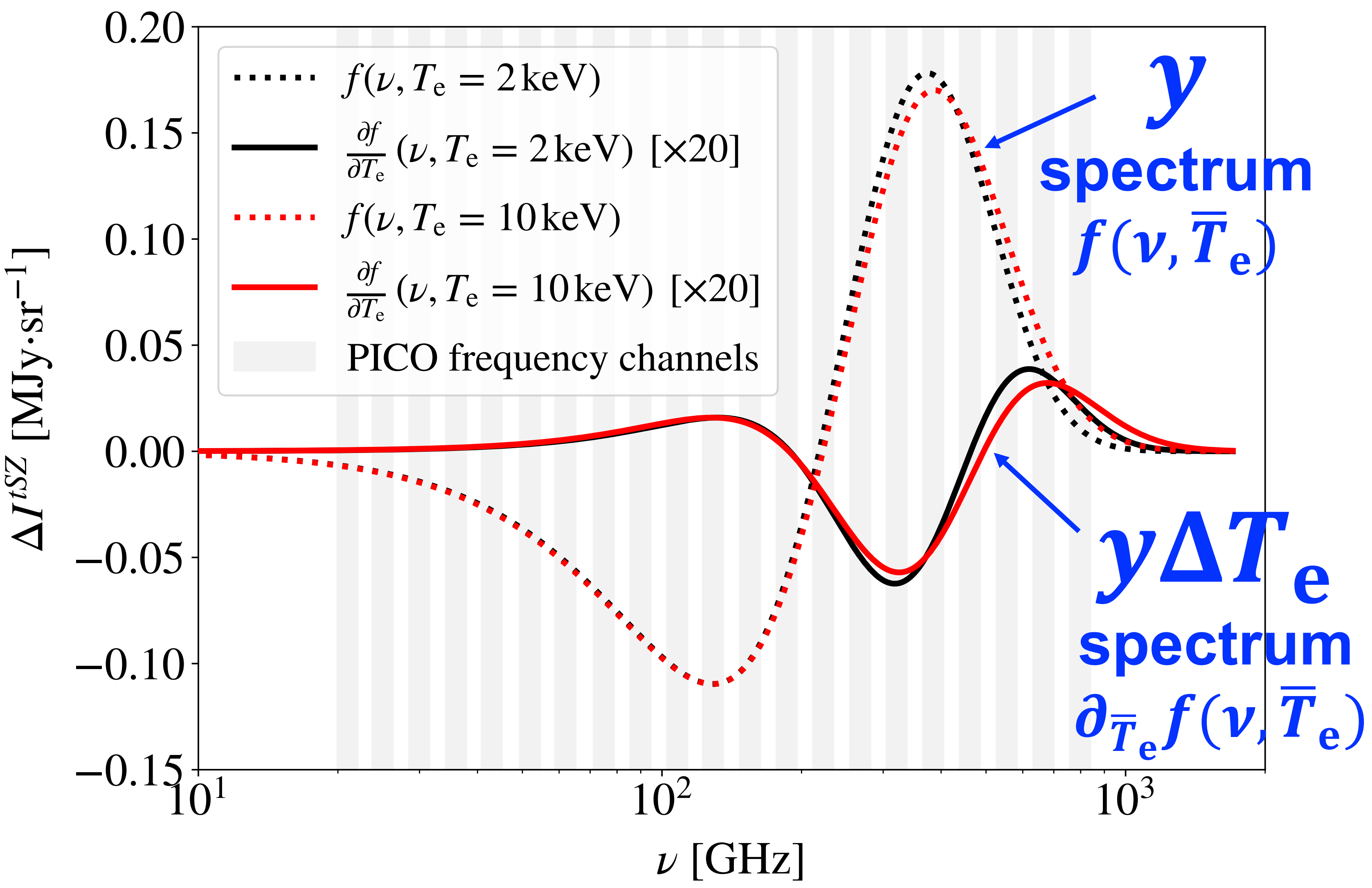
Two distinct components of emission, y and $y\Delta T_e$, with different spectral signatures!

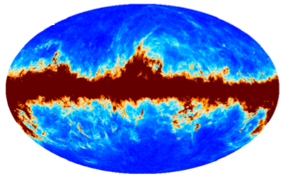
Remazeilles & Chluba, MNRAS (2020)

Two spectral components of the rSZ effect



It is possible in principle to disentangle y *and* $y\Delta T_e$ *through multi-frequency observations and component separation methods*

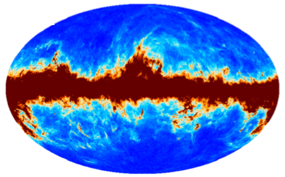
rSZ component separation



$$d(\nu,\vec{n}) = \underbrace{f(\nu,\bar{T}_\mathrm{e})}_{\text{spectrum of } y(\vec{n})} \underbrace{y(\vec{n})}_{y(\vec{n})} + \underbrace{\frac{\partial f(\nu,\bar{T}_\mathrm{e})}{\partial T_\mathrm{e}}}_{\text{spectrum of } y\Delta T_\mathrm{e}(\vec{n})} \underbrace{(T_\mathrm{e}(\vec{n}) - \bar{T}_\mathrm{e})y(\vec{n})}_{y\Delta T_\mathrm{e}(\vec{n})} + \underbrace{N(\nu,\vec{n})}_{\text{foregrounds + noise}}$$

Remazeilles & Chluba, MNRAS 2020

rSZ component separation



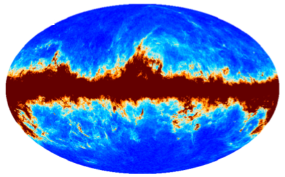
$$\underbrace{d(\nu,\vec{n})}_{} = \underbrace{f(\nu,\bar{T}_e)}_{\text{spectrum of } y(\vec{n})}\ \underbrace{y(\vec{n})}_{y(\vec{n})} + \underbrace{\frac{\partial f(\nu,\bar{T}_e)}{\partial T_e}}_{\text{spectrum of } y\Delta T_e(\vec{n})}\ \underbrace{(T_e(\vec{n}) - \bar{T}_e)\,y(\vec{n})}_{y\Delta T_e(\vec{n})} + \underbrace{N(\nu,\vec{n})}_{\text{foregrounds + noise}}$$

Component separation with the Constrained ILC method (*Remazeilles et al MNRAS 2011*)

$$\widehat{y\Delta T_e}(\vec{n}) = \sum_{\nu} w(\nu)\, d(\nu,\vec{n}) \quad \text{such that} \quad \begin{cases} \left\langle \left(\widehat{y\Delta T_e}\right)^2 \right\rangle \text{ of minimum variance} \\ \sum_{\nu} w(\nu) \dfrac{\partial f(\nu,\bar{T}_e)}{\partial T_e} = 1 \\ \sum_{\nu} w(\nu)\, f(\nu,\bar{T}_e) = 0 \end{cases}$$

Remazeilles & Chluba, MNRAS 2020

rSZ component separation



$$\boldsymbol{d(\nu,\vec{n})} = \underbrace{\boldsymbol{f(\nu,\overline{T}_{\rm e})}}_{\text{spectrum of } y(\vec{n})}\ \underbrace{\boldsymbol{y(\vec{n})}}_{y(\vec{n})} + \underbrace{\frac{\boldsymbol{\partial f(\nu,\overline{T}_{\rm e})}}{\boldsymbol{\partial T_{\rm e}}}}_{\text{spectrum of } y\Delta T_{\rm e}(\vec{n})}\ \underbrace{\boldsymbol{(T_{\rm e}(\vec{n}) - \overline{T}_{\rm e})y(\vec{n})}}_{y\Delta T_{\rm e}(\vec{n})} + \underbrace{\boldsymbol{N(\nu,\vec{n})}}_{\text{foregrounds + noise}}$$

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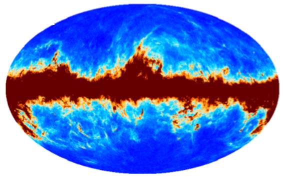
Guarantees the conservation of the signal of interest $y\Delta T_{\rm e}$

Remazeilles & Chluba, MNRAS 2020

rSZ component separation



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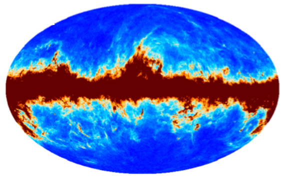
Guarantees the cancellation of y residuals in the $y\Delta T_e$ map

Remazeilles & Chluba, MNRAS 2020

rSZ component separation



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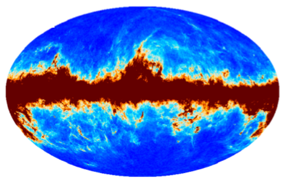
Guarantees the mitigation of foregrounds and noise

Remazeilles & Chluba, MNRAS 2020

rSZ component separation



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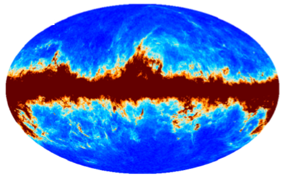
$$\Longrightarrow\ w = \frac{(f^T C^{-1} f)\partial f^T C^{-1} - (\partial f^T C^{-1} f) f^T C^{-1}}{(\partial f^T C^{-1} \partial f)(f^T C^{-1} f) - (\partial f^T C^{-1} f)^2} \quad \text{where} \quad C_{\nu\nu'} \equiv \langle d(\nu,\vec{n}) d(\nu',\vec{n}) \rangle$$

Remazeilles & Chluba, MNRAS 2020

rSZ component separation



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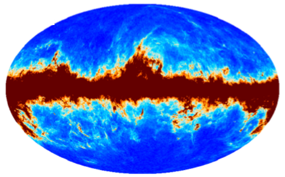
$$\Longrightarrow \widehat{y\Delta T_\mathrm{e}}(\vec{n}) = (w \cdot f)y(\vec{n}) + (w \cdot \partial_{T_\mathrm{e}} f)(T_\mathrm{e}(\vec{n}) - \bar{T}_\mathrm{e})\, y(n) + w \cdot N$$

Remazeilles & Chluba, MNRAS 2020

rSZ component separation



$$d(\nu,\vec{n}) = \underbrace{f(\nu,\bar{T}_e)}_{\text{spectrum of } y(\vec{n})}\ \underbrace{y(\vec{n})}_{y(\vec{n})} + \underbrace{\frac{\partial f(\nu,\bar{T}_e)}{\partial T_e}}_{\text{spectrum of } y\Delta T_e(\vec{n})}\ \underbrace{(T_e(\vec{n}) - \bar{T}_e)y(\vec{n})}_{y\Delta T_e(\vec{n})} + \underbrace{N(\nu,\vec{n})}_{\text{foregrounds + noise}}$$

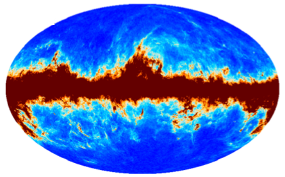
Component separation with the Constrained ILC method (*Remazeilles et al MNRAS 2011*)

$$\widehat{y\Delta T_e}(\vec{n}) = \sum_\nu w(\nu)\, d(\nu,\vec{n}) \quad \text{such that} \quad \begin{cases} \left\langle \left(\widehat{y\Delta T_e}\right)^2 \right\rangle \text{ of minimum variance} \\ \sum_\nu w(\nu) \frac{\partial f(\nu,\bar{T}_e)}{\partial T_e} = 1 \\ \sum_\nu w(\nu)\, f(\nu,\bar{T}_e) = 0 \end{cases}$$

$$\Rightarrow \widehat{y\Delta T_e}(\vec{n}) = \underbrace{(w\cdot f)}_{=0} y(\vec{n}) + \underbrace{(w\cdot \partial_{T_e} f)}_{=1}(T_e(\vec{n}) - \bar{T}_e)\, y(n) + \underbrace{w\cdot N}_{\text{minimised}}$$

Remazeilles & Chluba, MNRAS 2020

rSZ component separation



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$$\Longrightarrow \widehat{y\Delta T_e}(\vec{n}) = \underline{(T_e(\vec{n}) - \overline{T}_e)\, y(n)} + w \cdot N$$

T_e-modulated y-map!

Remazeilles & Chluba, MNRAS 2020

Why is this new SZ observable so interesting?

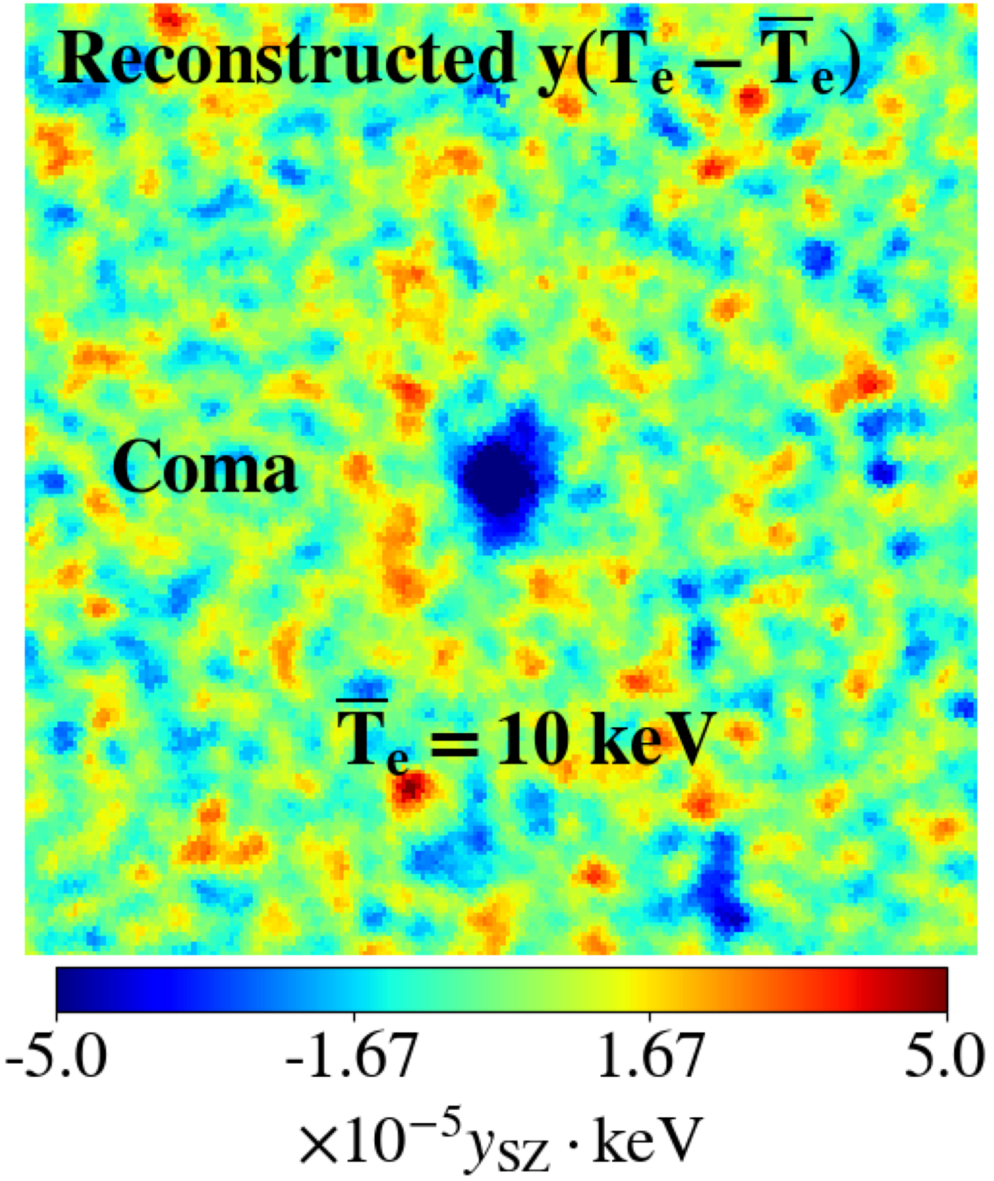
$$\boldsymbol{y\Delta T_{\mathrm{e}}(\vec{n}) \equiv y(\vec{n})(T_{\mathrm{e}}(\vec{n}) - \overline{T}_{\mathrm{e}})}$$

Changing the pivot temperature $\overline{T}_{\mathrm{e}}$ in the analysis allows us to conduct a real **temperature spectroscopy** of the cluster:

- Decrement if actual temperature $T_{\mathrm{e}}(\vec{n}) < \overline{T}_{\mathrm{e}}$
- Increment if actual temperature $T_{\mathrm{e}}(\vec{n}) > \overline{T}_{\mathrm{e}}$
- Null if actual temperature $T_{\mathrm{e}}(\vec{n}) \simeq \overline{T}_{\mathrm{e}}$

Remazeilles & Chluba, MNRAS 2020

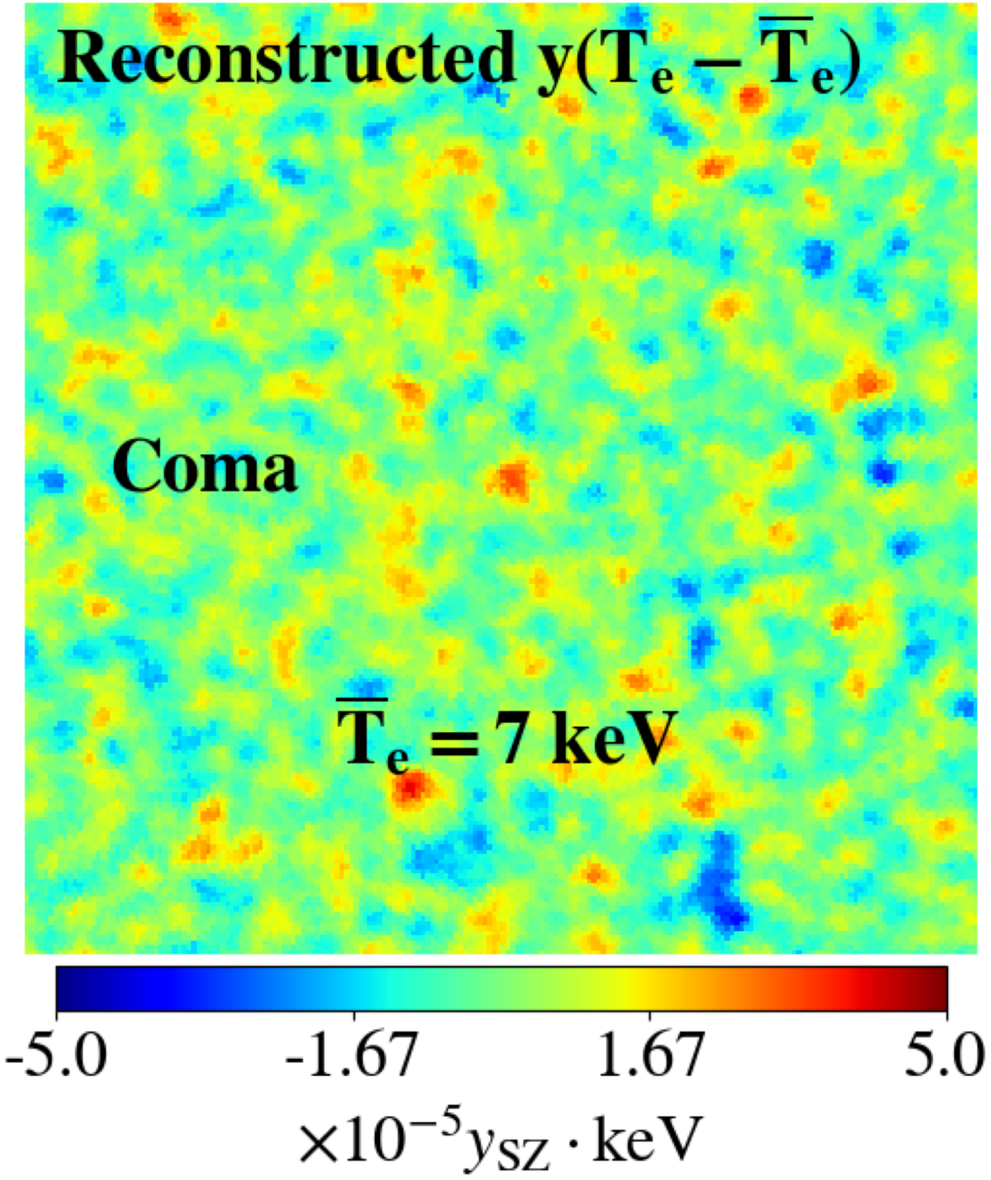
Cluster spectroscopy across temperature



$\bar{T}_e = 10$ keV

Remazeilles & Chluba, MNRAS 2020

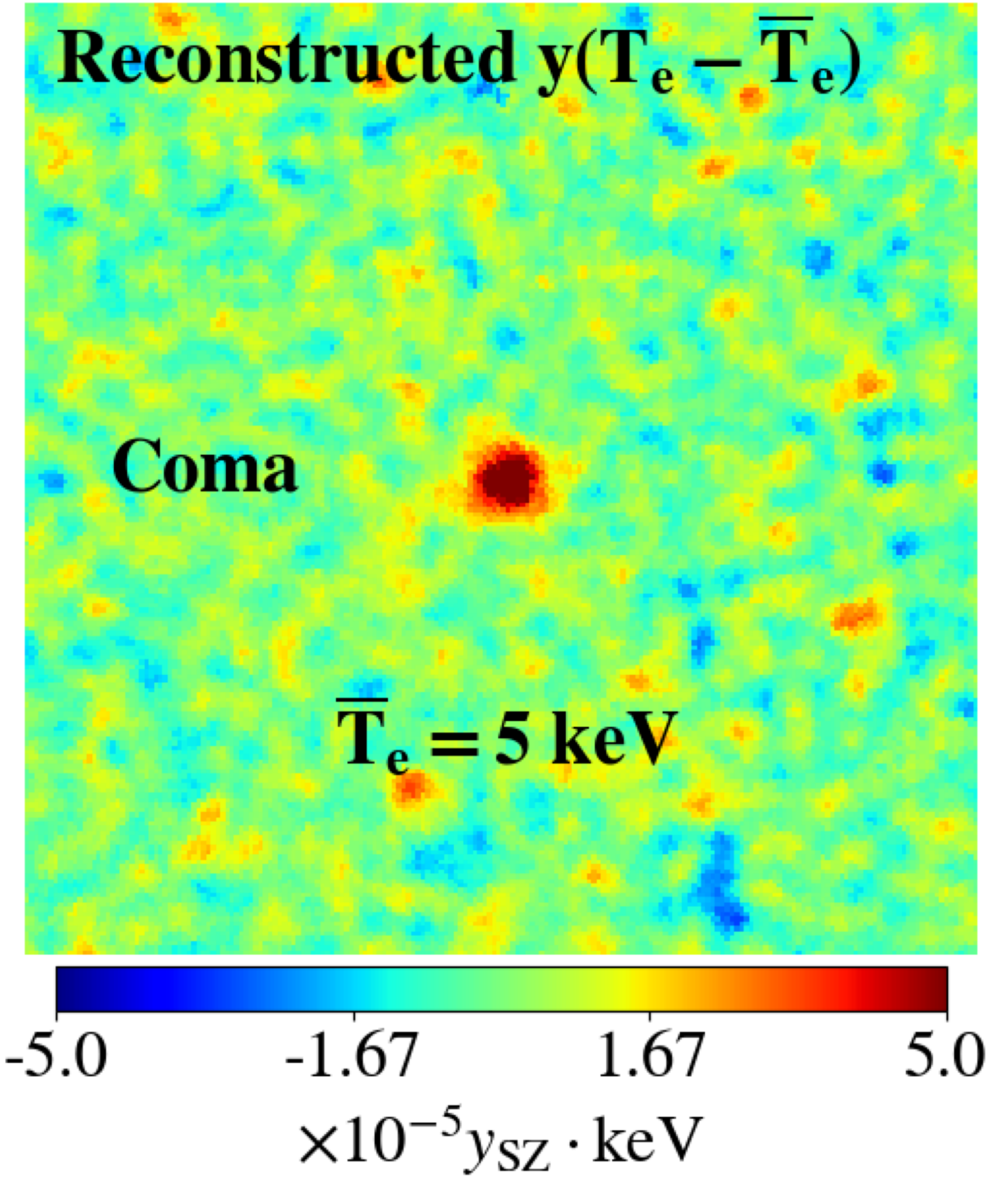
Cluster spectroscopy across temperature



$\bar{T}_e = 7$ keV

Remazeilles & Chluba, MNRAS 2020

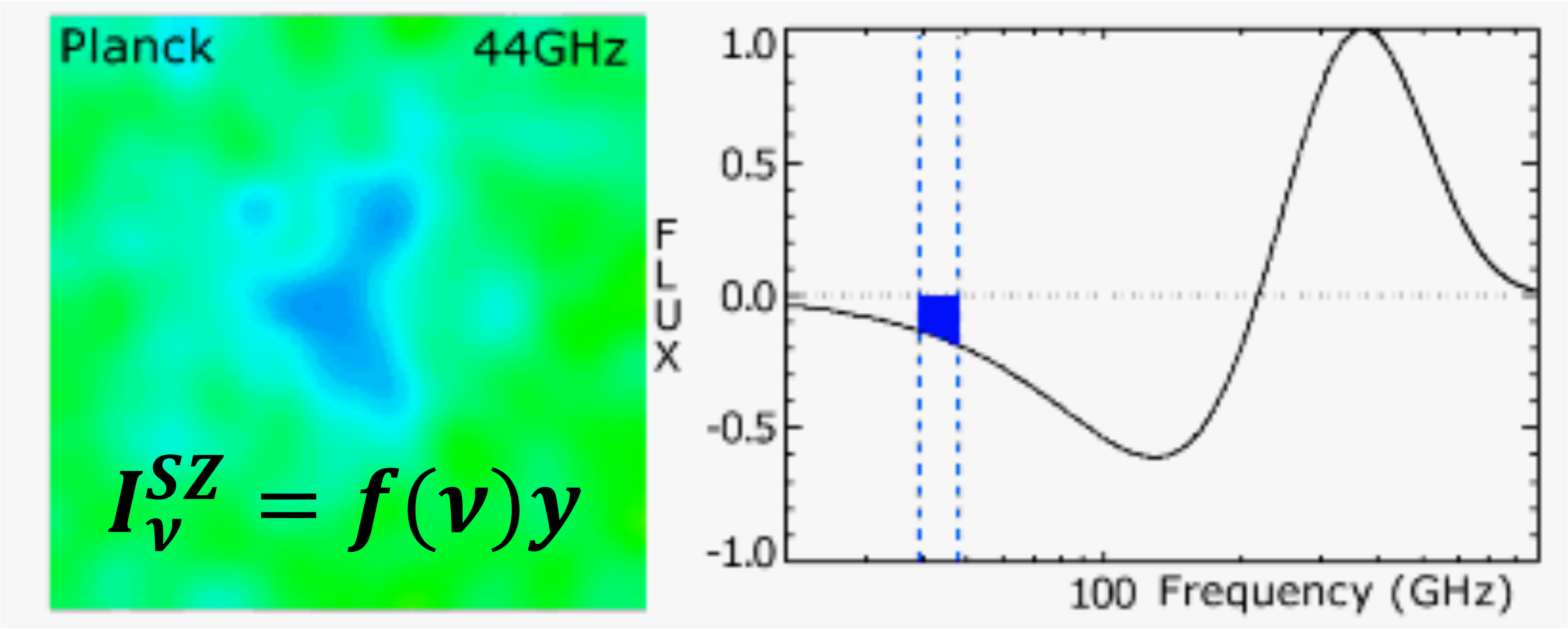
Cluster spectroscopy across temperature

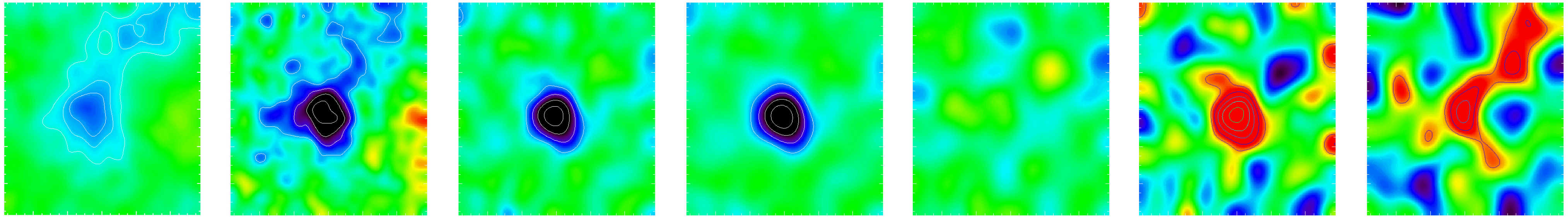


$\bar{T}_e = 5$ keV

Remazeilles & Chluba, MNRAS 2020

“First SZ revolution”:
cluster spectroscopy across frequency



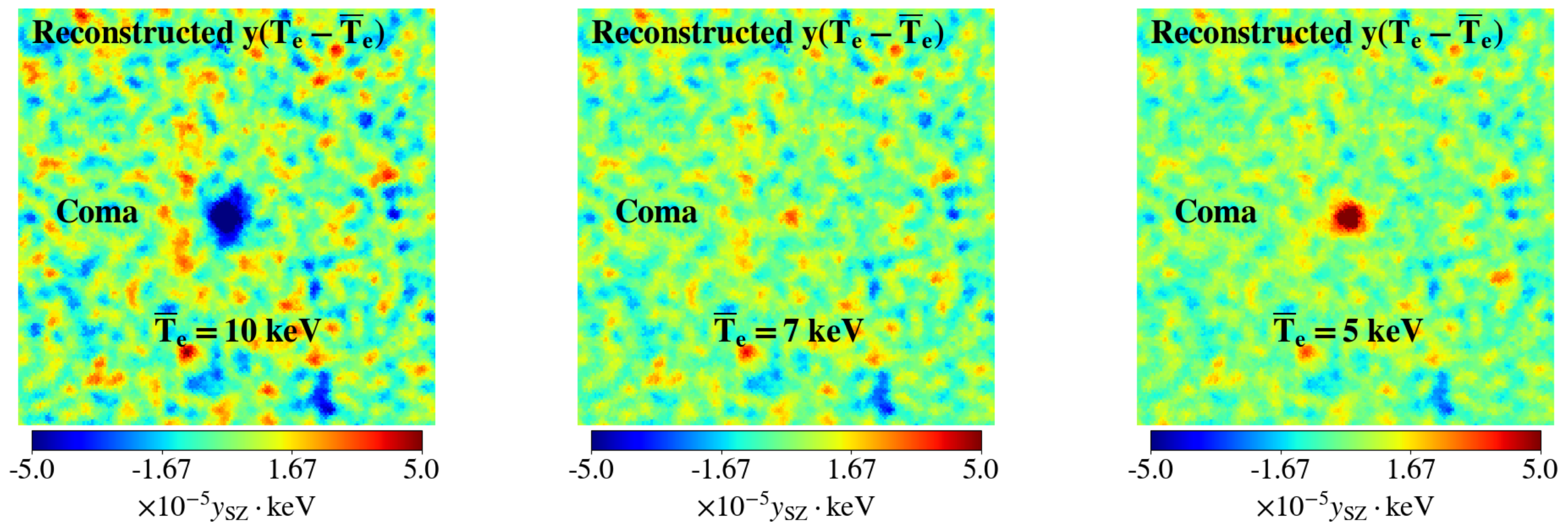


44 GHz | 70 GHz | 100 GHz | 143 GHz | 217 GHz | 353 GHz | 545 GHz

Credit: ESA/Planck Collaboration

“Second SZ revolution”:
cluster spectroscopy across temperature

Recovered $y(T_e - \overline{T}_e)$-map for different pivots



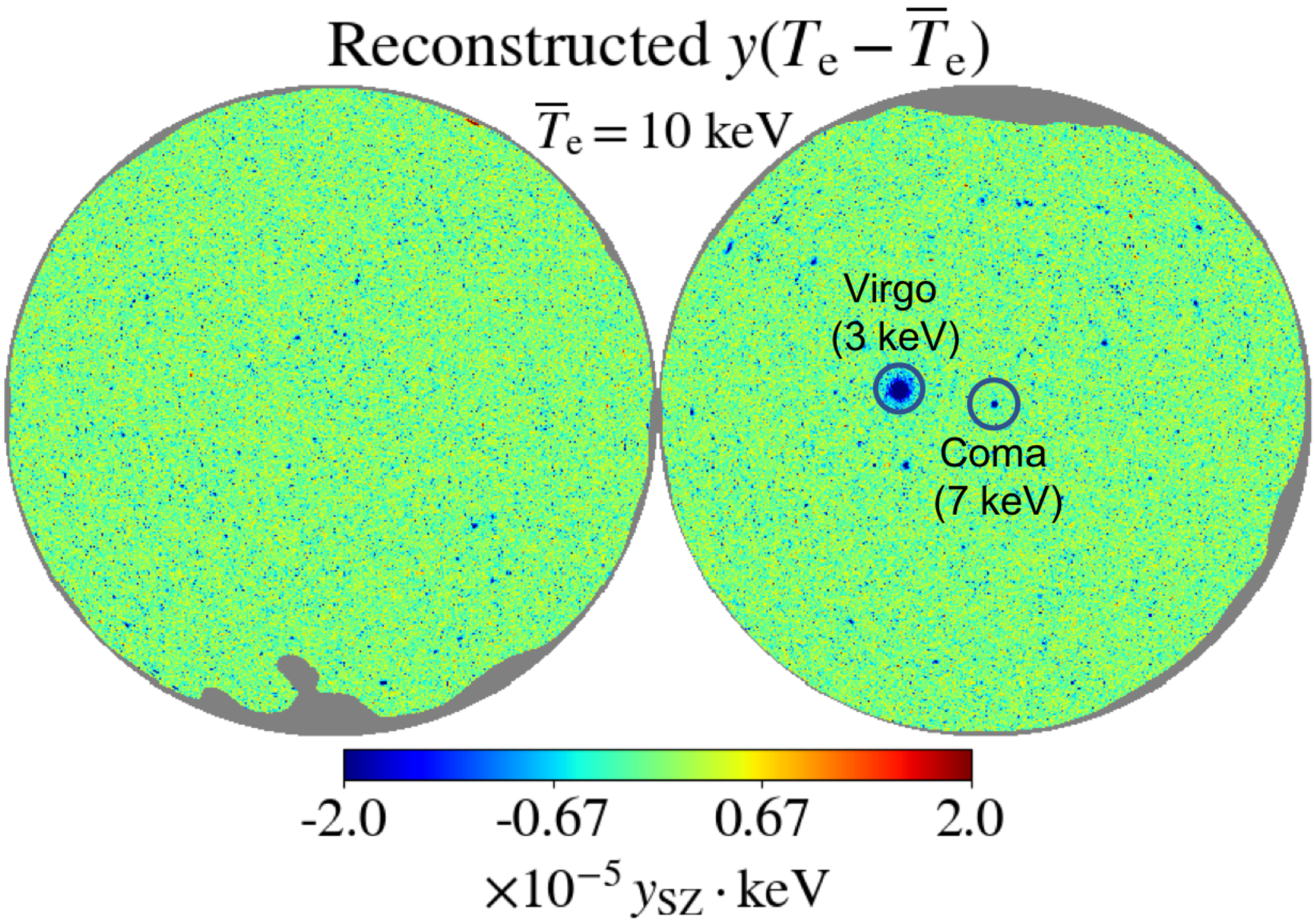
colder than 10 keV (decrement)

closer to 7 keV (null)

hotter than 5 keV (increment)

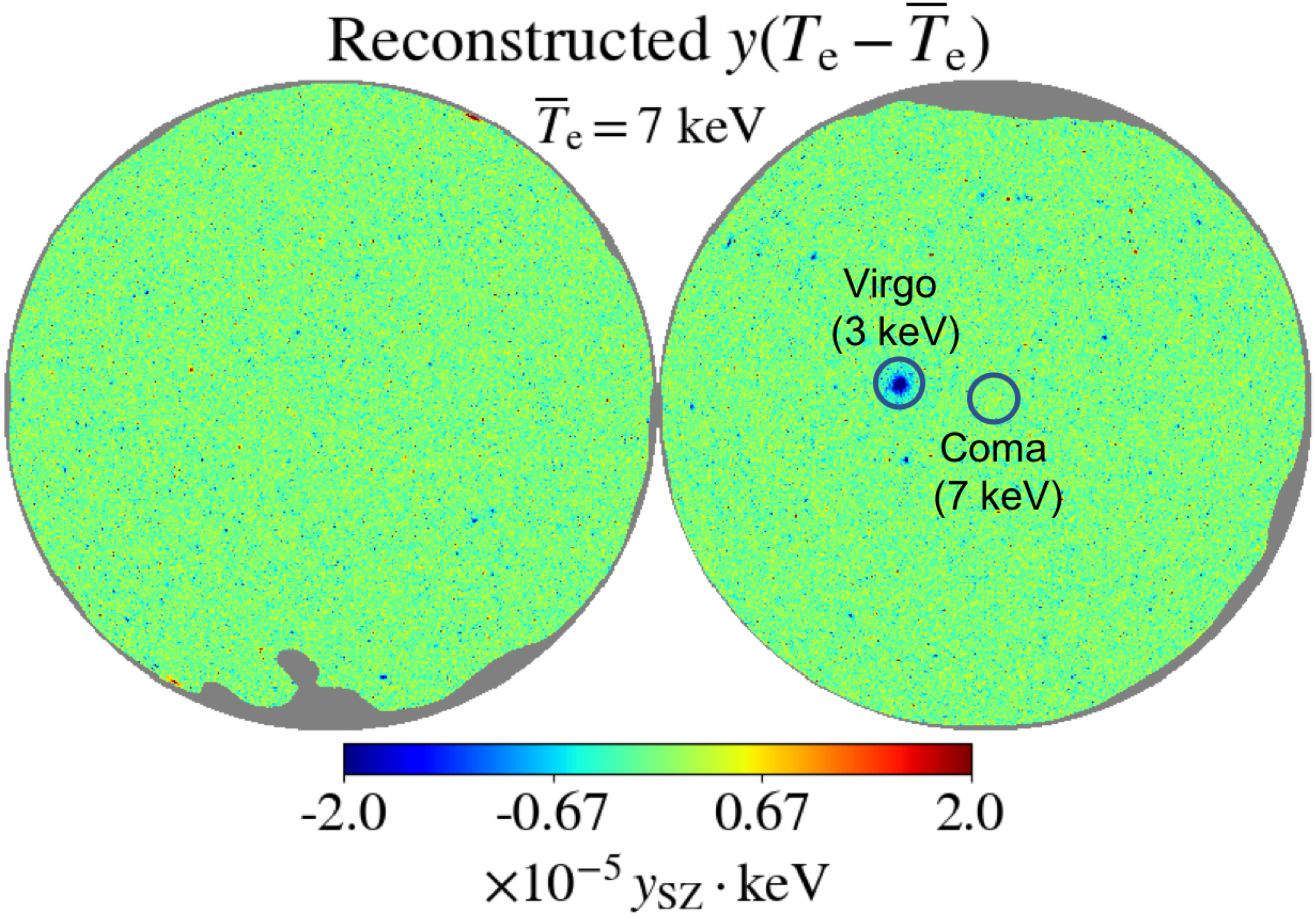
Remazeilles & Chluba, MNRAS 2020

Full–sky temperature spectroscopy



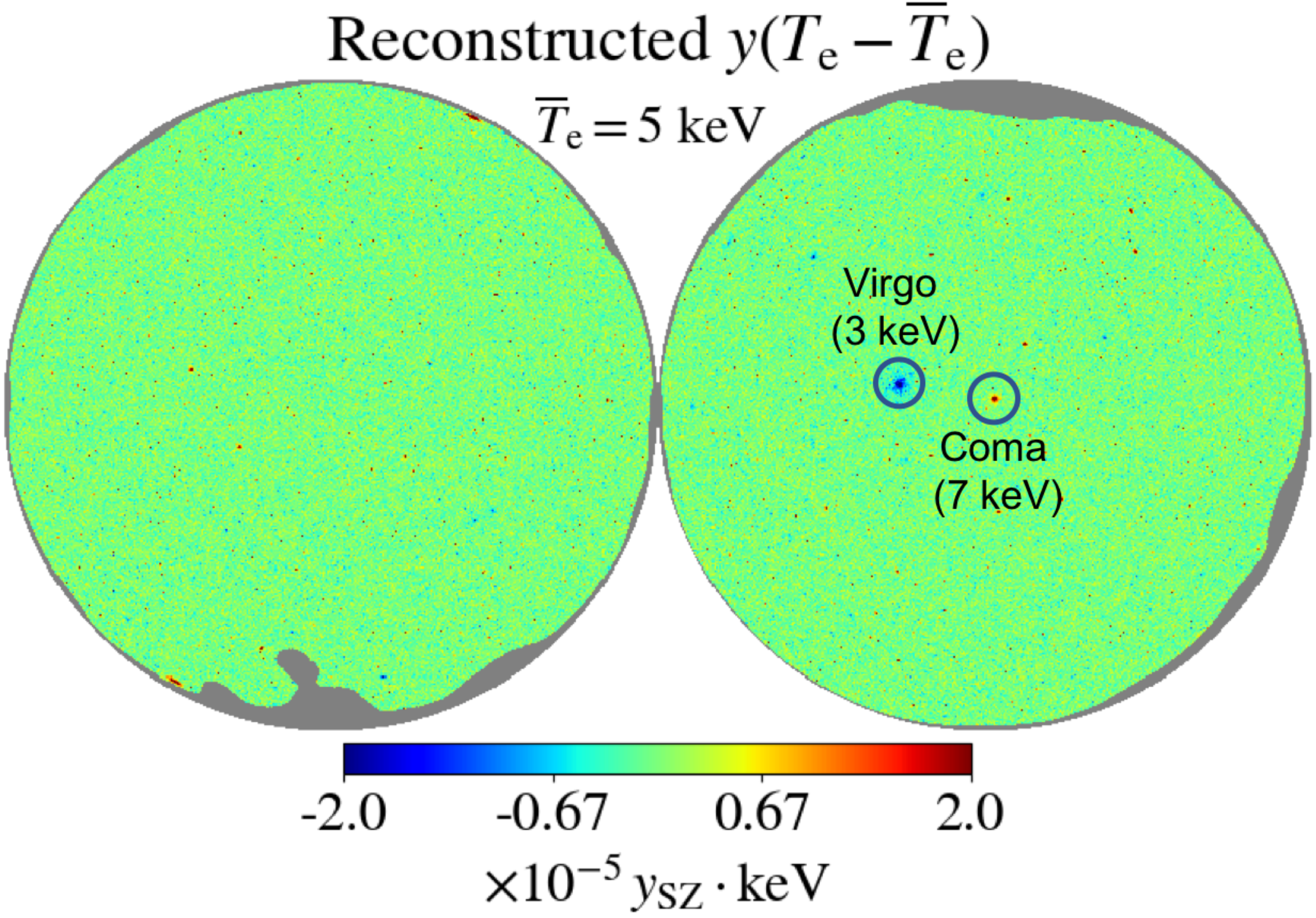
Remazeilles & Chluba, MNRAS 2020

Full–sky temperature spectroscopy



Remazeilles & Chluba, MNRAS 2020

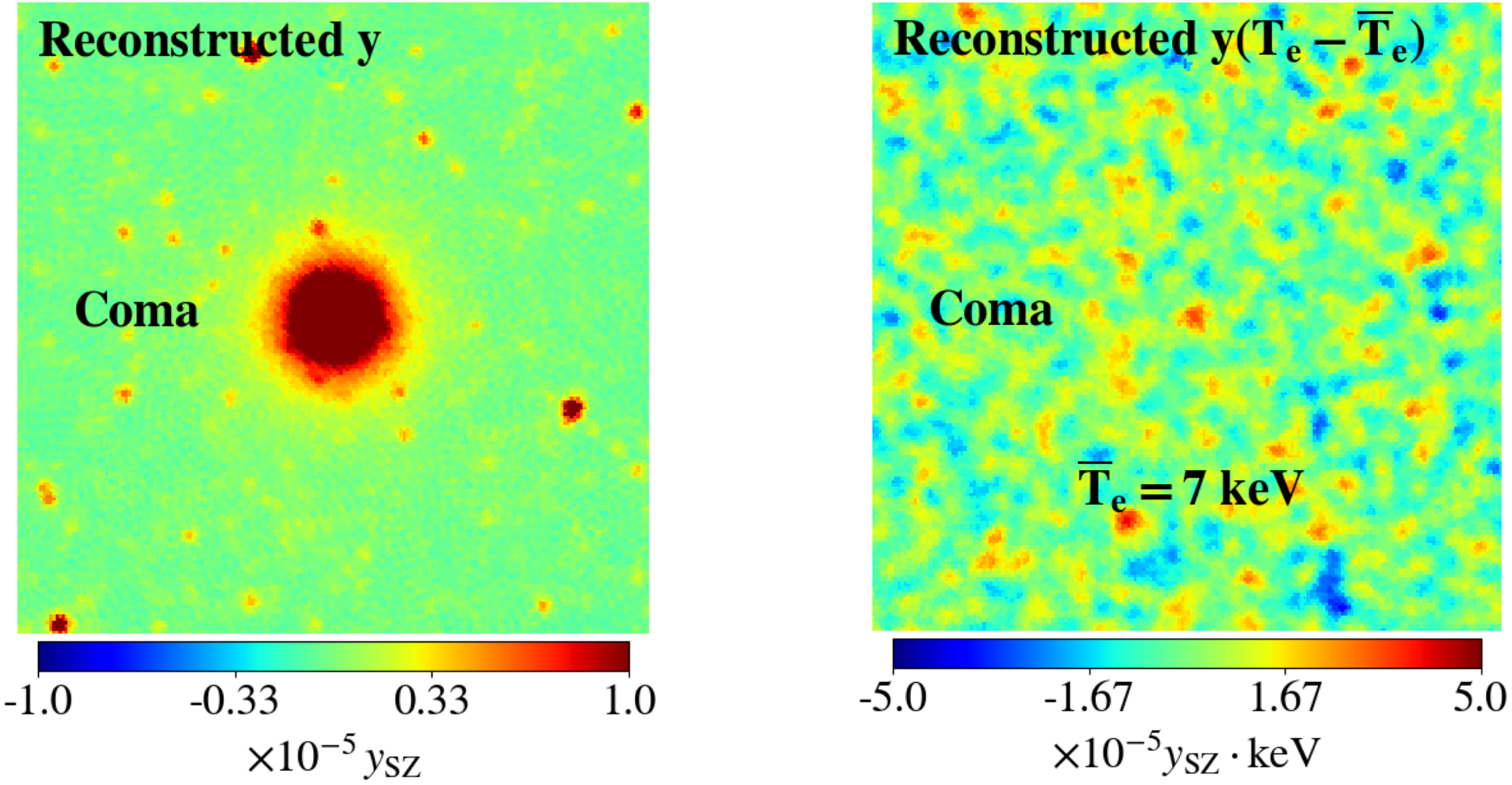
Full–sky temperature spectroscopy



Remazeilles & Chluba, MNRAS 2020

Reconstructed rSZ components

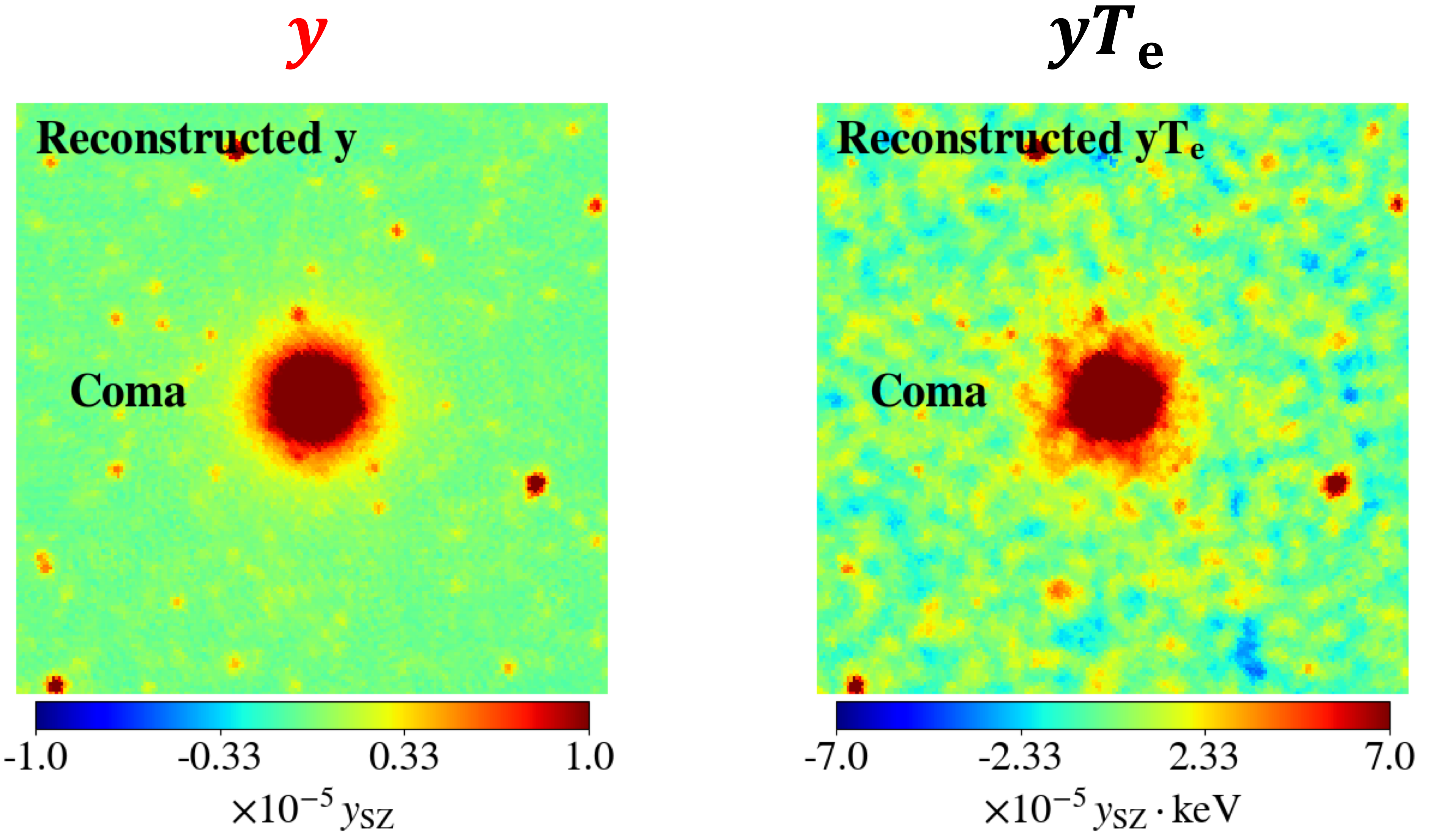
y $\qquad$ $y\Delta T_e \equiv y(T_e - \bar{T}_e)$



$$\Rightarrow \boxed{yT_e = y\Delta T_e + \bar{T}_e y}$$

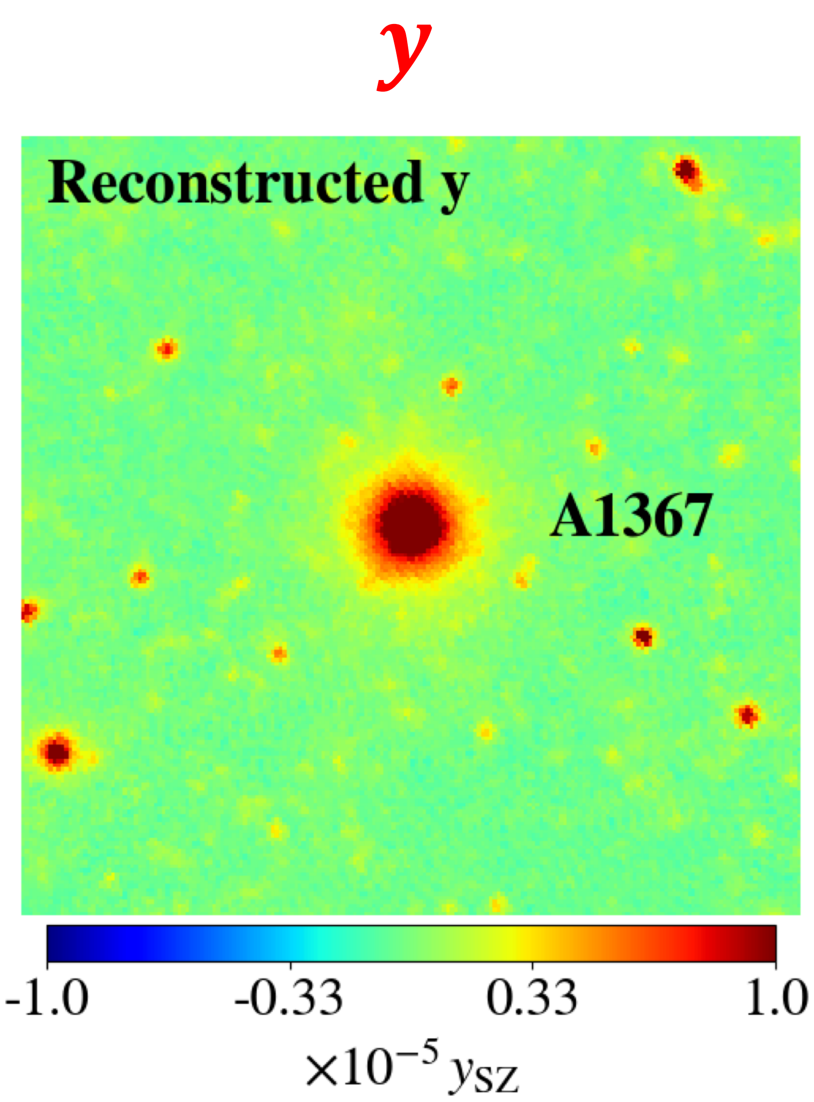
Remazeilles & Chluba, MNRAS 2020

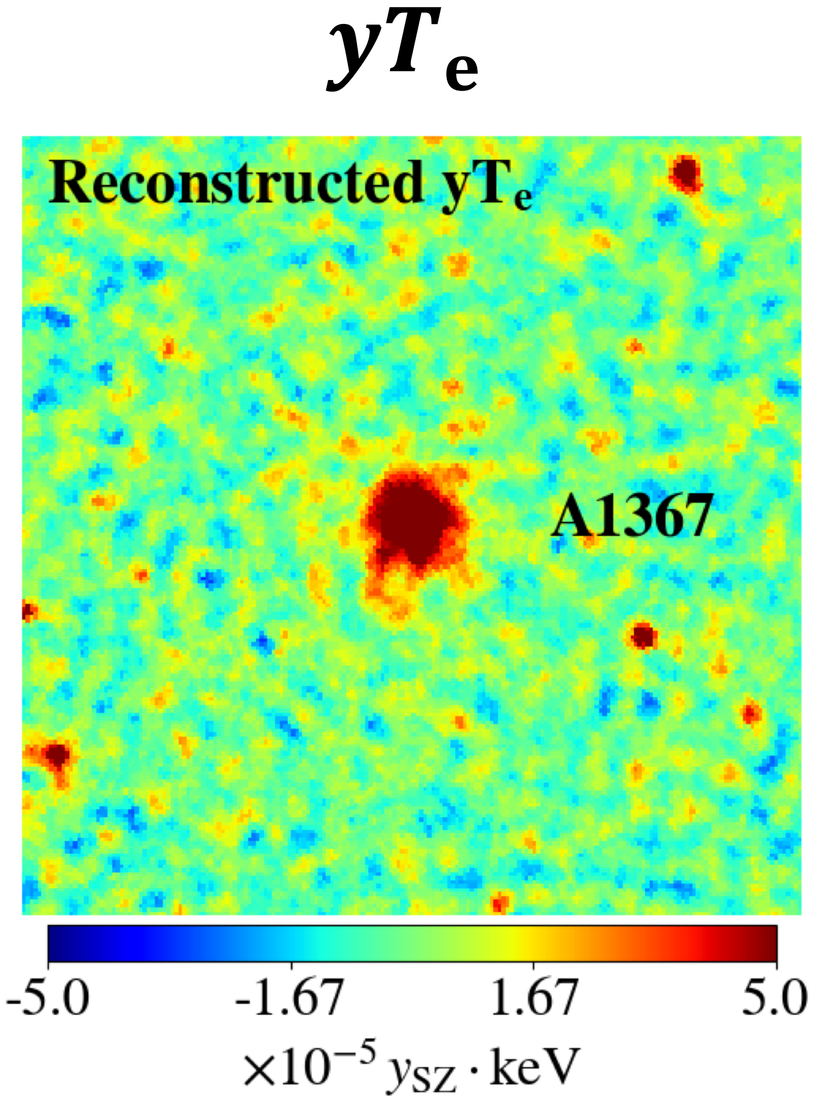
Mapping the y and yT_e components



Remazeilles & Chluba, MNRAS 2020

Mapping the y and yT_e components





Remazeilles & Chluba, MNRAS 2020

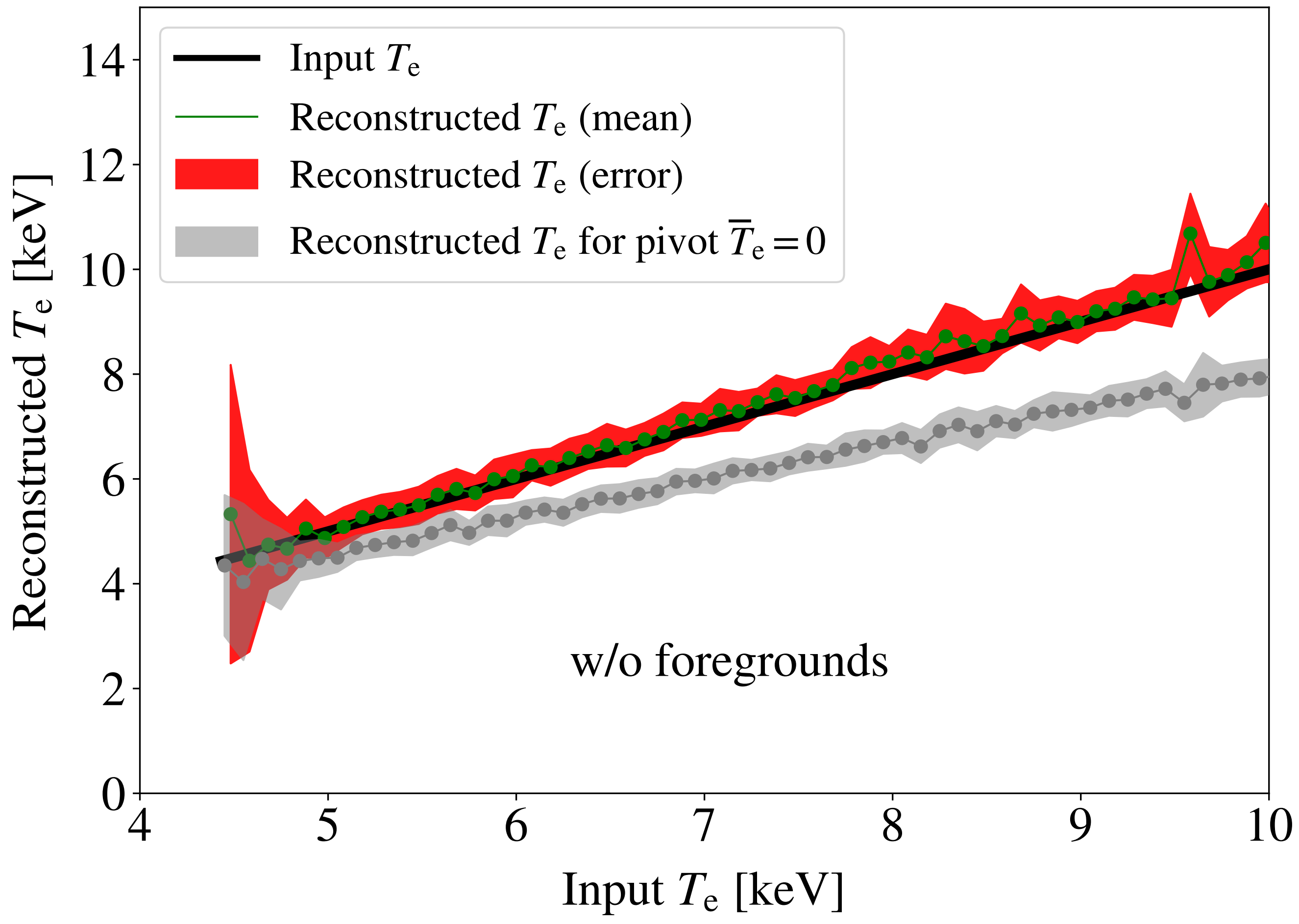
Mapping cluster temperatures T_e across the entire sky

$$T_\mathrm{e}^{y}[R_{500}] = \frac{\langle\, (yT_\mathrm{e})(\vec{n})\,\rangle_{|\vec{n}-\vec{n}_c|\leq R_{500}}}{\langle\, y(\vec{n})\,\rangle_{|\vec{n}-\vec{n}_c|\leq R_{500}}}$$

y-weighted average cluster temperature over R_{500}

Remazeilles & Chluba, MNRAS 2020

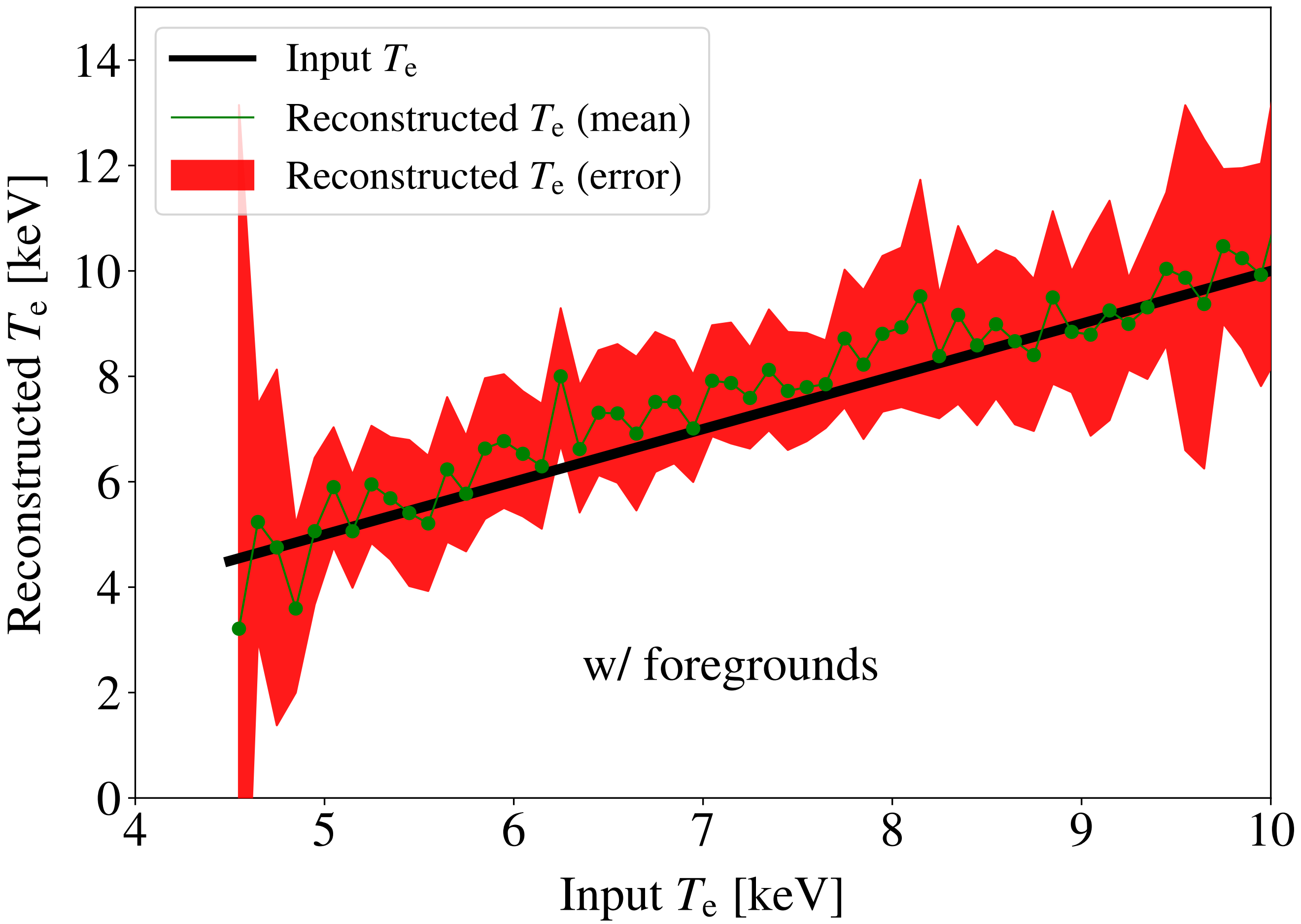
Recovered electron temperatures T_e of clusters across the entire sky



The recovered rSZ temperatures offer a new proxy for determining cluster masses without relying on X-rays

Remazeilles & Chluba, MNRAS 2020

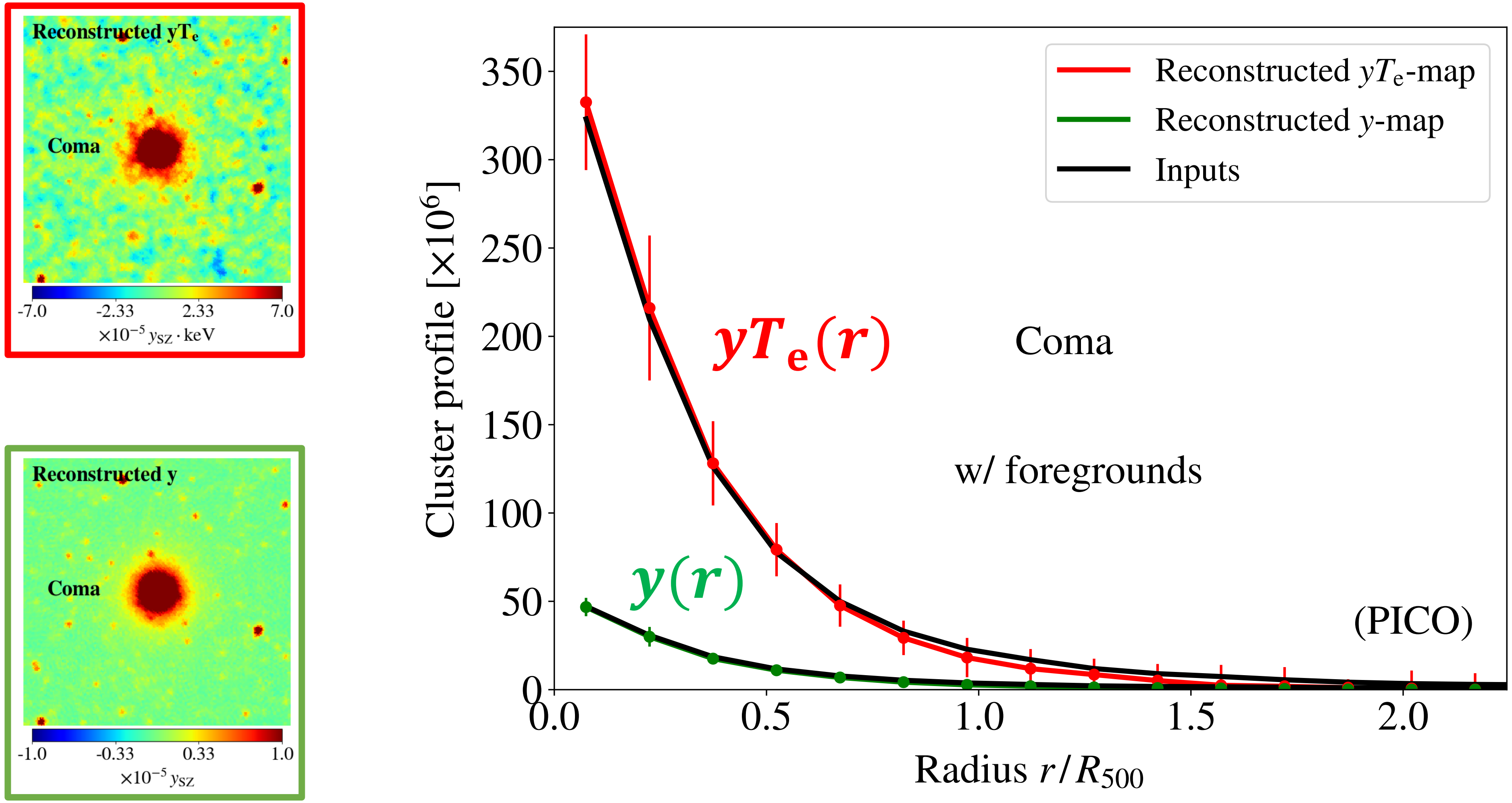
Recovered electron temperatures T_e of clusters across the entire sky



The recovered rSZ temperatures offer a new proxy for determining cluster masses without relying on X-rays

Remazeilles & Chluba, MNRAS 2020

Reconstructed cluster profiles



Remazeilles & Chluba, MNRAS 2020

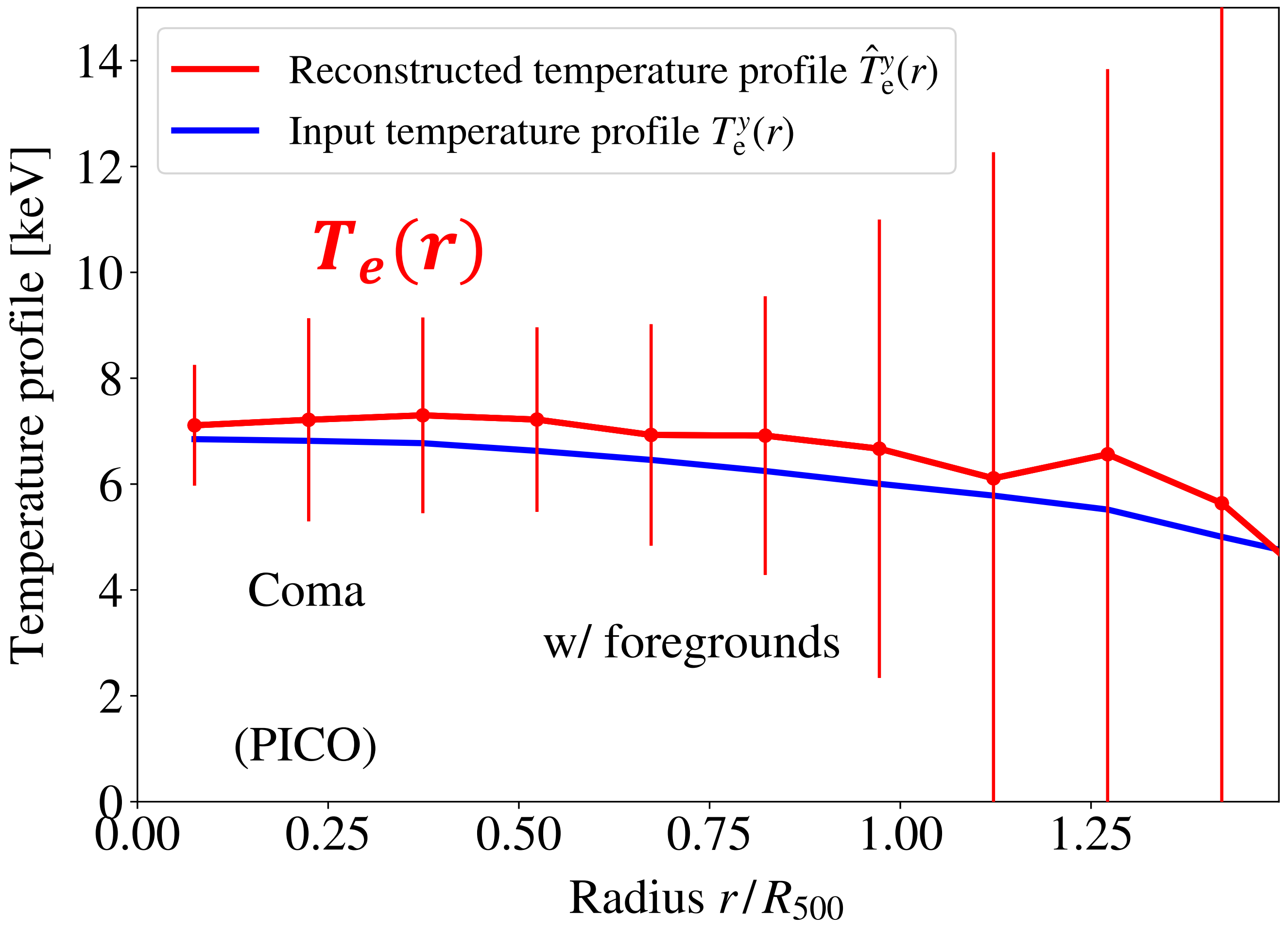
Temperature profiles of clusters

$$T_{\mathrm{e}}^{y}(r) = \frac{(yT_{\mathrm{e}})(r)}{y(r)}$$

y-weighted temperature profile

Remazeilles & Chluba, MNRAS 2020

Reconstructed cluster temperature profile



$$\langle T_e \rangle_{R_{500}} = (7.1 \pm 0.7)\ \mathbf{keV}$$

10σ measurement with PICO

Remazeilles & Chluba, MNRAS 2020

Electron temperature power spectrum

$$T_{\mathrm{e}}^{yy}(\ell) = \frac{\langle\, (yT_{\mathrm{e}})_{\ell m}\, y_{\ell m}^{*}\,\rangle}{\langle\, y_{\ell m}\, y_{\ell m}^{*}\,\rangle} = \frac{C_{\ell}^{y,yT_{\mathrm{e}}}}{C_{\ell}^{yy}}$$

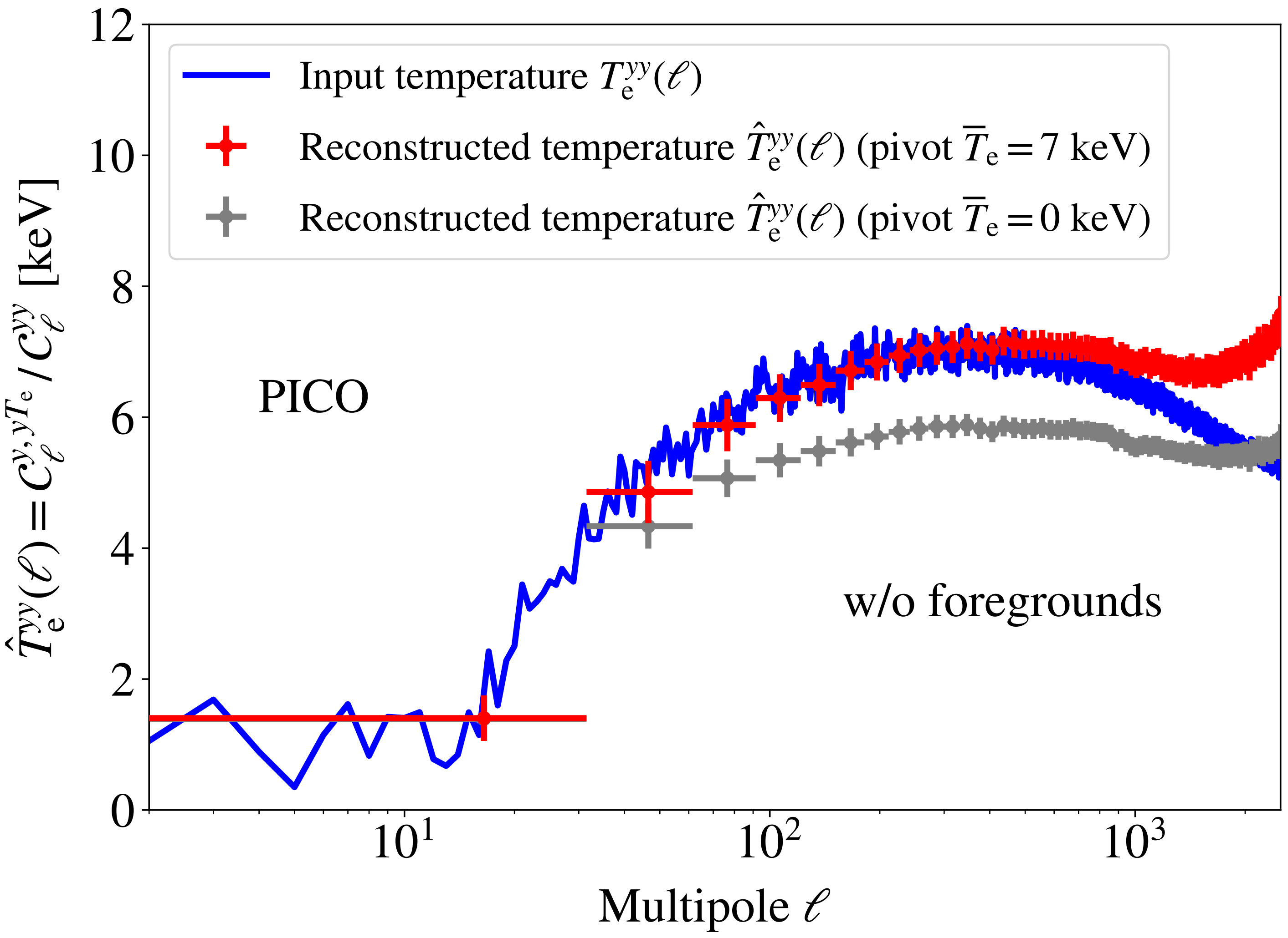
y^2-weighted average temperature over the full sky across multipoles

Ratio of cross-power spectrum between the $\boldsymbol{y}$- and $\boldsymbol{yT_{\mathrm{e}}}$-maps and auto-power spectrum of the $\boldsymbol{y}$-map

Remazeilles, Bolliet, Rotti, Chluba MNRAS 2019

Remazeilles & Chluba, MNRAS 2020

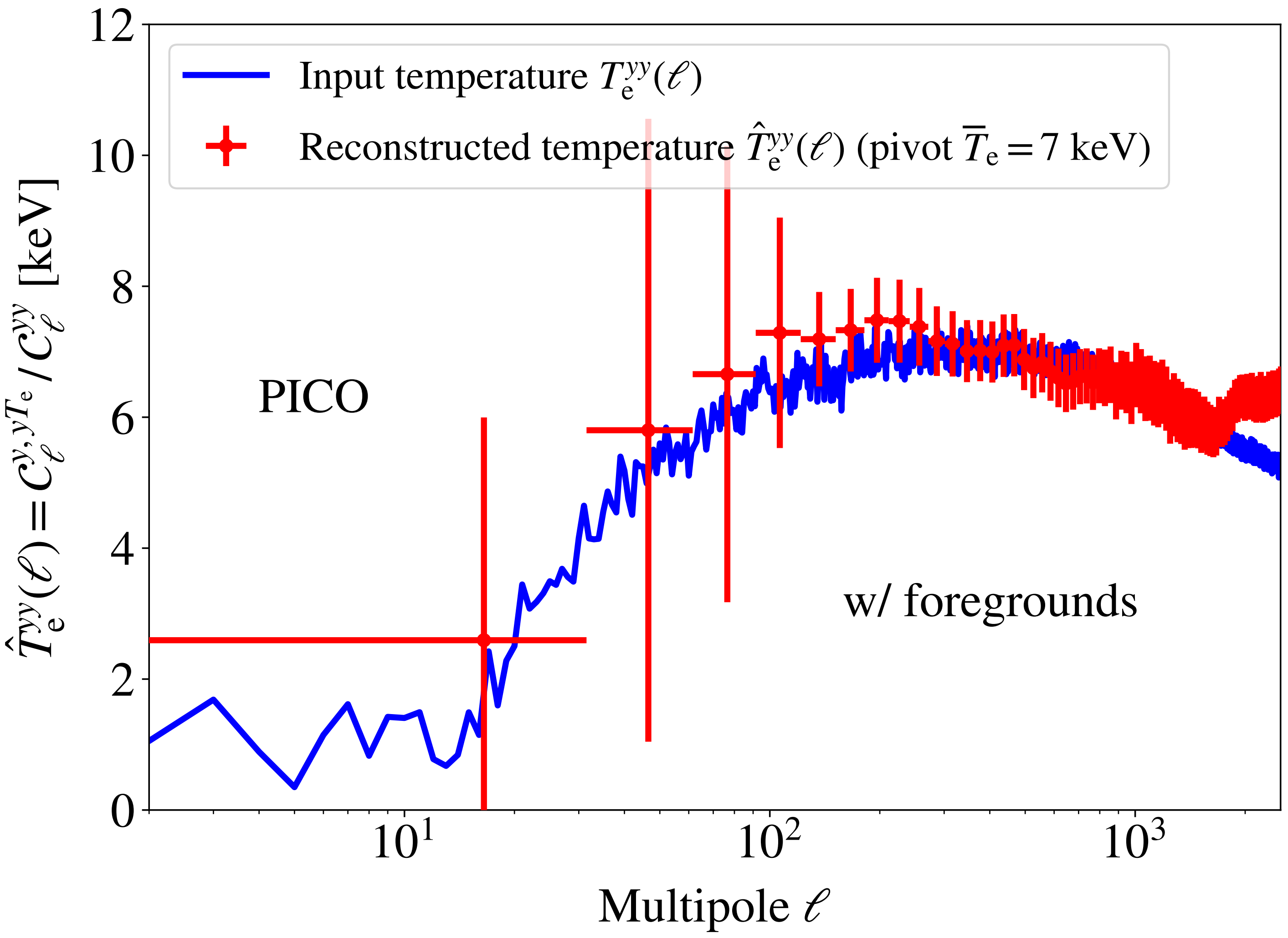
Electron temperature power spectrum $T_{\rm e}^{yy}(\ell)$



$\boldsymbol{T_{\rm e}^{yy}}(\ell)$ provides a new map-based observable, complementing the $\boldsymbol{y}$-map power spectrum $\boldsymbol{C_\ell^{yy}}$, to constrain cosmological parameters

Remazeilles & Chluba, MNRAS 2020

Electron temperature power spectrum $T_\mathrm{e}^{yy}(\ell)$



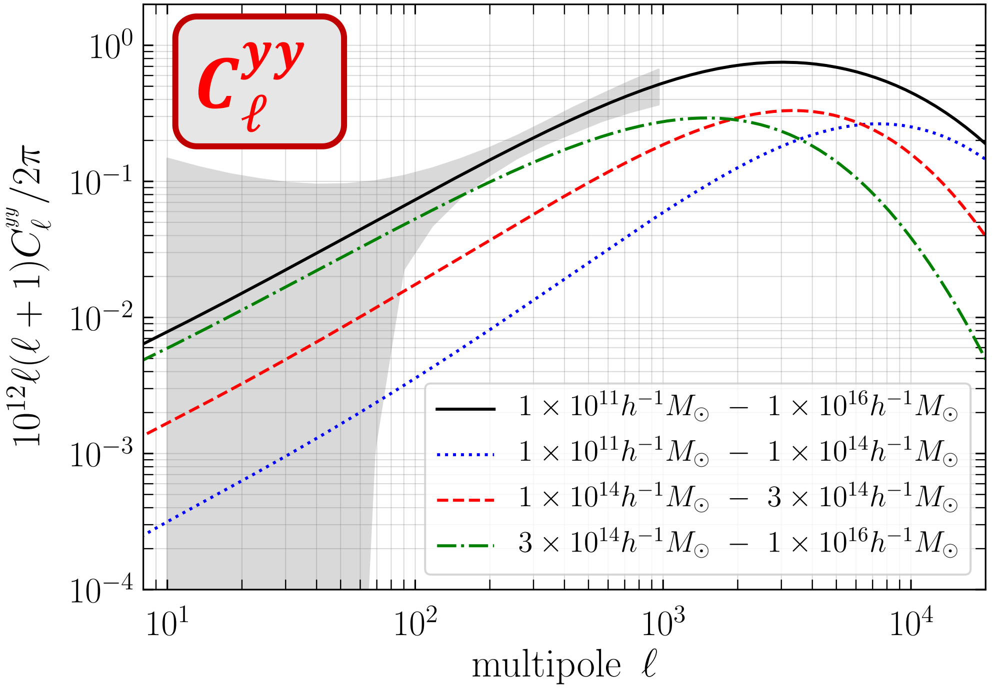
$T_\mathrm{e}^{yy}(\ell)$ provides a new map-based observable, complementing the y-map power spectrum C_ℓ^{yy}, to constrain cosmological parameters

Remazeilles & Chluba, MNRAS 2020

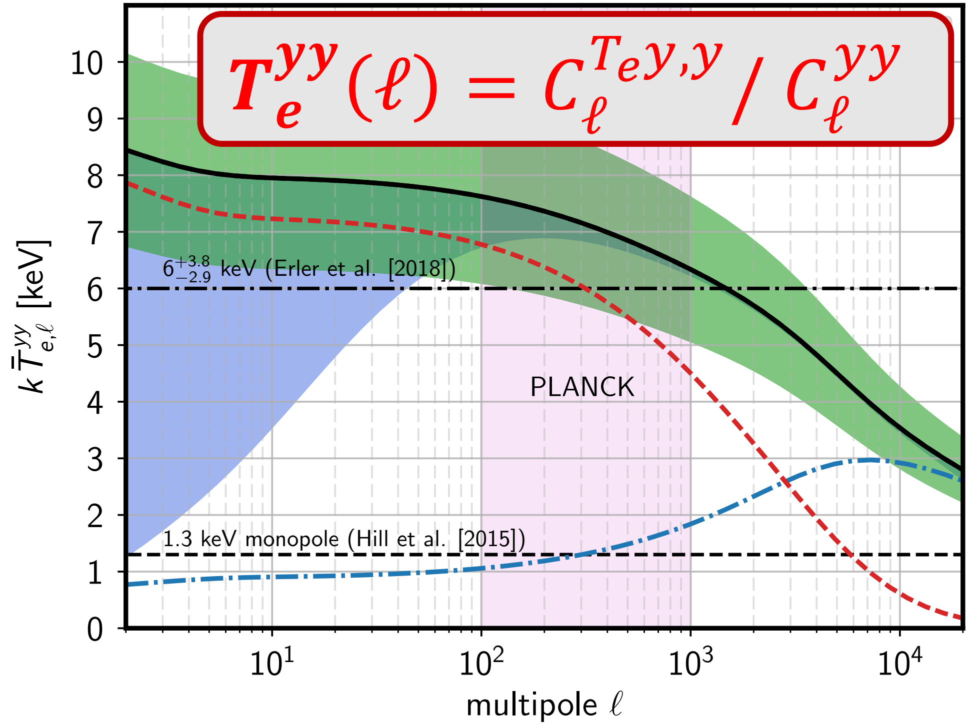
Cosmology with the relativistic SZ effect

Two independent observables for future cluster cosmology

Classic SZ Compton-y power spectrum



Electron-temperature T_e power spectrum



The shapes of the power spectra C_ℓ^{yy} and $T_e^{yy}(\ell)$ have different scaling with cosmological parameters!

Remazeilles et al MNRAS (2019)

Cosmology with the relativistic SZ effect

Breaking the σ_8-b degeneracy?

halo mass function *pressure profile*

$$C_\ell^{yy} = \int_{z_{\min}}^{z_{\max}} dz \frac{dV}{dz d\Omega} \int_{M_{\min}}^{M_{\max}} dM \underbrace{\frac{dn(M,z)}{dM}} \underbrace{|y_\ell(M,z)|^2}$$

different scaling with $\boldsymbol{\sigma_8}$

same scaling with mass bias $\boldsymbol{b}$

$$C_\ell^{y,yT_e} = \int_{z_{\min}}^{z_{\max}} dz \frac{dV}{dz d\Omega} \int_{M_{\min}}^{M_{\max}} dM \overbrace{\frac{dn(M,z)}{dM} \boldsymbol{T_e(M)}} \overbrace{|y_\ell(M,z)|^2}$$

temperature-modulated halo mass function *pressure profile*

$\Longrightarrow$

$$T_e^{yy}(\ell) \equiv \frac{C_\ell^{y,yT_e}}{C_\ell^{yy}}$$

depends only on σ_8

Remazeilles et al, MNRAS (2019)
Remazeilles & Chluba, MNRAS (2020)

Two independent map-based observables for future cluster cosmology

- ✓ The shapes of the power spectra $\boldsymbol{T_e^{yy}}(\ell)$ and $\boldsymbol{C_\ell^{yy}}$ have different scaling with cosmological parameters

  $\boldsymbol{C_\ell^{yy}}$ depends on $\boldsymbol{\sigma_8}$ and mass-bias $\boldsymbol{b}$ in a degenerate form, while $\boldsymbol{T_e^{yy}}(\ell)$ depends on $\boldsymbol{\sigma_8}$ but is insensitive to $\boldsymbol{b}$

- ✓ $\boldsymbol{T_e^{yy}}(\ell)$ will allow to break parameter degeneracies, possibly alleviating some of the current tensions on cosmological parameters

Conclusions

- New component separation approach to disentangle the $\boldsymbol{y}$ and $\boldsymbol{T_e}$ observables of the rSZ effect

- High frequencies $\gtrsim$ 300 GHz are essential to break the y-T_e degeneracy in rSZ measurements

  PICO, LiteBIRD, "ESA Voyage 2050" missions would be of great value!

- A PICO-type mission would allow us to map rSZ temperatures of thousands of clusters across the entire sky, thus offering a new proxy for determining cluster masses

- A PICO-type mission would allows us to reconstruct the temperature profiles of many individual clusters, thus offering a deep understanding of the thermodynamics of clusters

- We may anticipate a "second SZ revolution" in the next decade:
  - ✓ Release of a "$\boldsymbol{T_e}$-map" along with the $\boldsymbol{y}$-map
  - ✓ Cluster spectroscopy across temperatures
  - ✓ The relativistic electron-temperature power spectrum $\boldsymbol{T_e^{yy}}(\ell)$ will offer a new map-based observable, complementing $\boldsymbol{C_\ell^{yy}}$, to constrain cosmological parameters with clusters

Thank you!

Backup

Constrained moment ILC for rSZ

We actually impose additional constraints in the Constrained ILC in order to deproject the kSZ (CMB) contamination and also remove bulk of the dust contamination:

$$\widehat{y\Delta T_e}\,(\vec{n}) = \sum_{\nu} w(\nu)\, d(\nu,\vec{n}) \;\text{ such that }\; \begin{cases} \left\langle \left(\widehat{y\Delta T_e}\right)^2 \right\rangle \text{ of minimum variance} \\ \sum_{\nu} w(\nu)\, \partial_{T_e} f^{\mathrm{rSZ}}(\nu, \overline{T}_e) = 1 & \text{rSZ: 1st-order moment} \\ \sum_{\nu} w(\nu)\, f^{\mathrm{rSZ}}(\nu, \overline{T}_e) = 0 & \text{rSZ: 0th-order moment} \\ \sum_{\nu} w(\nu)\, f^{\mathrm{CMB+kSZ}}(\nu) = 0 & \text{kSZ, CMB} \\ \sum_{\nu} w(\nu)\, f^{\mathrm{dust}}(\nu, \overline{\beta}_d, \overline{T}_d) = 0 & \text{dust: 0th-order moment} \end{cases}$$

$$w = e^{\mathrm{T}} \left(A^{\mathrm{T}} \mathrm{C}^{-1} A\right)^{-1} \mathrm{C}^{-1} A$$

$$A = \left[\partial_{T_e} f^{\mathrm{rSZ}} \; f^{\mathrm{rSZ}} \; f^{\mathrm{CMB+kSZ}} \; f^{\mathrm{dust}}\right] \qquad e = [1\ 0\ 0\ 0\ 0]^{\mathrm{T}}$$

Remazeilles & Chluba, MNRAS 2020
Remazeilles, Rotti, Chluba, MNRAS 2021