Mapping the hot baryonic gas across the entire sky with LiteBIRD

Mathieu Remazeilles

Instituto de Física de Cantabria (CSIC-UC)

JCAP 12 (2024) 026

Colloque National CMB-France #6
IHP, Paris, Dec 18 -19, 2024

LiteBIRD

APC
ASI
Berkeley UNIVERSITY OF CALIFORNIA
BERKELEY LAB
UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA
CARDIFF UNIVERSITY PRIFYSGOL CAERDYD
cea
Centre Pierre Binétruy CNRS • Berkeley
cnes
cnrs
CSA ASC Canada

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS
CSL CENTRE SPATIAL DE LIÈGE
ENS | PSL
erc European Research Council Established by the European Commission
EXCELENCIA MARÍA DE MAEZTU
EXCELENCIA SEVERO OCHOA
FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG
Forskningsrådet The Research Council of Norway
GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN

NASA Goddard Space Flight Center
GRAN SASSO SCIENCE INSTITUTE
INSTITUTO DE ASTROFISICA DE CANARIAS IAC
IAP
IAS Orsay
IFCA Instituto de Física de Cantabria
ifpU
IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

INFN
INAF ISTITUTO NAZIONALE DI ASTROFISICA
IPMU
IPNS 素粒子原子核研究所 Institute of Particle and Nuclear Studies
irap astrophysique & planétologie
JAXA
NASA Jet Propulsion Laboratory California Institute of Technology

NATIONAL INSTITUTE OF TECHNOLOGY KAGAWA COLLEGE 香川高専
KEK
KIPAC
Kobayashi-Maskawa Institute Nagoya University
LMU
LPSC GRENOBLE | MODANE

MAX-PLANCK-INSTITUT FÜR ASTROPHYSIK
McGill
Maynooth University National University of Ireland Maynooth
名古屋大学 NAGOYA UNIVERSITY
NÉEL institut
NIST

Norwegian Directorate for Higher Education and Skills
OAC
岡山大学 OKAYAMA UNIVERSITY
International Center for Quantum-field Measurement Systems for Studies of the Universe and Particles
POLITÉCNICA
idr
RWTH AACHEN UNIVERSITY

SAPIENZA UNIVERSITÀ DI ROMA
SISSA
SORBONNE UNIVERSITÉ
SRON
SSDC SPACE SCIENCE DATA CENTER
LELAND STANFORD JUNIOR UNIVERSITY 1891
Stockholm University
公立諏訪東京理科大学 Suwa University of Science
TOR VERGATA UNIVERSITÀ DEGLI STUDI DI ROMA

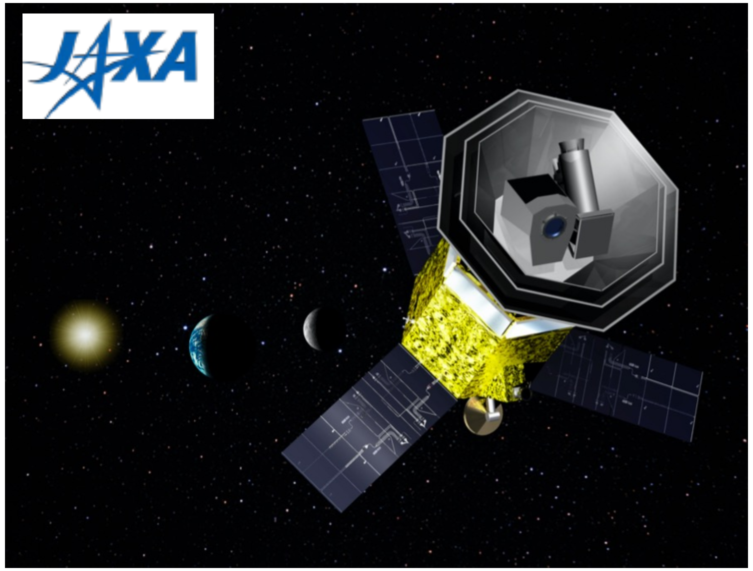
UCL
UBC THE UNIVERSITY OF BRITISH COLUMBIA
UC UNIVERSIDAD DE CANTABRIA
Università di Catania
University of Colorado Boulder
Science and Technology Facilities Council
ULB UNIVERSITÉ LIBRE DE BRUXELLES
Universidad de La Laguna

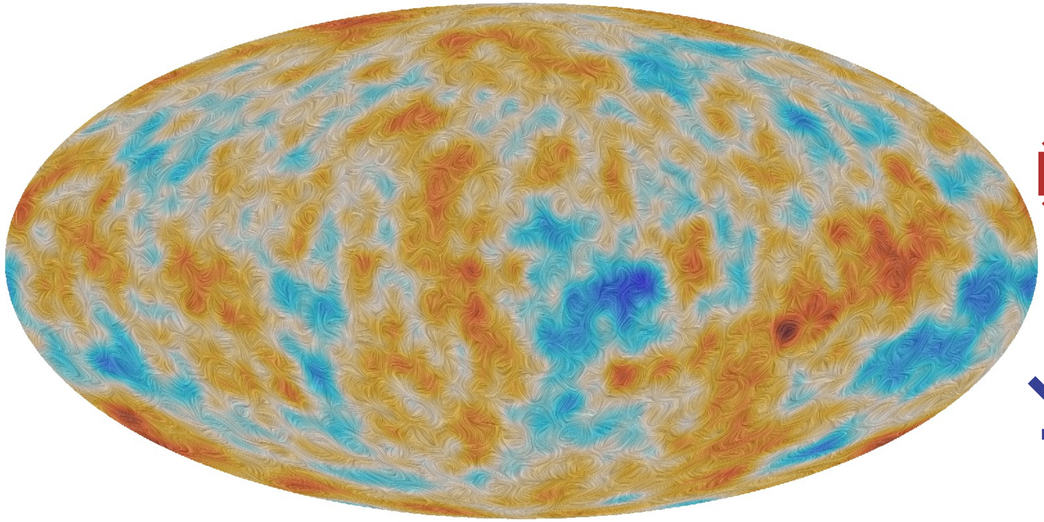
MANCHESTER 1824 The University of Manchester
UiO University of Oslo
UNIVERSITY OF OXFORD
UNIVERSITÀ DI PISA
Università degli Studi di Ferrara
UNIVERSITÀ DEGLI STUDI DI MILANO
UNIVERSITÀ DEGLI STUDI DI PADOVA
THE UNIVERSITY OF TOKYO
UNIVERSITY OF TORONTO

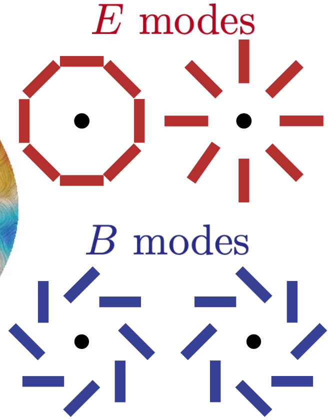
LiteBIRD overview

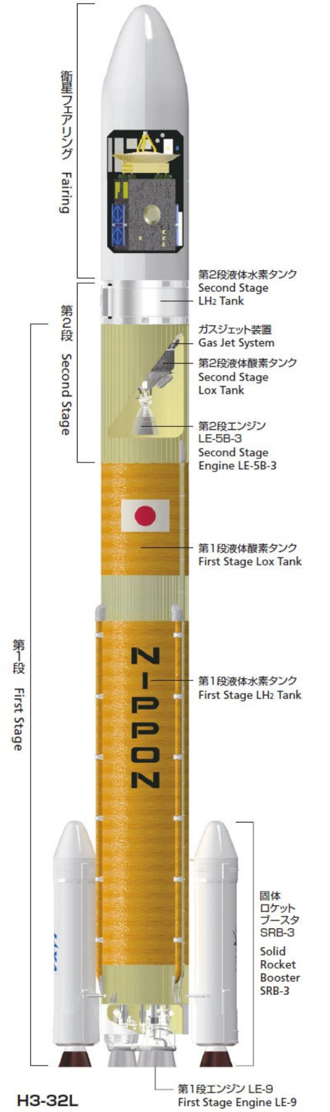
📖 LiteBIRD collaboration PTEP 2023

- Lite (Light) spacecraft for the study of *B*-mode polarization and Inflation from cosmic background Radiation Detection
- JAXA's L-class mission was selected in May 2019 to be launched by JAXA's H3 rocket.
- **All-sky 3-year survey**, from Sun-Earth Lagrangian point L2
- Large frequency coverage (**40–402 GHz**, 15 bands) at **70–18 arcmin** angular resolution for precision measurements of the **CMB *B*-modes**
- Final combined sensitivity: **2.2 μK·arcmin**









Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Received: *July 26, 2024*
Revised: *October 10, 2024*
Accepted: *October 21, 2024*
Published: *December 11, 2024*

LiteBIRD science goals and forecasts. Mapping the hot gas in the Universe

The LiteBIRD collaboration

M. Remazeilles,[1,*] M. Douspis,[2] J.A. Rubiño-Martín,[3,4] A.J. Banday,[5] J. Chluba,[6] P. de Bernardis,[7,8] M. De Petris,[7,8] C. Hernández-Monteagudo,[3] G. Luzzi,[9] J. Macias-Perez,[10] S. Masi,[7,8] T. Namikawa,[11] L. Salvati,[2] H. Tanimura,[11] K. Aizawa,[12] A. Anand,[13] J. Aumont,[5] C. Baccigalupi,[14,15,16] M. Ballardini,[17,18,19] R.B. Barreiro,[1] N. Bartolo,[20,21,22] S. Basak,[23] M. Bersanelli,[24,25] D. Blinov,[26,27] M. Bortolami,[17,18] T. Brinckmann,[17] E. Calabrese,[28] P. Campeti,[18,29,30] E. Carinos,[5] A. Carones,[14] F.J. Casas,[1] K. Cheung,[6,31,32,33] L. Clermont,[34] F. Columbro,[7,8] A. Coppolecchia,[7,8] F. Cuttaia,[19] T. de Haan,[35,36] E. de la Hoz,[37,1,38] S. Della Torre,[39] P. Diego-Palazuelos,[29,38] G. D'Alessandro,[7,8] H.K. Eriksen,[40] F. Finelli,[19,41] U. Fuskeland,[40] G. Galloni,[17,13] M. Galloway,[40] M. Gervasi,[42,39] R.T. Génova-Santos,[3,4] T. Ghigna,[36] S. Giardiello,[28] C. Gimeno-Amo,[1] E. Gjerløw,[40] R. González González,[3] A. Gruppuso,[19,41] M. Hazumi,[36,35,43,11,44] S. Henrot-Versillé,[45] L.T. Hergt,[46] D. Herranz,[1] K. Kohri,[35] E. Komatsu,[29,11] L. Lamagna,[7,8] M. Lattanzi,[18] C. Leloup,[11] F. Levrier,[47] A.I. Lonappan,[48] M. López-Caniego,[49,50] B. Maffei,[2] E. Martínez-González,[1] S. Matarrese,[20,21,22,51] T. Matsumura,[11] S. Micheli,[7] M. Migliaccio,[13,52] M. Monelli,[29] L. Montier,[5] G. Morgante,[19] Y. Nagano,[53] R. Nagata,[43] A. Novelli,[7] R. Omae,[53] L. Pagano,[17,18,2] D. Paoletti,[19,41] V. Pavlidou,[26,27] F. Piacentini,[7,8] M. Pinchera,[54] G. Polenta,[9] L. Porcelli,[55] A. Ritacco,[52,47] M. Ruiz-Granda,[1,38] Y. Sakurai,[56,11] D. Scott,[46] M. Shiraishi,[56] S.L. Stever,[53,11] R.M. Sullivan,[46] Y. Takase,[53] K. Tassis,[26,27] L. Terenzi,[19] M. Tomasi,[24,25] M. Tristram,[45] L. Vacher,[14] B. van Tent,[45] P. Vielva,[1] I.K. Wehus,[40] B. Westbrook,[31] G. Weymann-Despres,[45] E.J. Wollack,[57] M. Zannoni[42,39] and Y. Zhou[36]

[1]*Instituto de Fisica de Cantabria (IFCA, CSIC-UC), Avenida los Castros SN, 39005, Santander, Spain*
[2]*Université Paris-Saclay, CNRS, Institut d'Astrophysique Spatiale, 91405, Orsay, France*
[3]*Instituto de Astrofísica de Canarias, E-38200 La Laguna, Tenerife, Canary Islands, Spain*

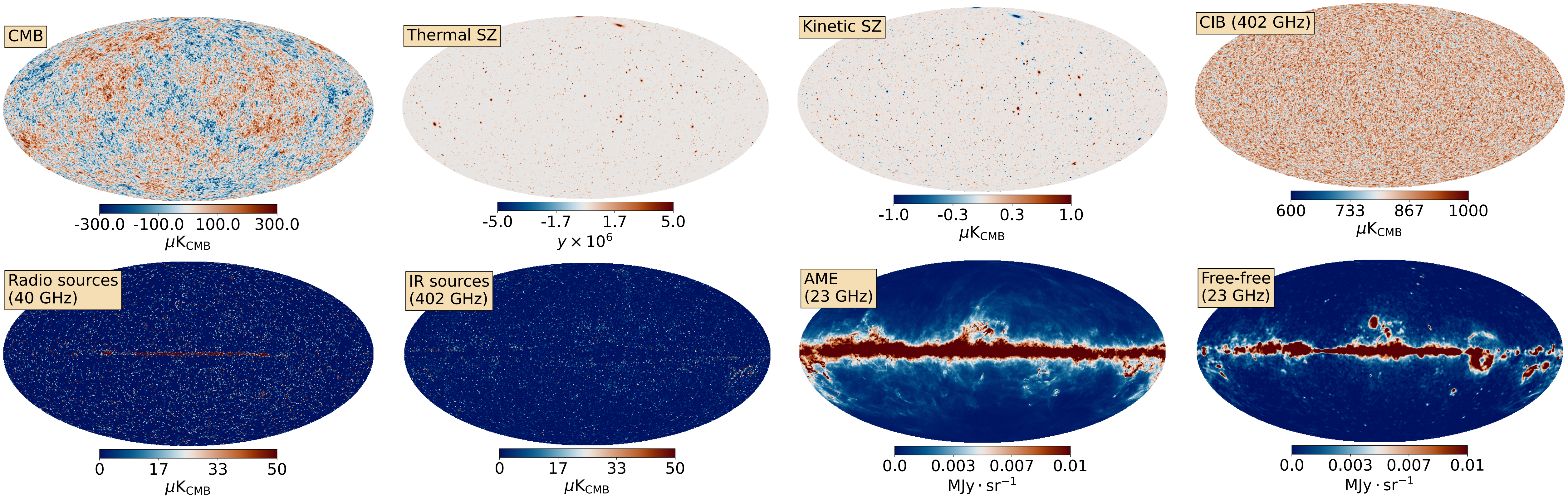
*Corresponding author.

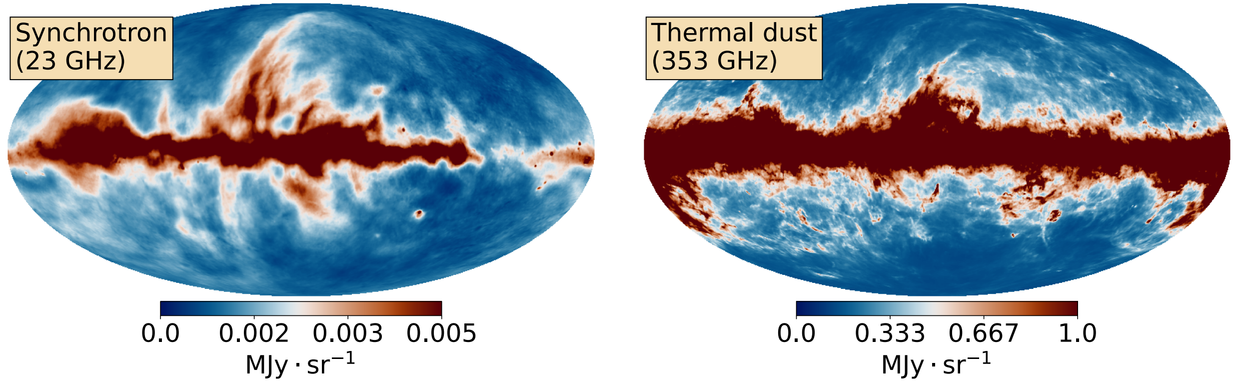
https://doi.org/10.1088/1475-7516/2024/12/026

JCAP12(2024)026

- Unlike cluster catalogues, which only capture thermal Sunyaev-Zeldovich (SZ) emission from massive, well-resolved clusters, the Compton y-map probes the entire hot gas distribution over the sky.
- The Planck Compton y-map is the first and unique all-sky map of the thermal SZ effect to date.
- Despite low angular resolution for galaxy cluster science, LiteBIRD offers **enhanced sensitivity**, **full-sky coverage**, and **multiple frequency bands** compared to Planck.
- LiteBIRD is well-positioned to deliver the next all-sky thermal SZ map, with reduced foreground contamination compared to Planck.
  - ➔ *Important legacy data from LiteBIRD*
  - ➔ *Important impact on cosmology and astrophysics*
- We propose to combine both LiteBIRD and Planck channels to leverage the advantages of each experiment for optimal y-map reconstruction and improved constraints on σ_8.

Sky simulations for LiteBIRD and Planck





- Comprehensive sky simulations
- Both LiteBIRD and Planck instruments
- Including $1/f$ noise

JCAP 12 (2024) 026

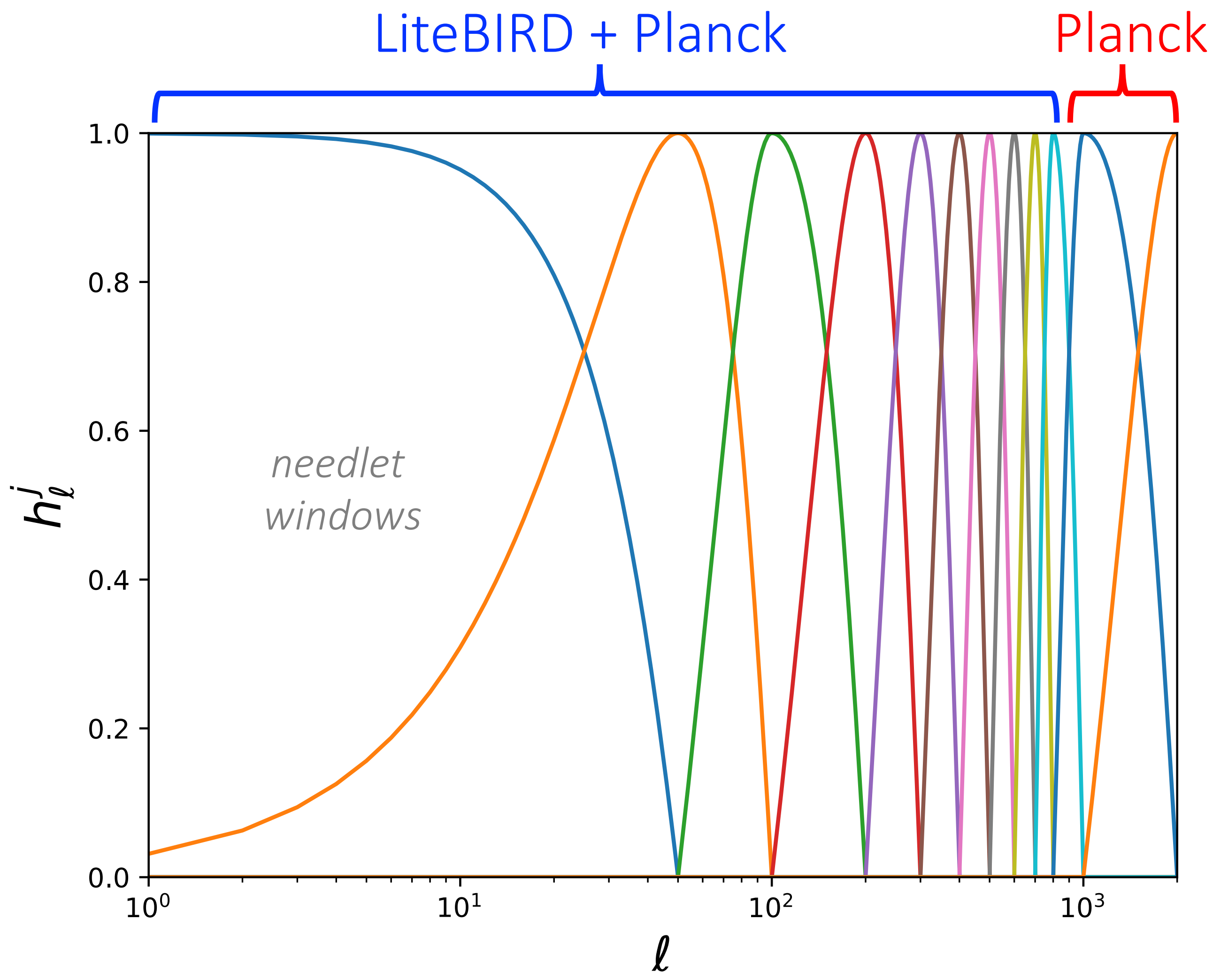
Combining LiteBIRD and Planck channels for component separation with NILC

NILC: Needlet Internal Linear Combination
Delabrouille et al, A&A (2009)

NILC enables the combination of multi-resolution data from multiple different experiments

Remazeilles, Aghanim, Douspis MNRAS (2013)

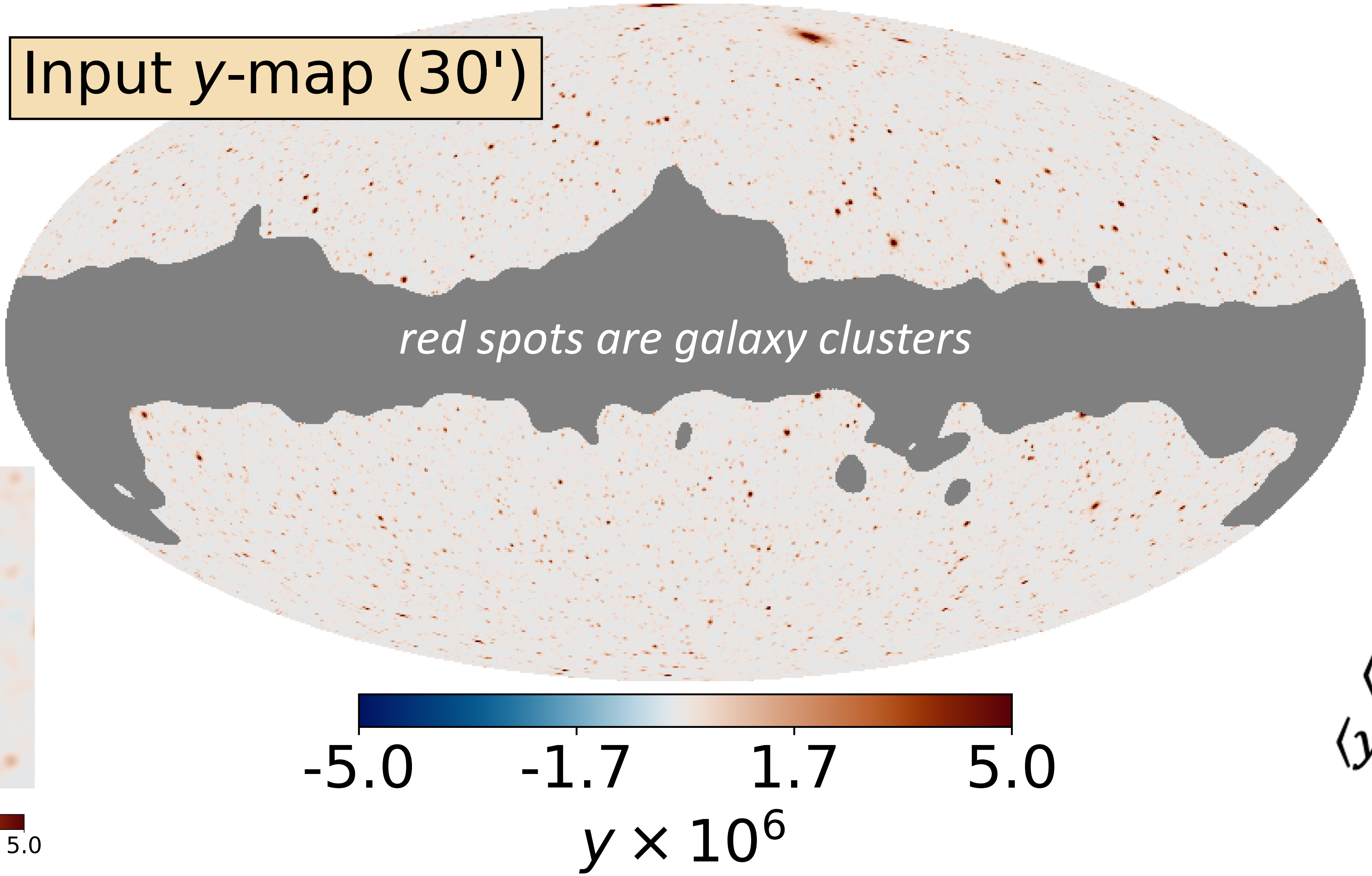
LiteBIRD channels enhance foreground cleaning, while Planck channels provide resolution beyond LiteBIRD beam limits

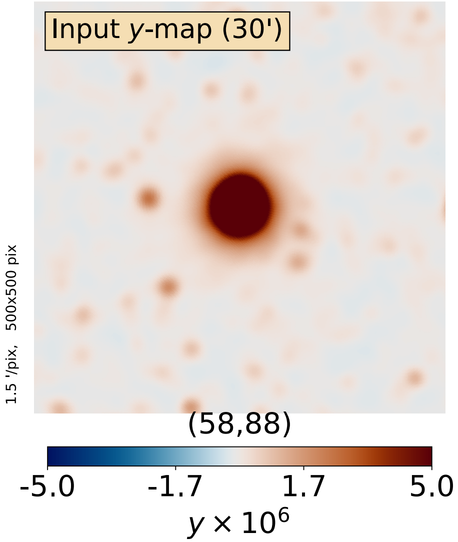


JCAP 12 (2024) 026

Thermal SZ y-map reconstruction

JCAP 12 (2024) 026





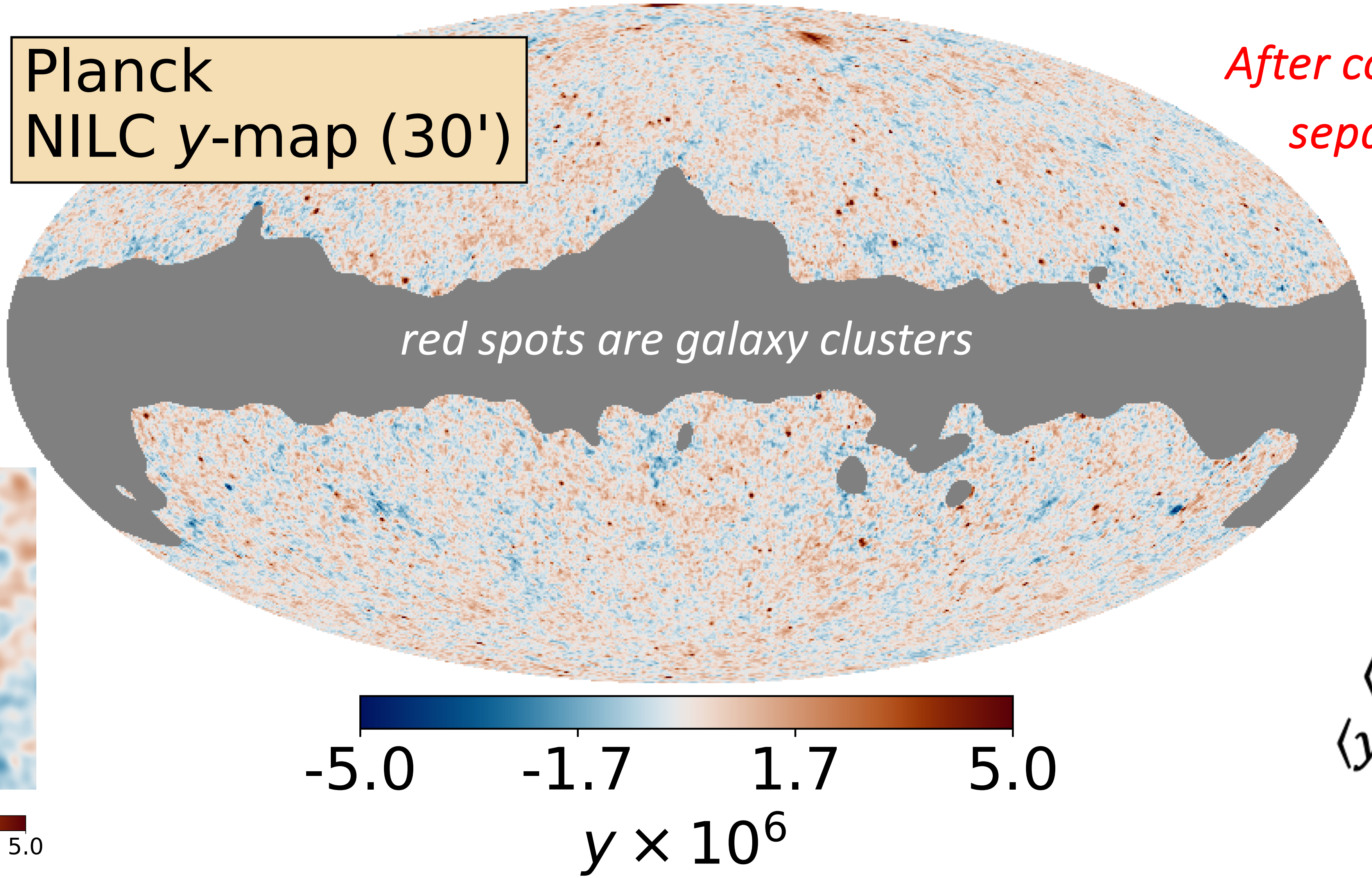
$$\langle yy \rangle \sim \sigma_8^8$$
$$\langle yyy \rangle \sim \sigma_8^{11}$$

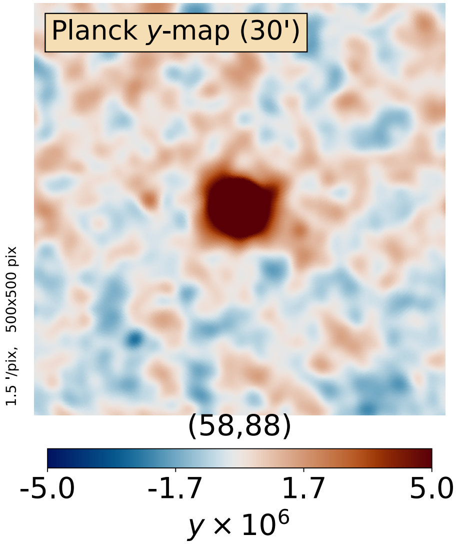
M. Remazeilles

Thermal SZ y-map reconstruction

JCAP 12 (2024) 026

After component separation





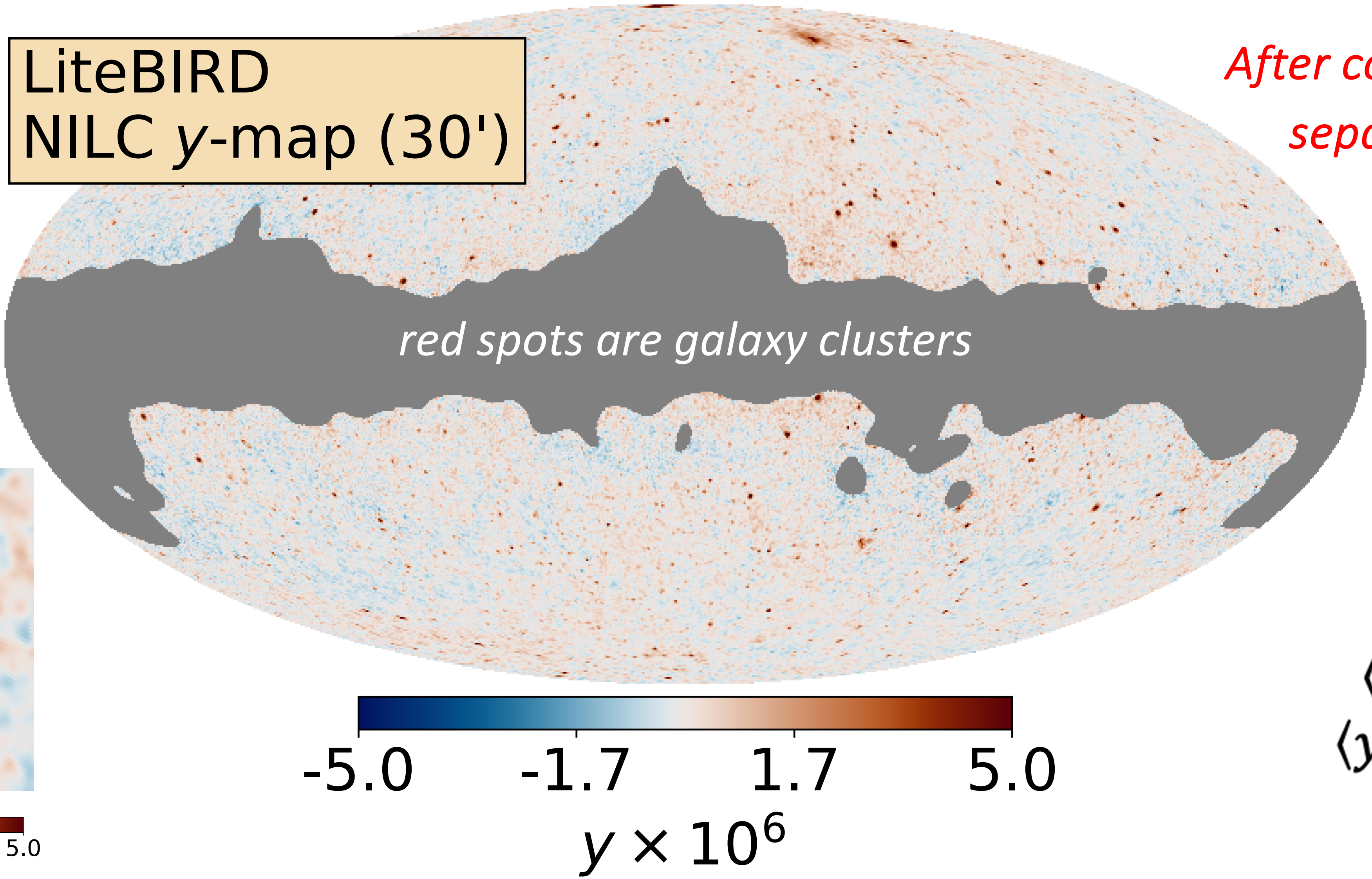
$$\langle yy\rangle \sim \sigma_8^8$$
$$\langle yyy\rangle \sim \sigma_8^{11}$$

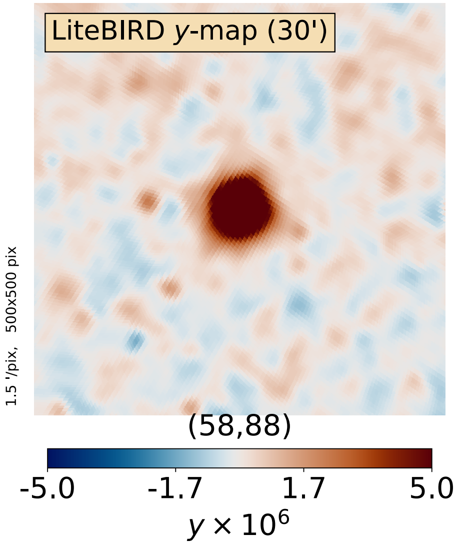
M. Remazeilles

Thermal SZ y-map reconstruction

JCAP 12 (2024) 026

After component separation



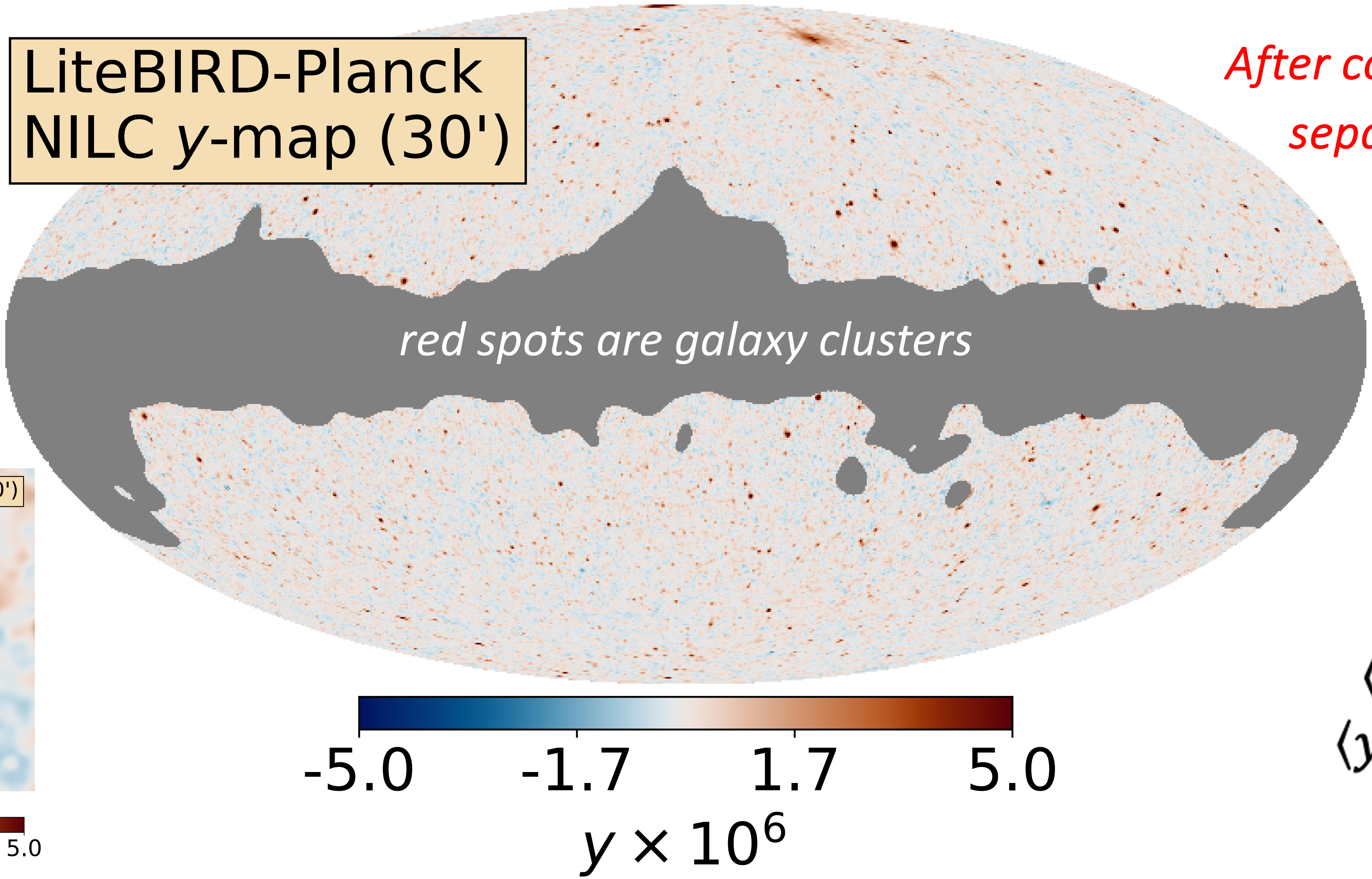


$$\langle yy \rangle \sim \sigma_8^8$$
$$\langle yyy \rangle \sim \sigma_8^{11}$$

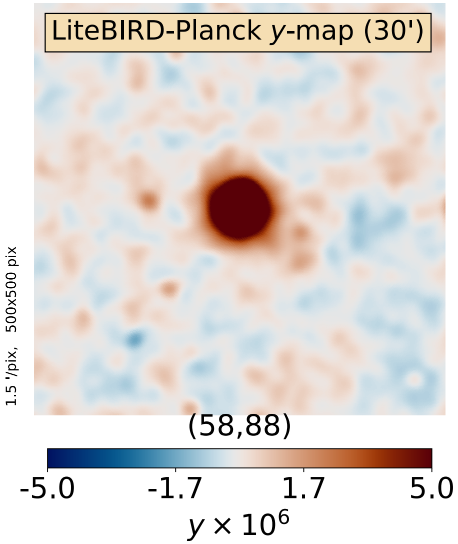
M. Remazeilles

Thermal SZ y-map reconstruction

JCAP 12 (2024) 026



After component separation

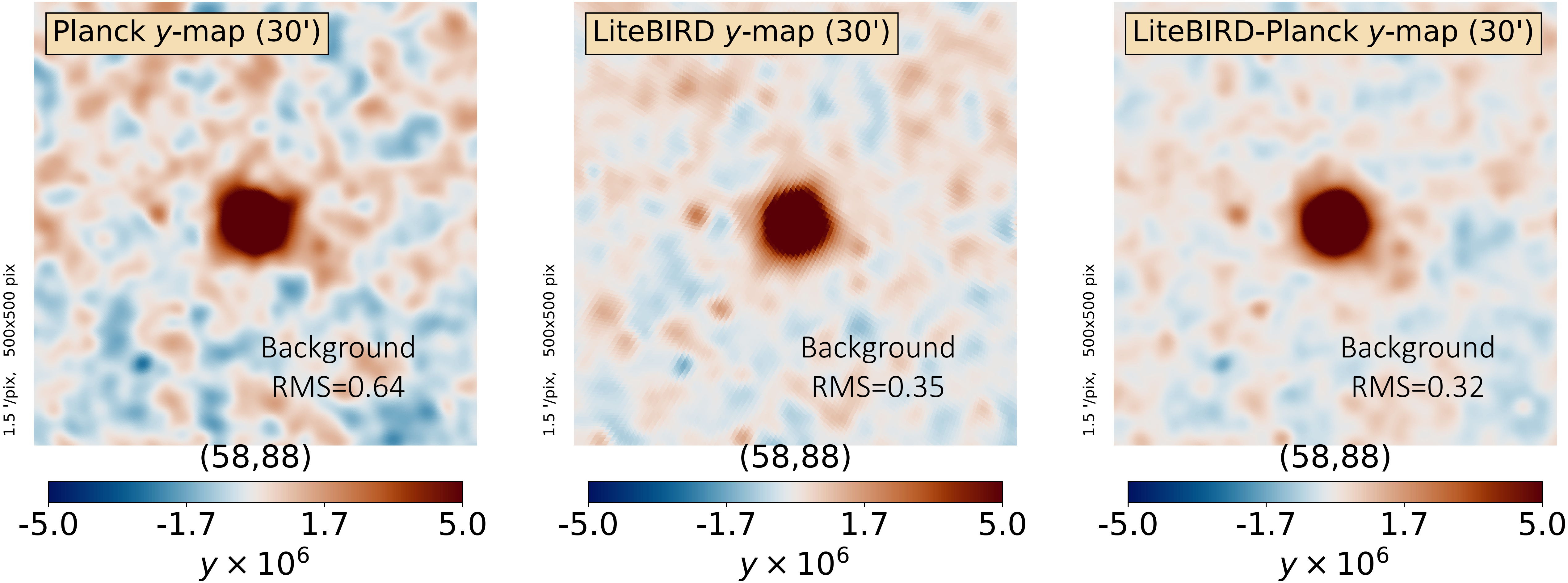


$\langle yy \rangle \sim \sigma_8^8$

$\langle yyy \rangle \sim \sigma_8^{11}$

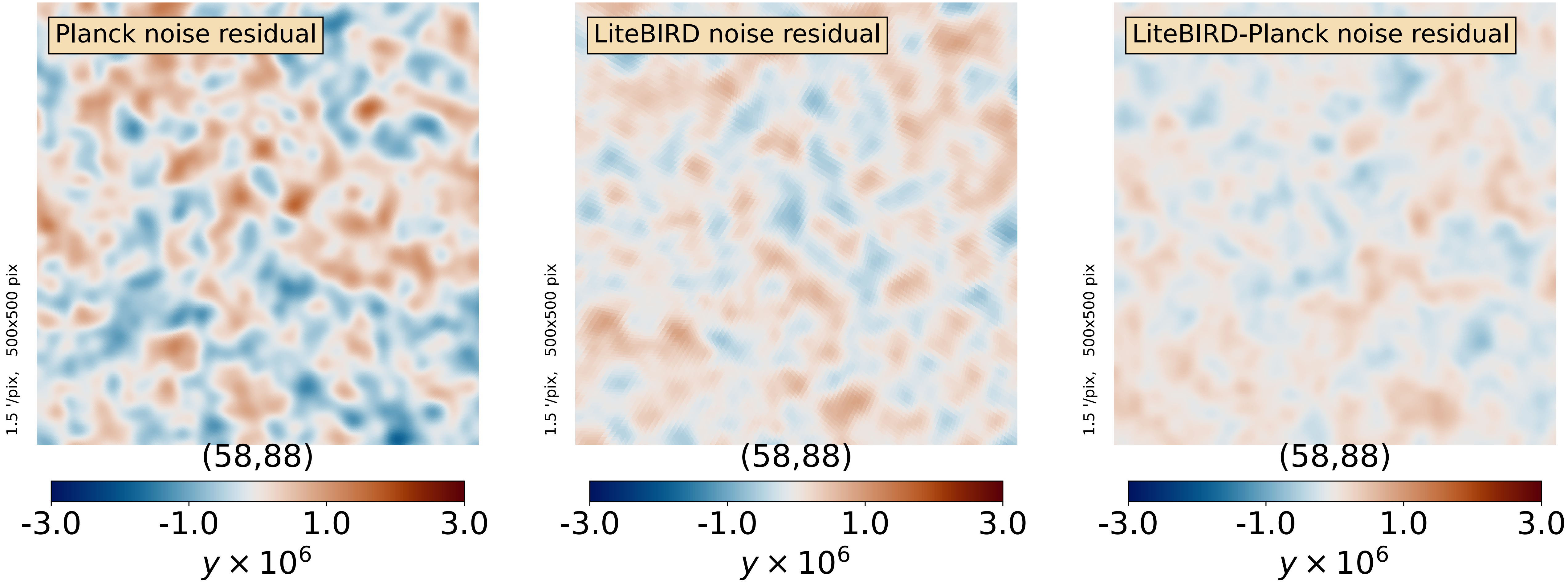
M. Remazeilles

Comparison of y-maps around Coma



Improvement in SZ map quality from Planck to LiteBIRD, and from LiteBIRD to joint LiteBIRD-Planck

Residual noise contamination

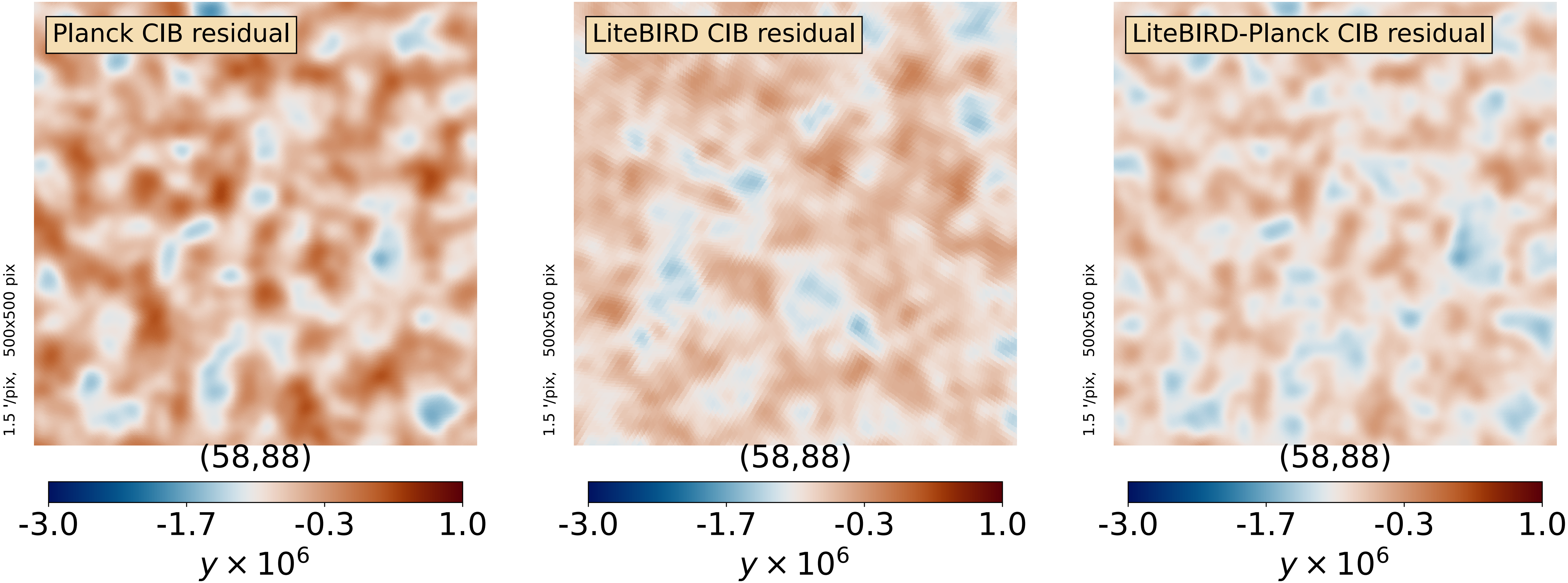


Reduction in noise contamination from Planck to LiteBIRD, with further reduction in the joint LiteBIRD-Planck y-map

JCAP 12 (2024) 026

M. Remazeilles

Residual CIB contamination

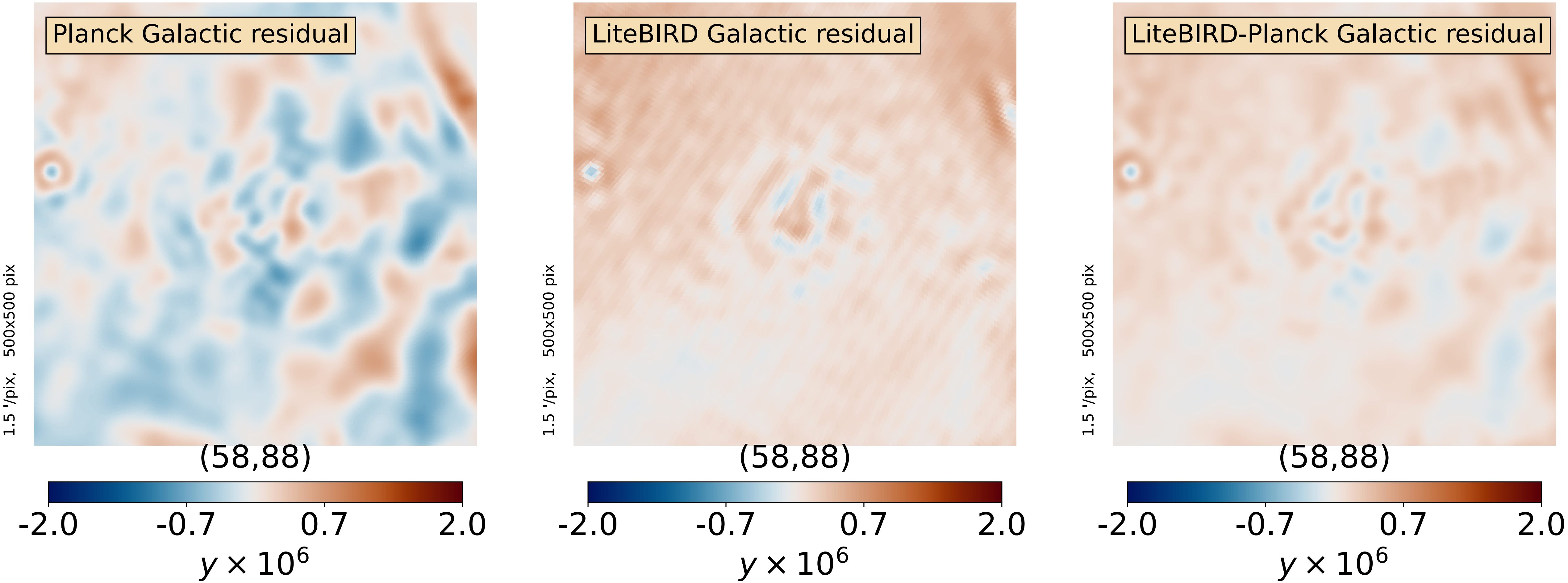


Reduction in CIB contamination from Planck to LiteBIRD, with further reduction in the joint LiteBIRD-Planck y-map

JCAP 12 (2024) 026

M. Remazeilles

Residual Galactic foreground contamination



Reduction in Galactic contamination from Planck to LiteBIRD, with further reduction in the joint LiteBIRD-Planck y-map

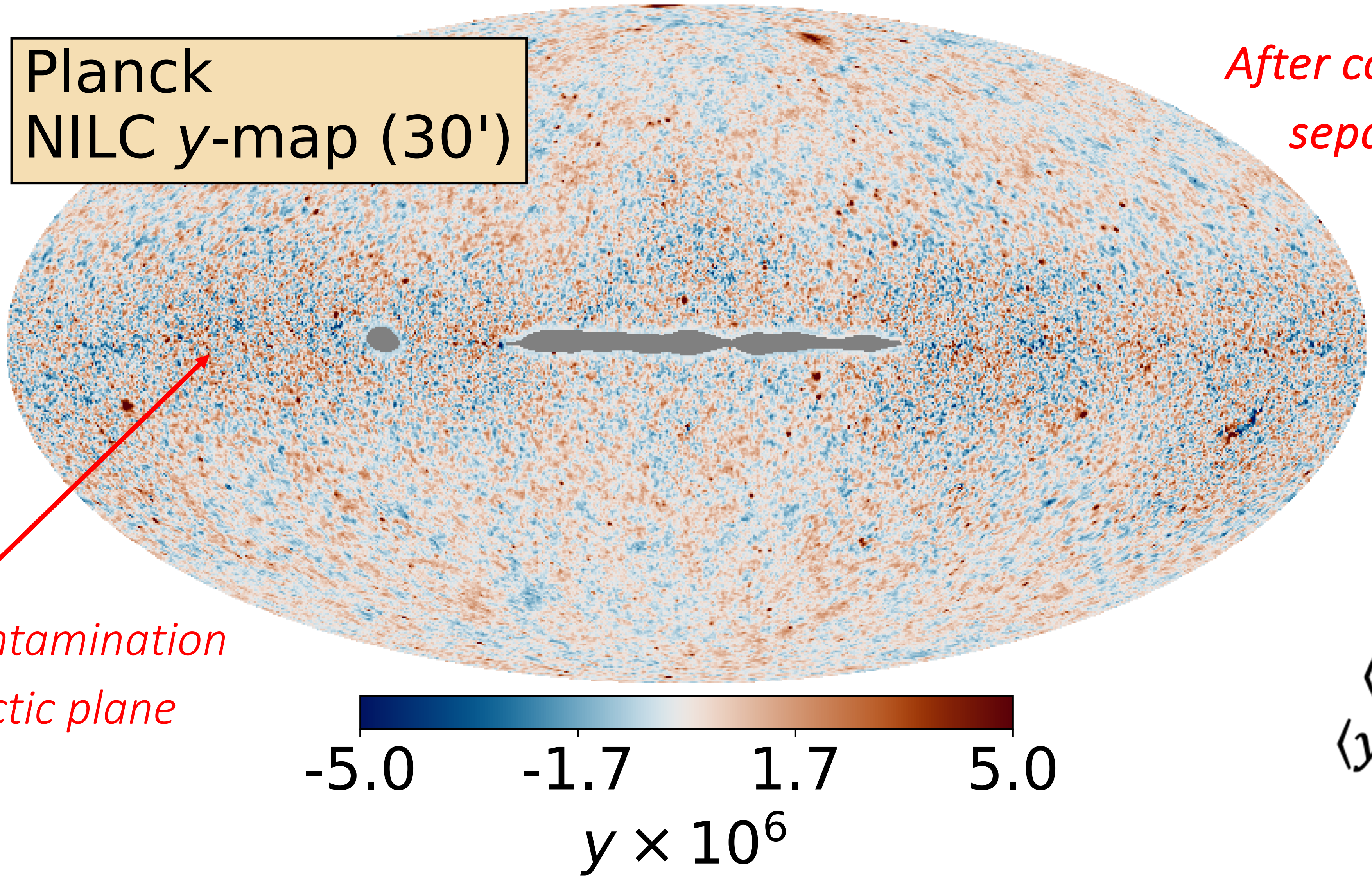
JCAP 12 (2024) 026

M. Remazeilles

Reconstructed y-map over 98% of the sky

JCAP 12 (2024) 026

98% sky



After component separation

Significant contamination in the Galactic plane

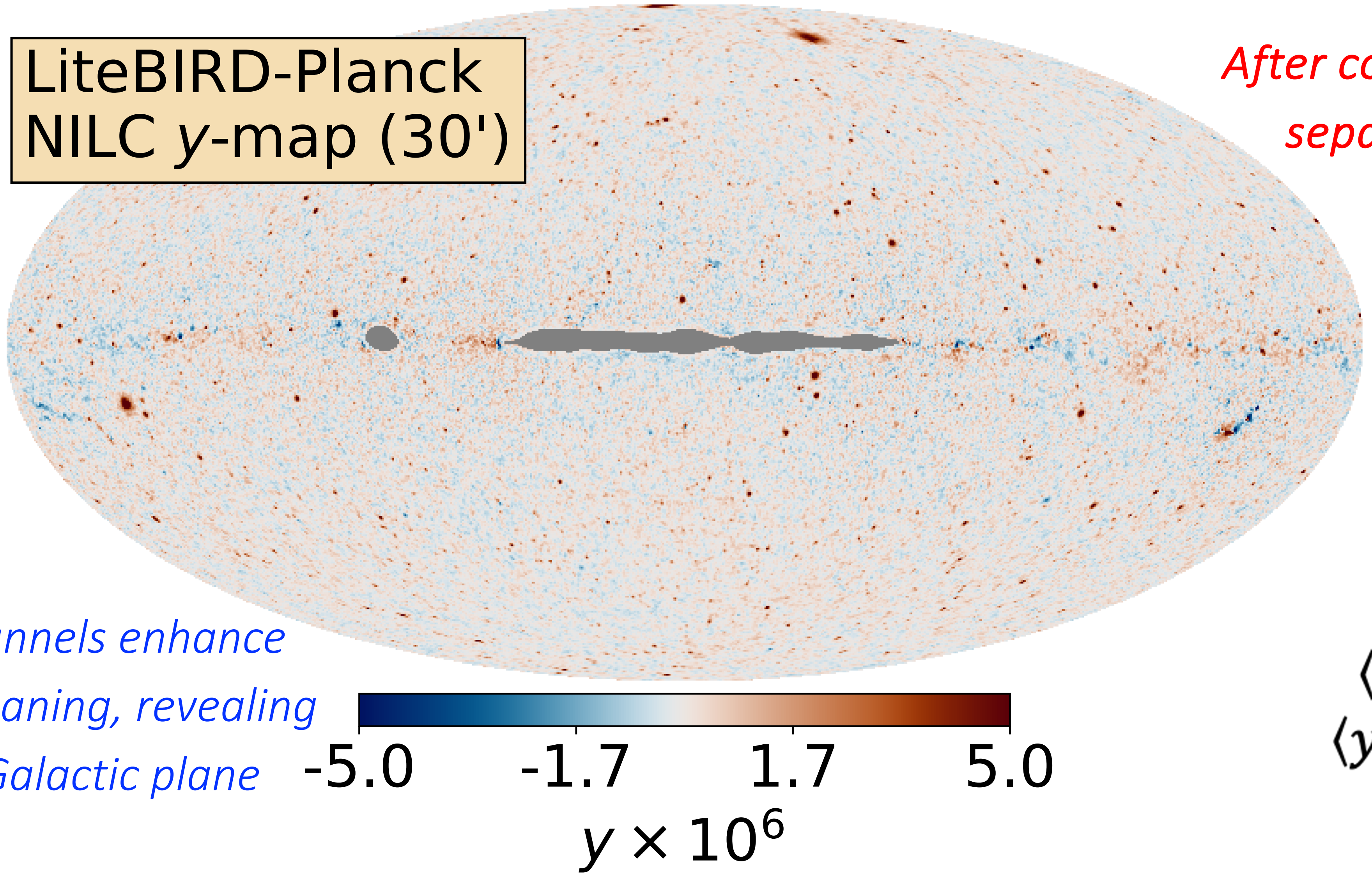
$\langle yy \rangle \sim \sigma_8^8$

$\langle yyy \rangle \sim \sigma_8^{11}$

M. Remazeilles

Reconstructed y-map over 98% of the sky

JCAP 12 (2024) 026



After component separation

98% sky

LiteBIRD channels enhance foreground cleaning, revealing clusters in Galactic plane

$\langle yy \rangle \sim \sigma_8^8$

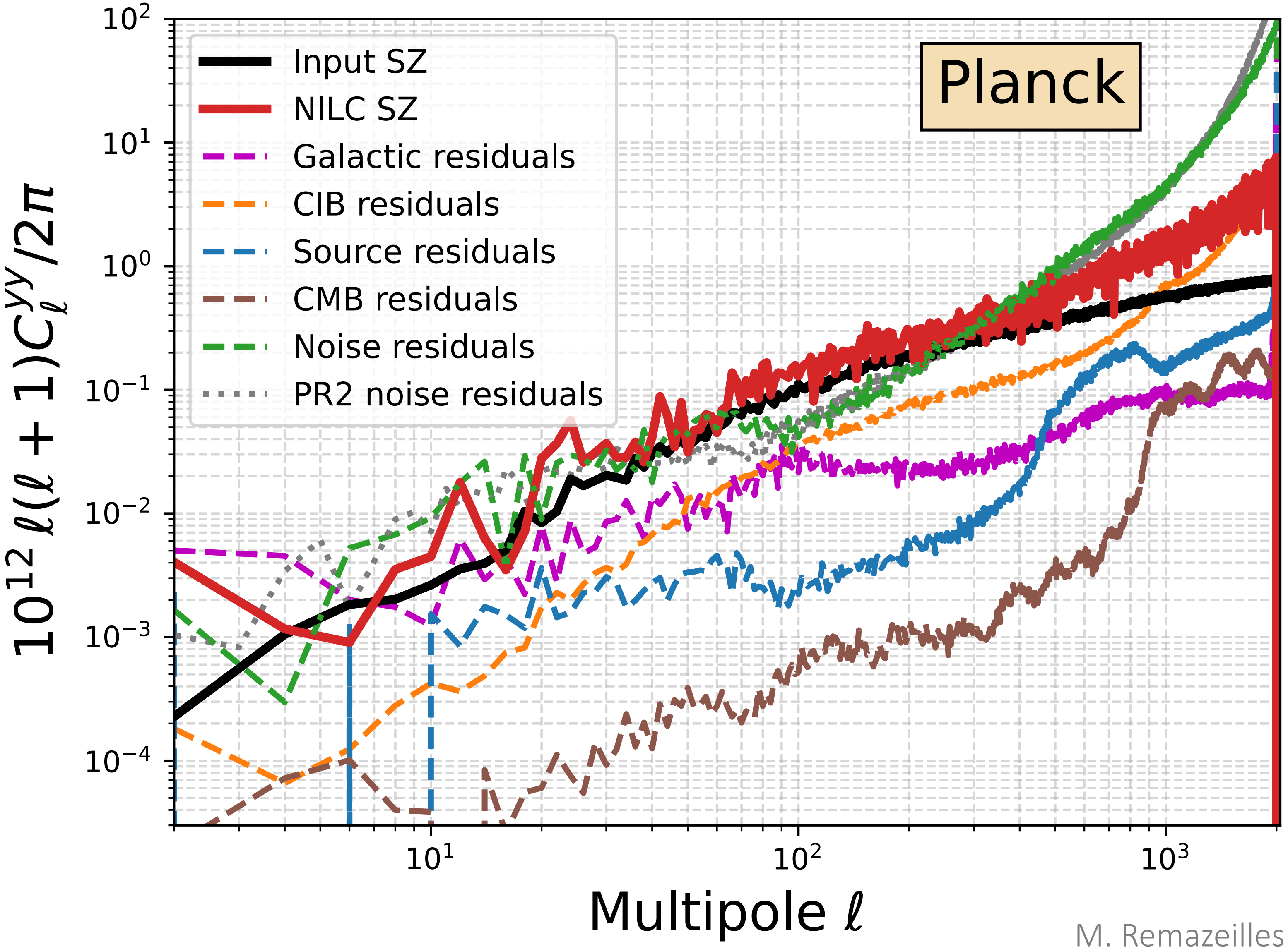
$\langle yyy \rangle \sim \sigma_8^{11}$

M. Remazeilles

y-map power spectrum and residuals

SZ power spectrum
and residuals

Planck



JCAP 12 (2024) 026

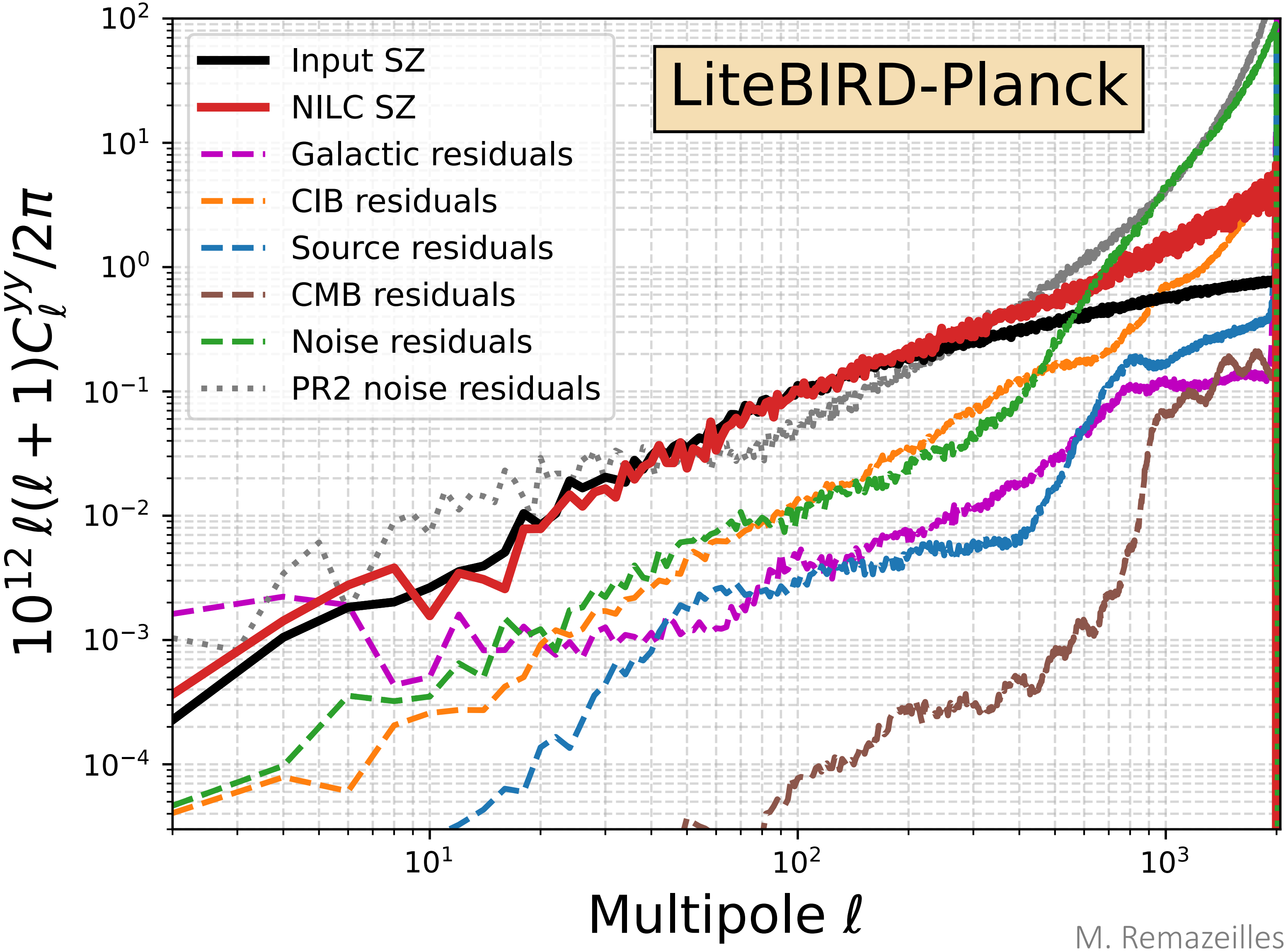
M. Remazeilles

y-map power spectrum and residuals

SZ power spectrum
and residuals

LiteBIRD + Planck

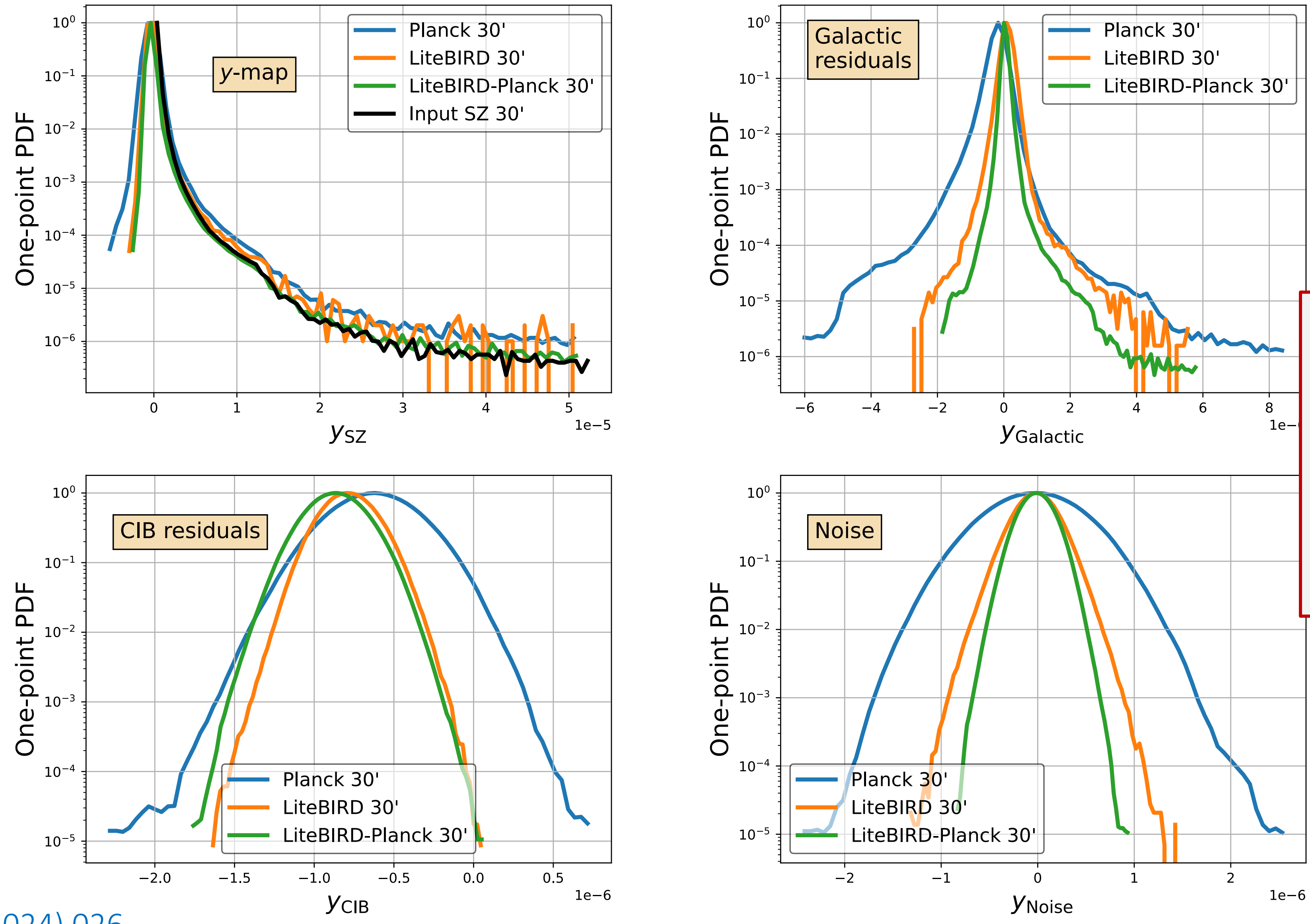
Noise and foreground residuals reduced by an order of magnitude at large and intermediate scales



JCAP 12 (2024) 026

M. Remazeilles

One-point PDF of y-map and residuals



Reduction of noise and foreground residuals from Planck to LiteBIRD, with further reduction in joint LiteBIRD-Planck y-map

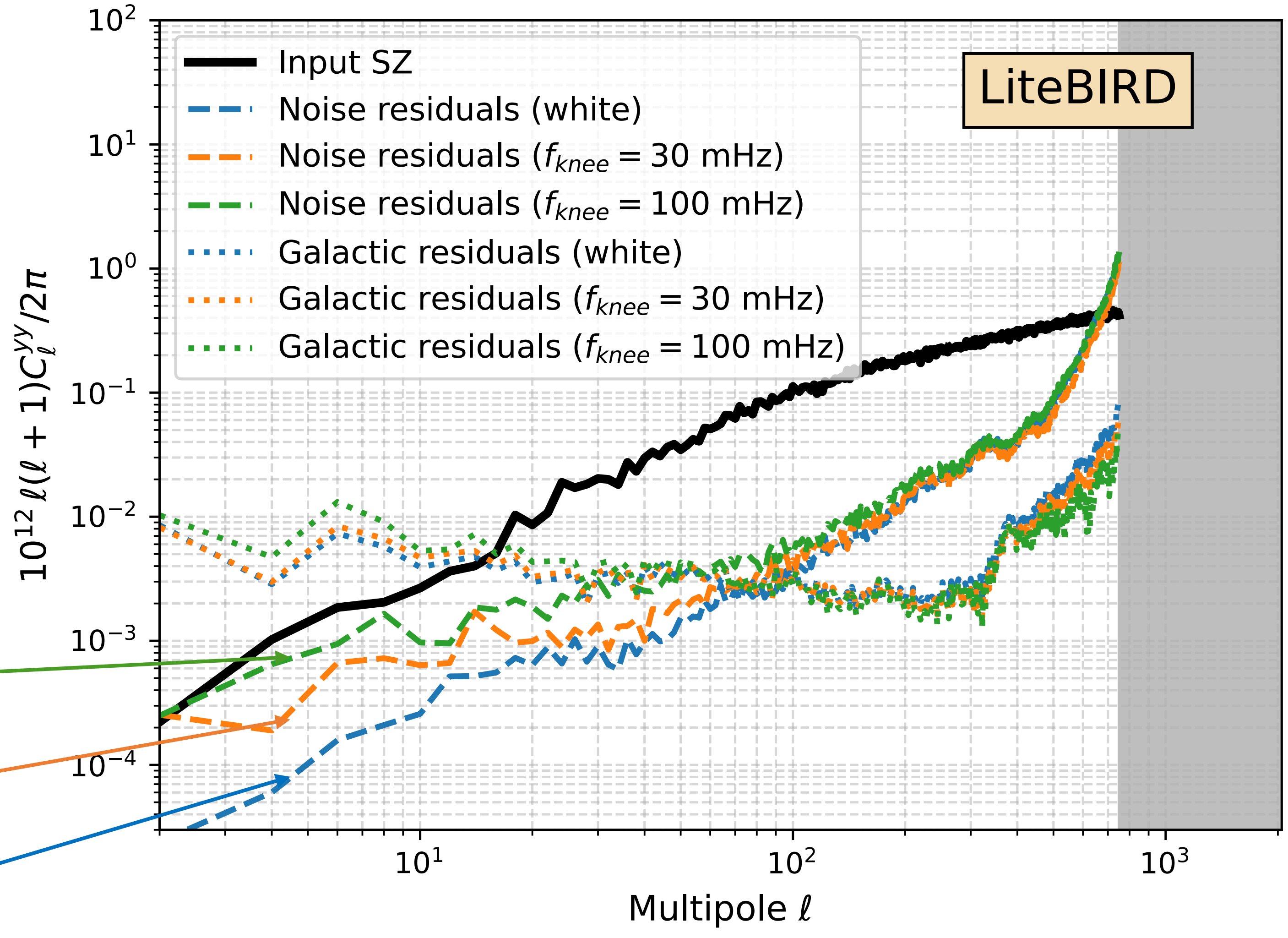
Impact of LiteBIRD $1/f$ noise

LiteBIRD 1/f noise reduced below the SZ signal at all multipoles after component separation with NILC

$1/f$ noise ($f_{\mathbf{knee}} = 100$ mHz)

$1/f$ noise ($f_{\mathbf{knee}} = 30$ mHz)

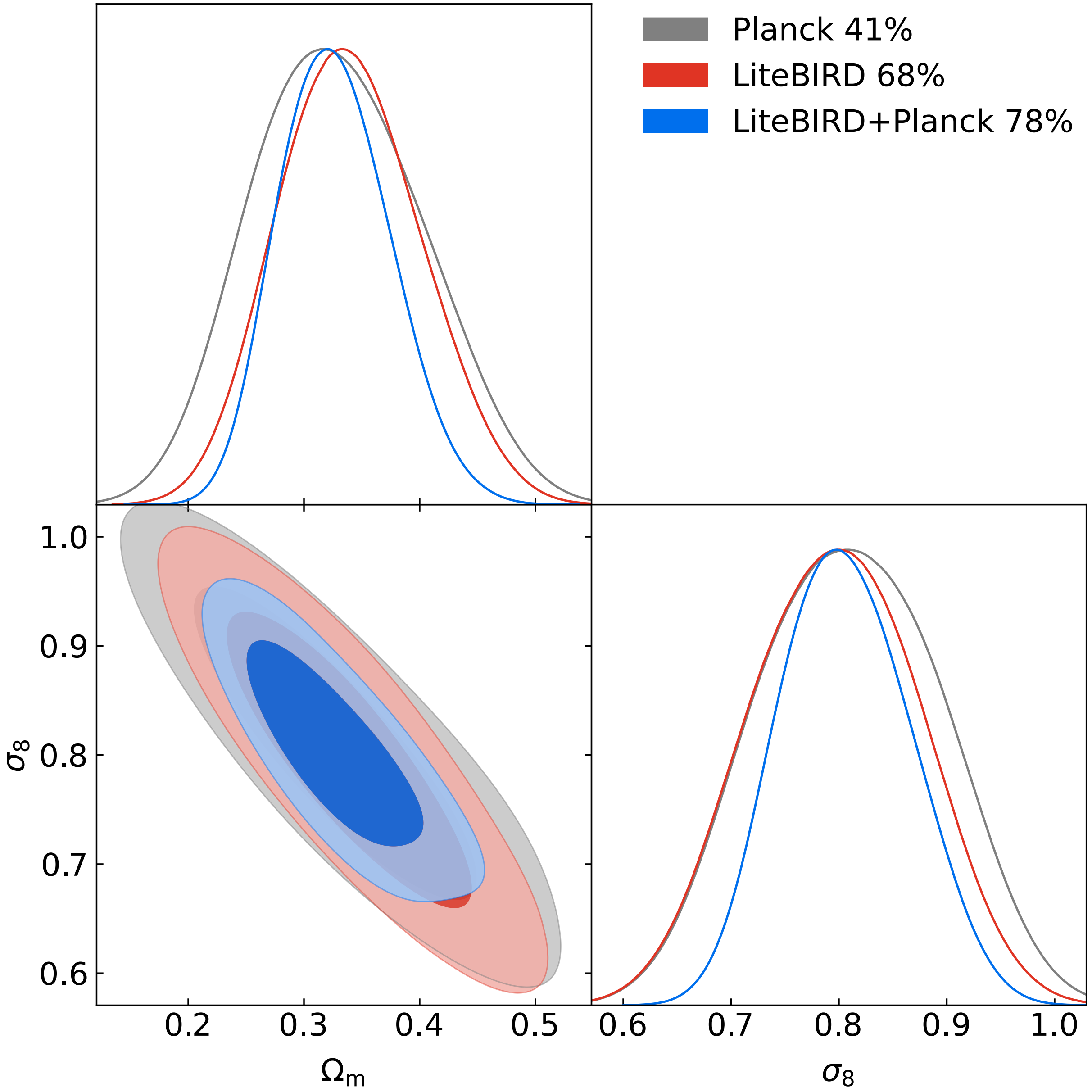
white noise



JCAP 12 (2024) 026

M. Remazeilles

Cosmological parameter constraints



Non-Gaussian contribution to SZ cosmic variance included

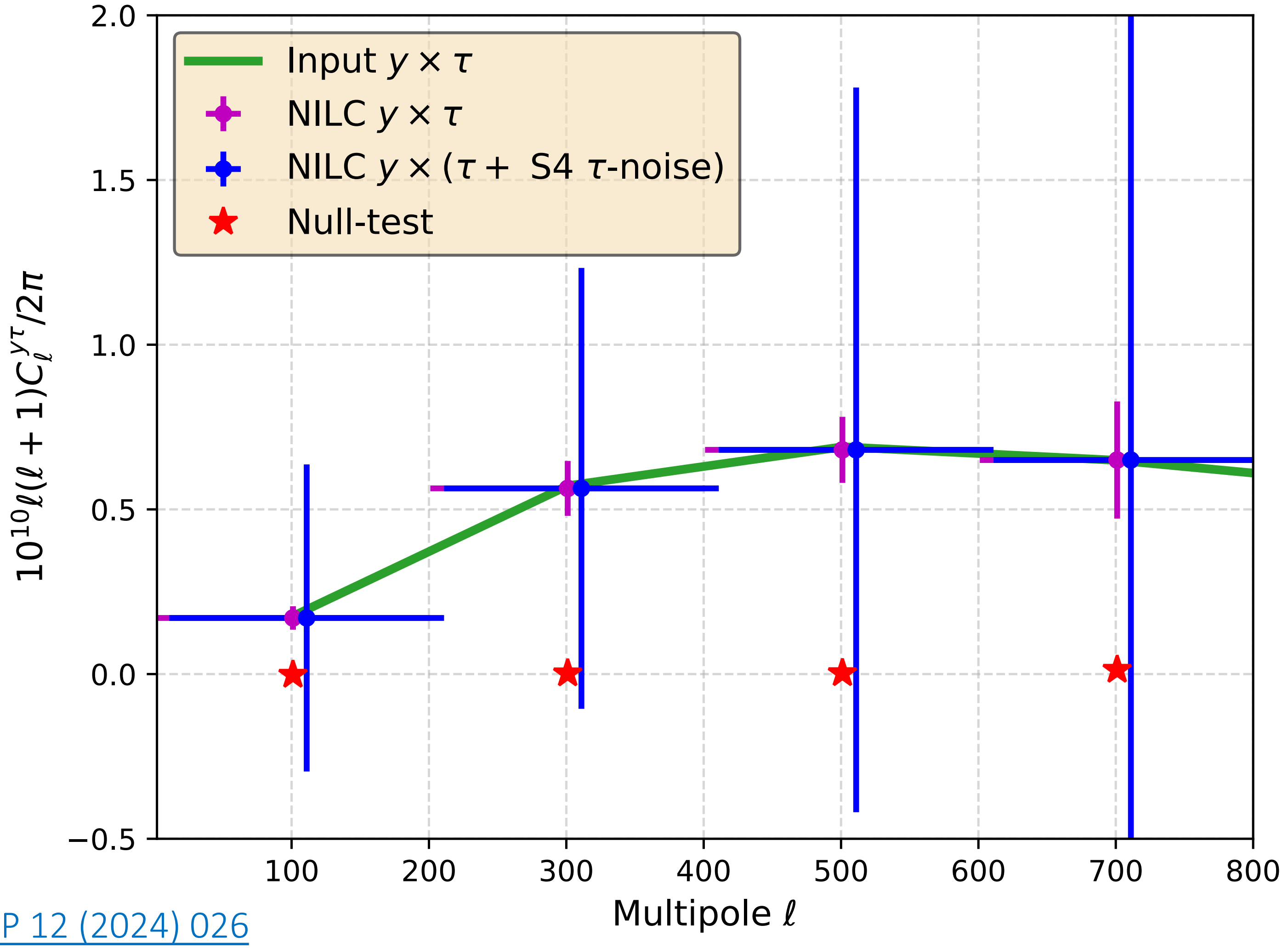
15% reduction in uncertainty on $S_8 = \sigma_8(\Omega_m / 0.3)^{0.5}$ from the combined LiteBIRD-Planck y-map

JCAP 12 (2024) 026

Thermal SZ effect from patchy reionisation

Cross-correlating the LiteBIRD SZ map with the CMB-S4 optical depth map

(following Namikawa, Roy, Sherwin, Battaglia, Spergel, PRD 2021)



LiteBIRD will provide preliminary evidence of the faint thermal SZ signal from pachy reionisation with a modest SNR of 1.6

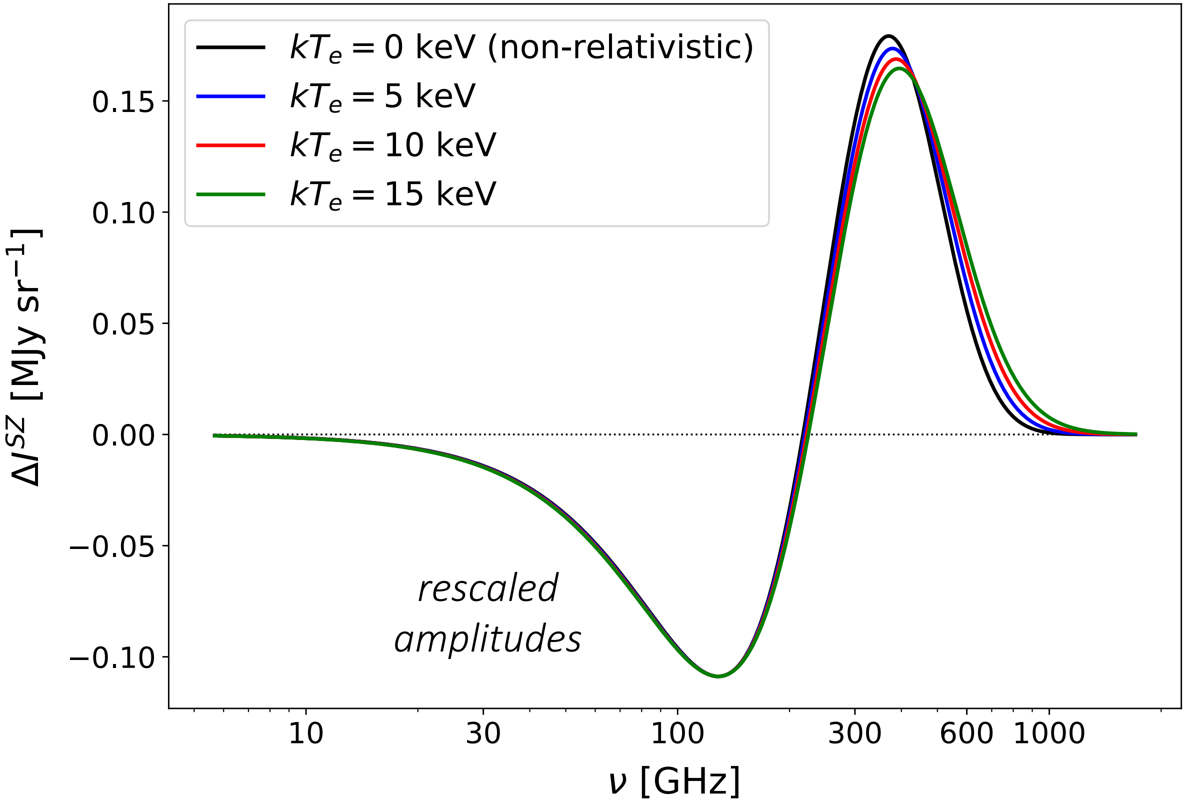
Perspectives on diffuse SZ science from a clean all-sky LiteBIRD y-map

- Relativistic SZ effect and gas temperature (capitalizing on LiteBIRD's high frequencies > 300 GHz)
- ISW-SZ cross-correlation at large angular scales
- CMB monopole y-distortion
- Two-halo contribution to SZ power spectrum at low multipoles
- Testing theories of structure formation via hot-gas tomography from SZ-LSS cross-correlations
- Quadrupole-like SZ effect from structures in local Universe such as the Milky Way or local supercluster
- SZ-coloured dipole-modulated CMB anisotropies via SZ-CMB cross-correlation as an alternative measurement of the dipole with higher significance than Planck Collaboration LVI (2020)
- Testing decaying dark matter models with SZ power spectrum

M. Remazeilles

Relativistic SZ effect

$$I_\nu(\hat{n}) = y(\hat{n}) f(\nu, T_e(\hat{n}))$$



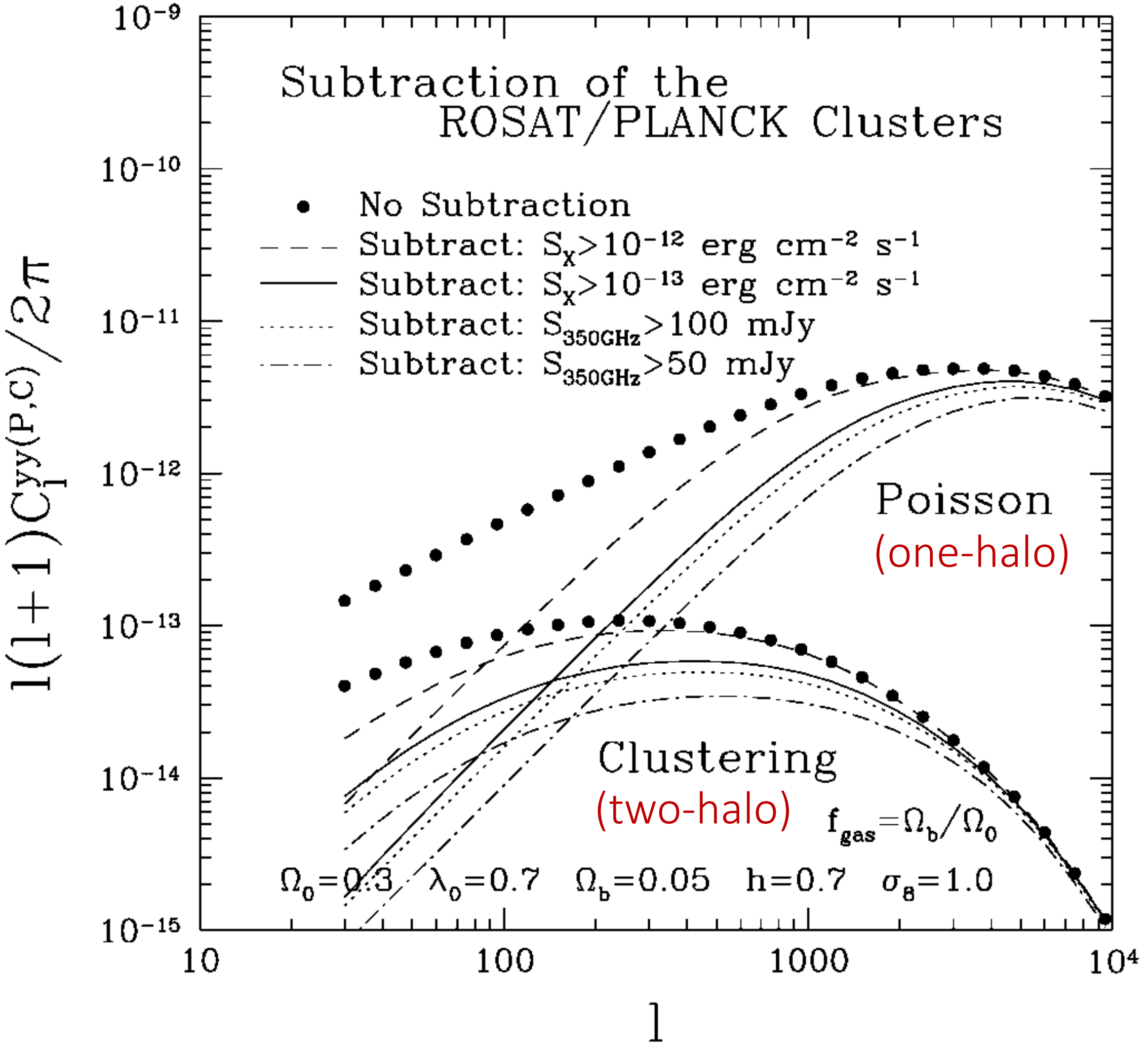
- *Capitalizing on LiteBIRD + Planck high frequencies above 300 GHz to disentangle the relativistic SZ effect*
- *LiteBIRD narrow bandpasses will also help detection*

See "Remazeilles & Chluba, MNRAS (2020)"
"Remazeilles & Chluba, 2410.02488 (2024)"

M. Remazeilles

Two-halo contribution to diffuse SZ effect

Komatsu & Kitayama (1999)

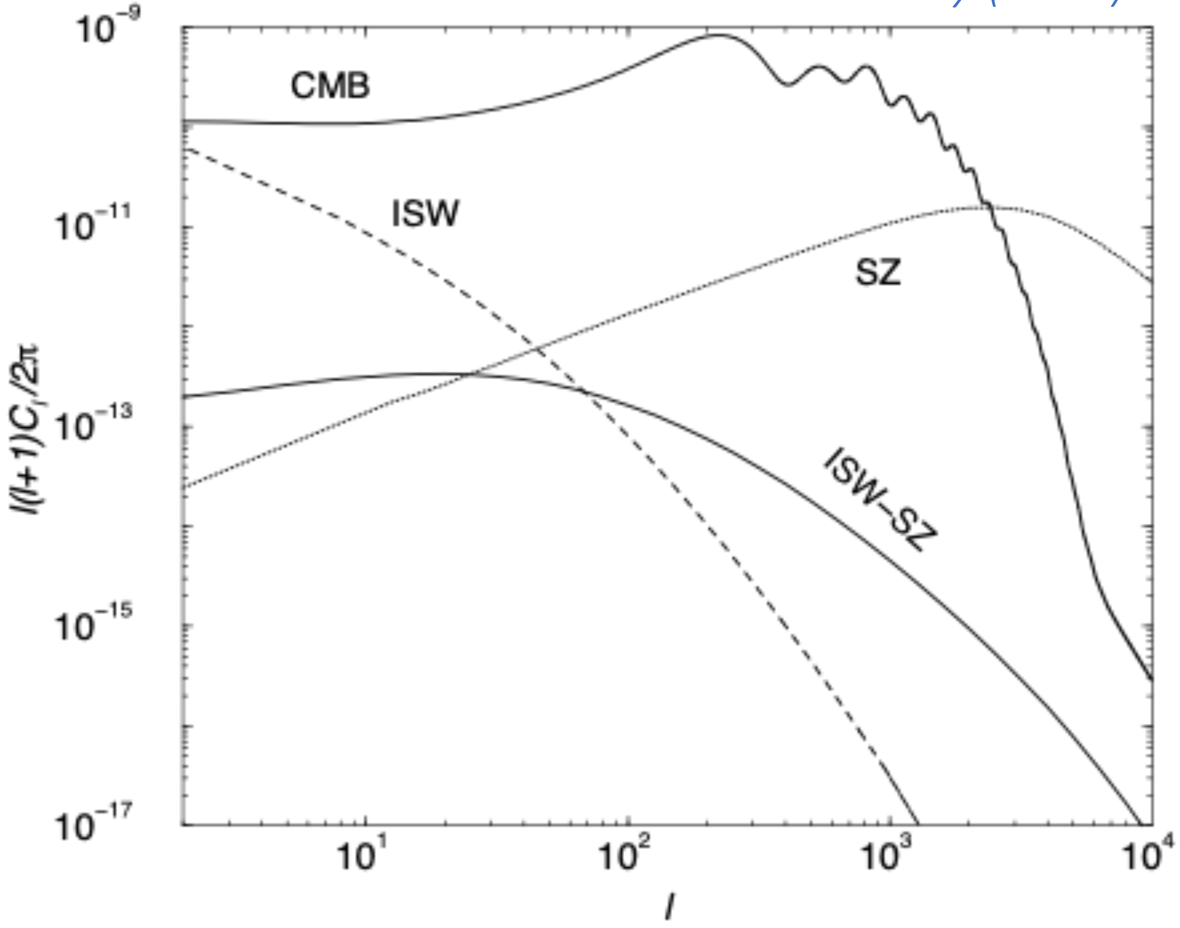


- *Masking massive clusters in the y-map to "Gaussianize" it and enhance the two-halo contribution over the one-halo signal in the diffuse SZ power spectrum at low multipoles*

See "Rotti, Bolliet, Chluba, and Remazeilles, MNRAS (2021)"

ISW-SZ cross-correlation at large scales

Cooray (2001)



- *Expected y-T cross-correlation at large angular scales between SZ and CMB temperature anisotropies due to the ISW effect*
- *LiteBIRD all-sky SZ map provides access to largest angular scales*

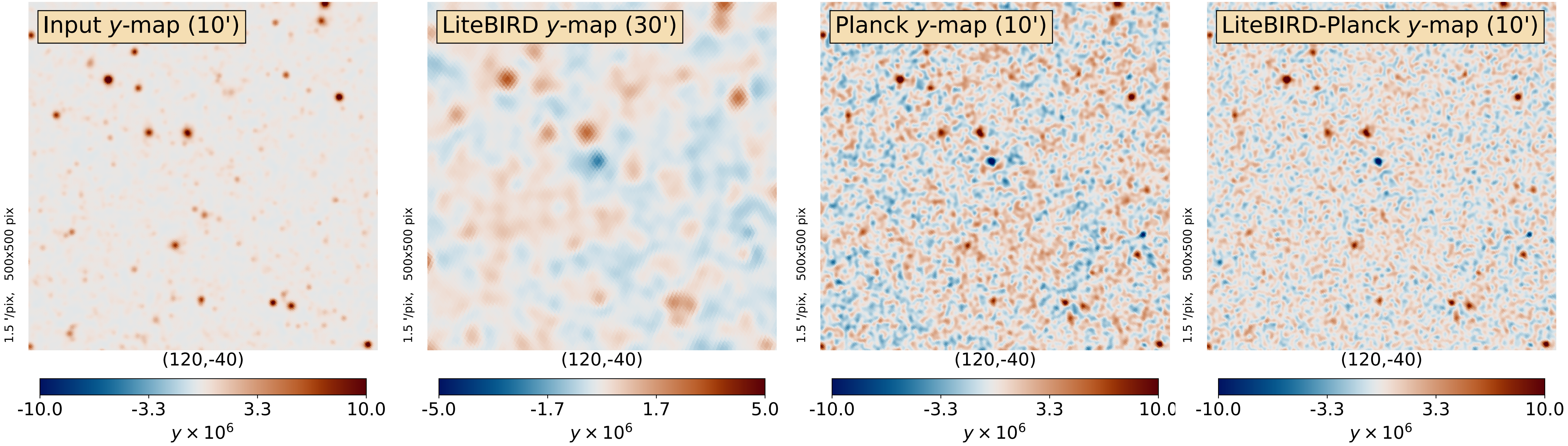
See "Taburet, Hernandez-Monteagudo, Aghanim, Douspis, and Sunyaev, MNRAS (2011)"

Conclusions

- An all-sky map of the thermal SZ Compton y-parameter from LiteBIRD will probe the hot baryonic gas distribution across the entire sky
- LiteBIRD’s enhanced sensitivity and frequency coverage outperform Planck's SZ mapping results over the entire sky
- The combined LiteBIRD-Planck SZ map leverages both Planck's angular resolution and LiteBIRD's sensitivity
- Noise and foreground contamination reduced by a factor of 10 at large and intermediate scales in the combined LiteBIRD-Planck SZ map compared to the Planck SZ map
- Constraints on $S_8 = \sigma_8(\Omega_\mathrm{m}/0.3)^{0.5}$ improved by 15% compared to Planck SZ map
- Many perspectives on diffuse SZ science from the all-sky LiteBIRD y-map

Backup

Leveraging LiteBIRD sensitivity and Planck resolution for the y-map

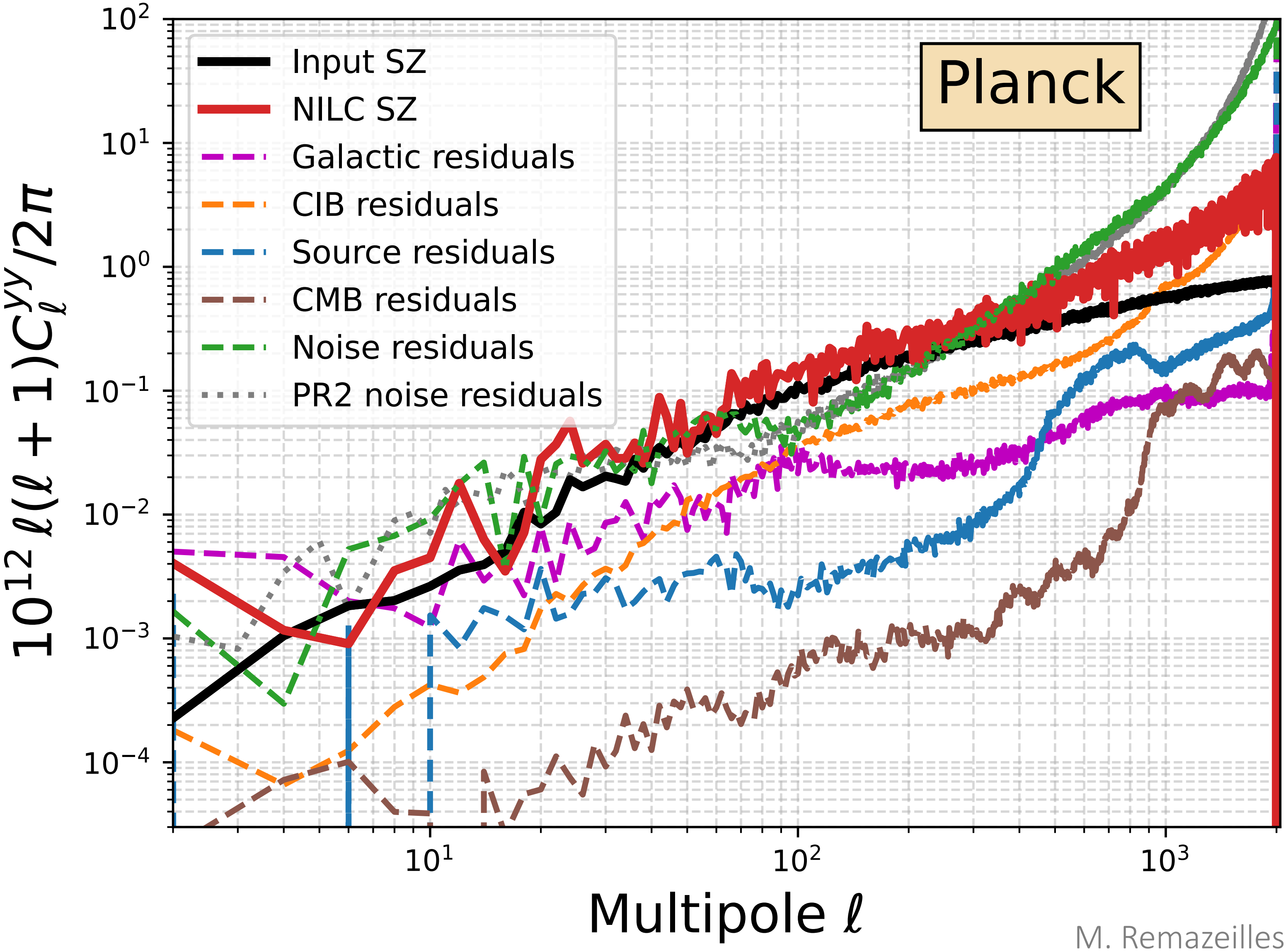


LiteBIRD enhances foreground cleaning, while Planck provides resolution beyond the LiteBIRD beam limits

y-map power spectrum and residuals

SZ power spectrum and residuals

Planck



JCAP 12 (2024) 026

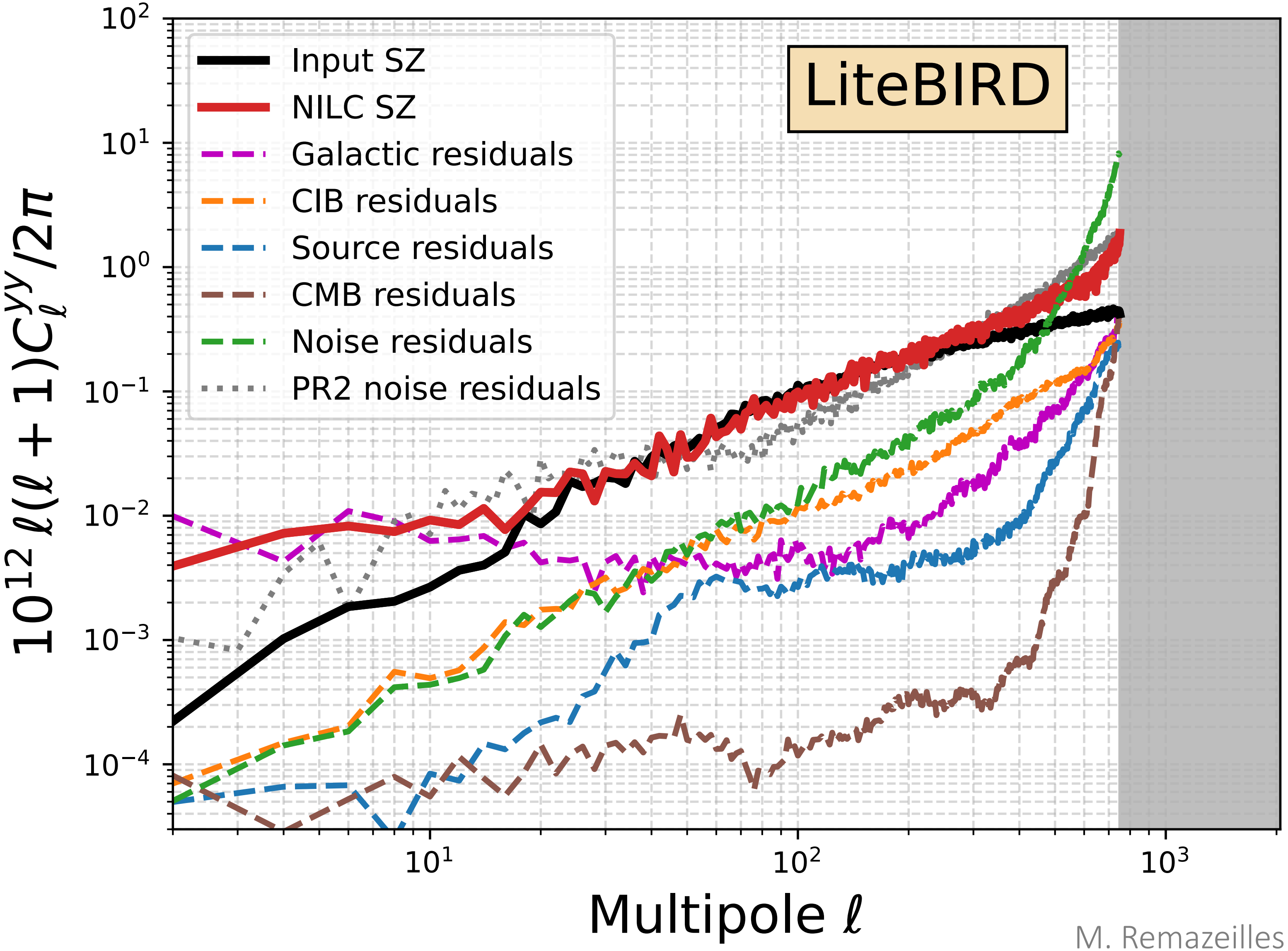
M. Remazeilles

y-map power spectrum and residuals

SZ power spectrum
and residuals

LiteBIRD

Noise and foreground residuals reduced by an order of magnitude at large and intermediate scales



JCAP 12 (2024) 026

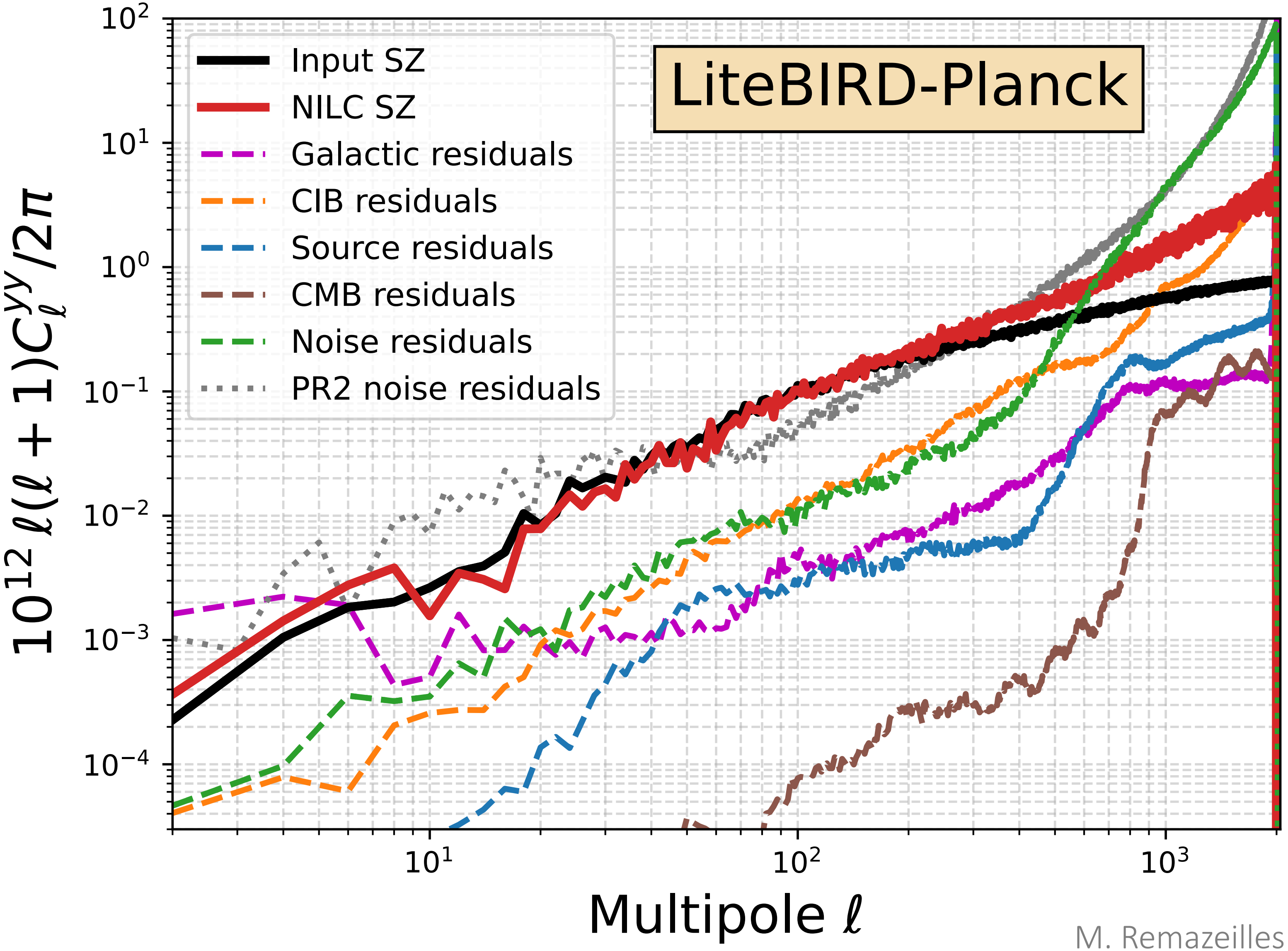
M. Remazeilles

y-map power spectrum and residuals

SZ power spectrum
and residuals

LiteBIRD + Planck

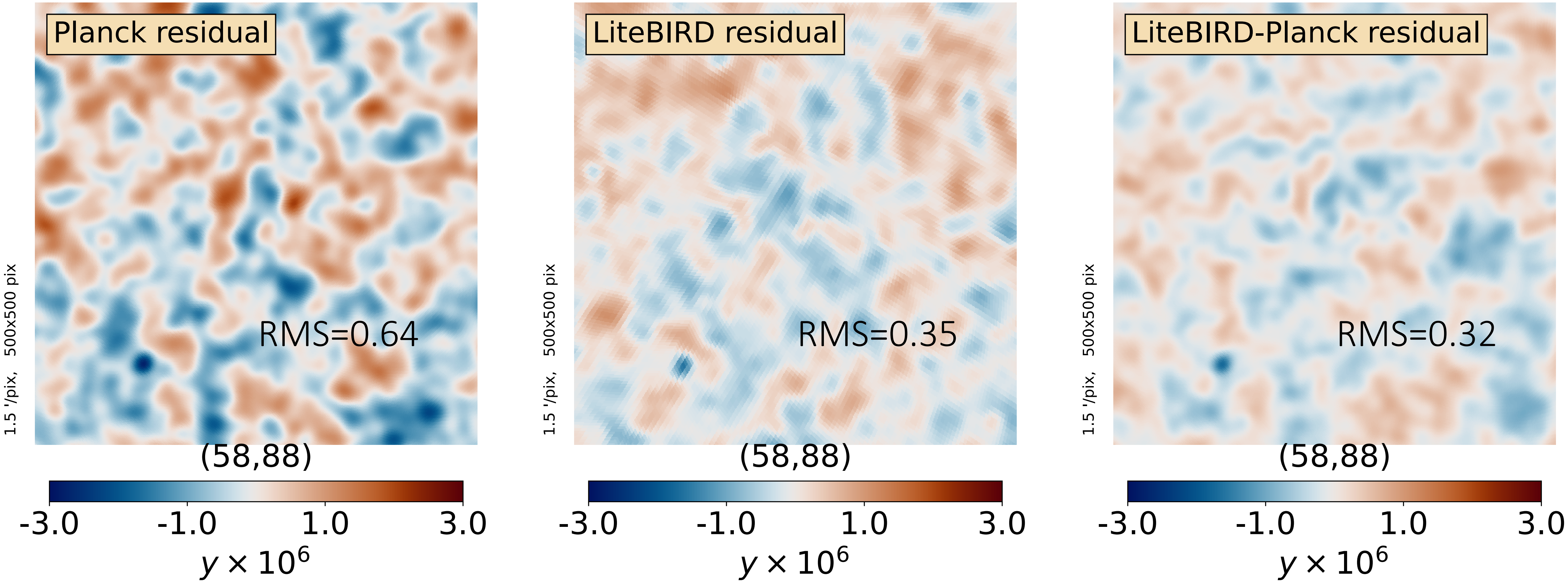
Noise and foreground residuals reduced by an order of magnitude at large and intermediate scales



JCAP 12 (2024) 026

M. Remazeilles

Comparison of residuals around Coma



Improvement in SZ map quality from Planck to LiteBIRD, and from LiteBIRD to joint LiteBIRD-Planck

JCAP 12 (2024) 026

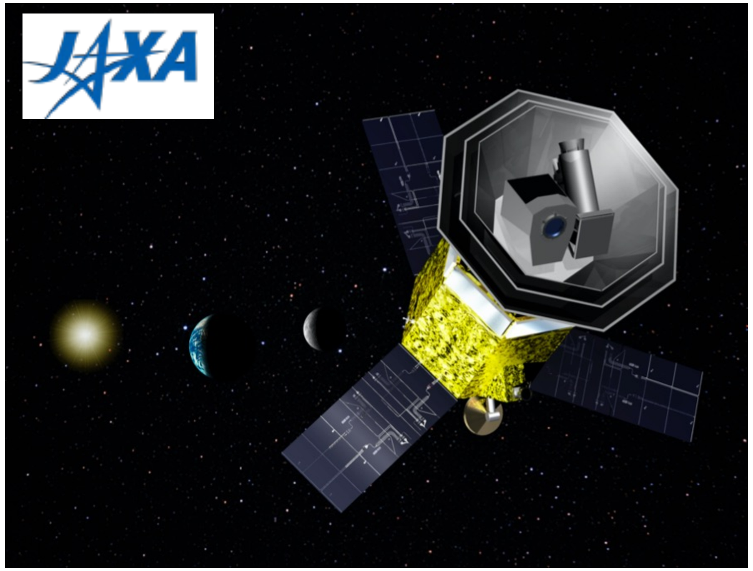
M. Remazeilles

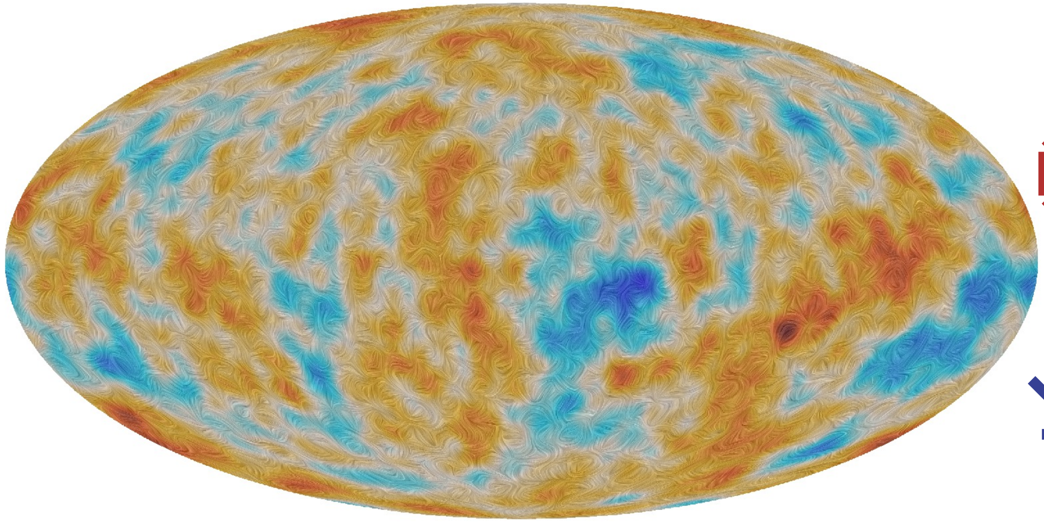
LiteBIRD overview

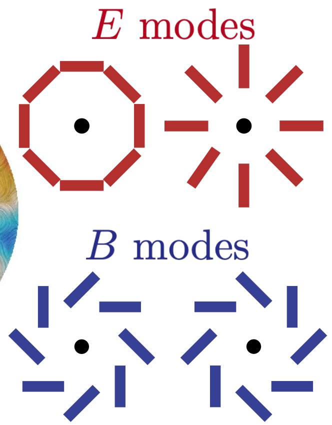
LiteBIRD reformation phase

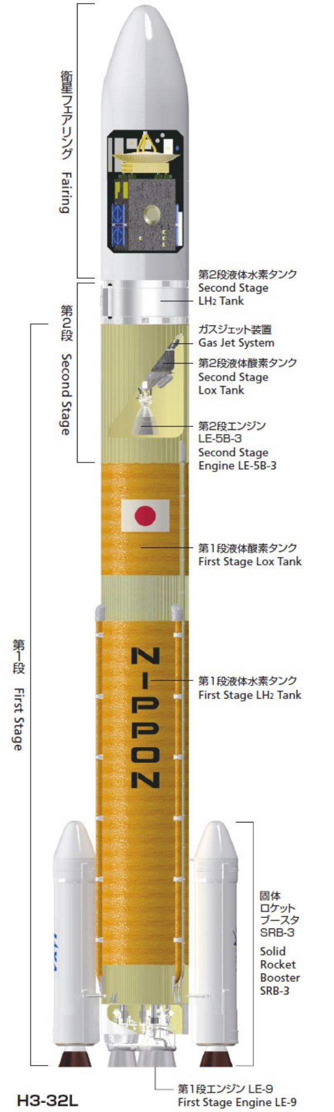
📖 LiteBIRD collaboration PTEP 2023

- After the ISAS/JAXA mission definition review, LiteBIRD is under rescope studies to consolidate the mission's feasibility with the same scientific objectives.
- The LiteBIRD collaboration will spend approximately one year (~ late 2025) on the studies of the reformation plan.

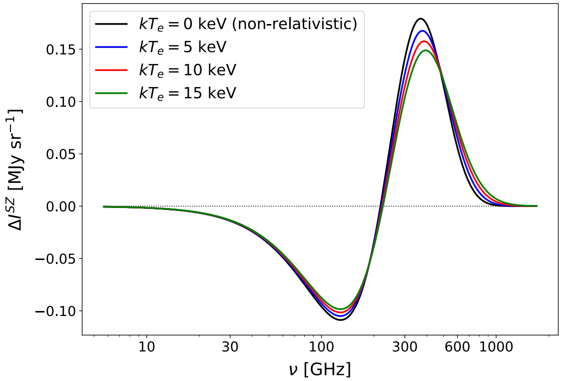








Remazeilles & Chluba, arXiv:2410.02488

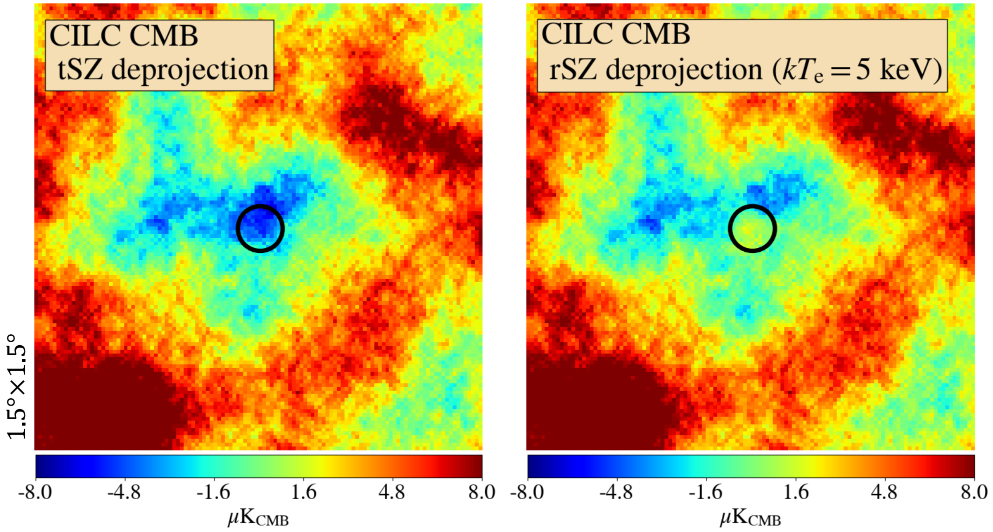


Which SED for tSZ deprojection in CMB maps?

Evidence for relativistic SZ effect in Planck CMB maps with an average cluster temperature of T_e = 5 keV

$$I_\nu^{\mathrm{rSZ}}(\vec{n}) = f(\nu,\bar{T}_e)\,y(\vec{n}) + \partial_{T_e} f(\nu,\bar{T}_e)\,y(\vec{n})(T_e(\vec{n}) - \bar{T}_e) + \cdots$$

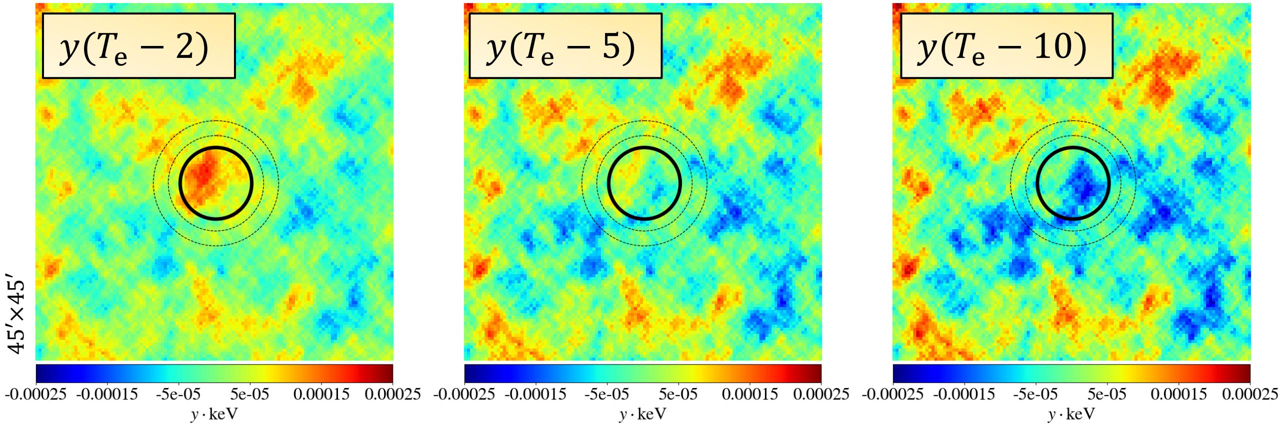
Planck SZ-free CMB maps stacked on clusters



tSZ deprojection
(T_e = 0, non-relativistic)

rSZ deprojection
(T_e = 5 keV, relativistic)

Planck rSZ moment maps stacked on clusters for different pivot $\bar{T}_e$



Increment
$\Longrightarrow T_e > 2$ keV

Null
$\Longrightarrow T_e \simeq 5$ keV

Decrement
$\Longrightarrow T_e < 10$ keV

Application of Remazeilles & Chluba, MNRAS (2020) to Planck data