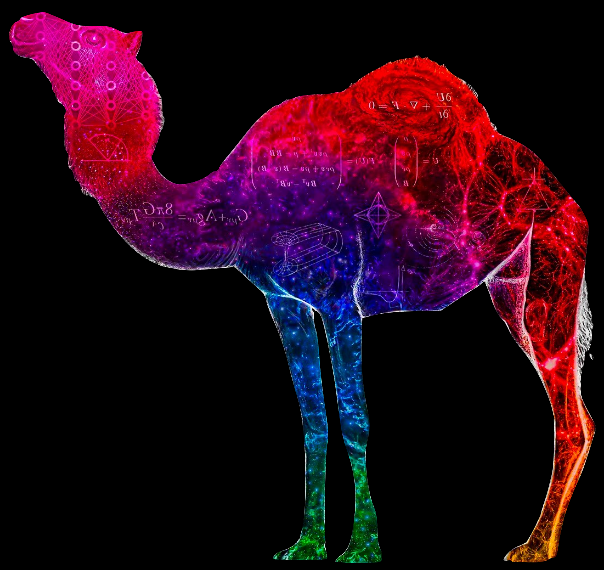
REVISITING FIRAS IN 2025: BARYONIC FEEDBACK CONSTRAINTS FROM CMB SPECTRAL DISTORTIONS

GIULIO FABBIAN

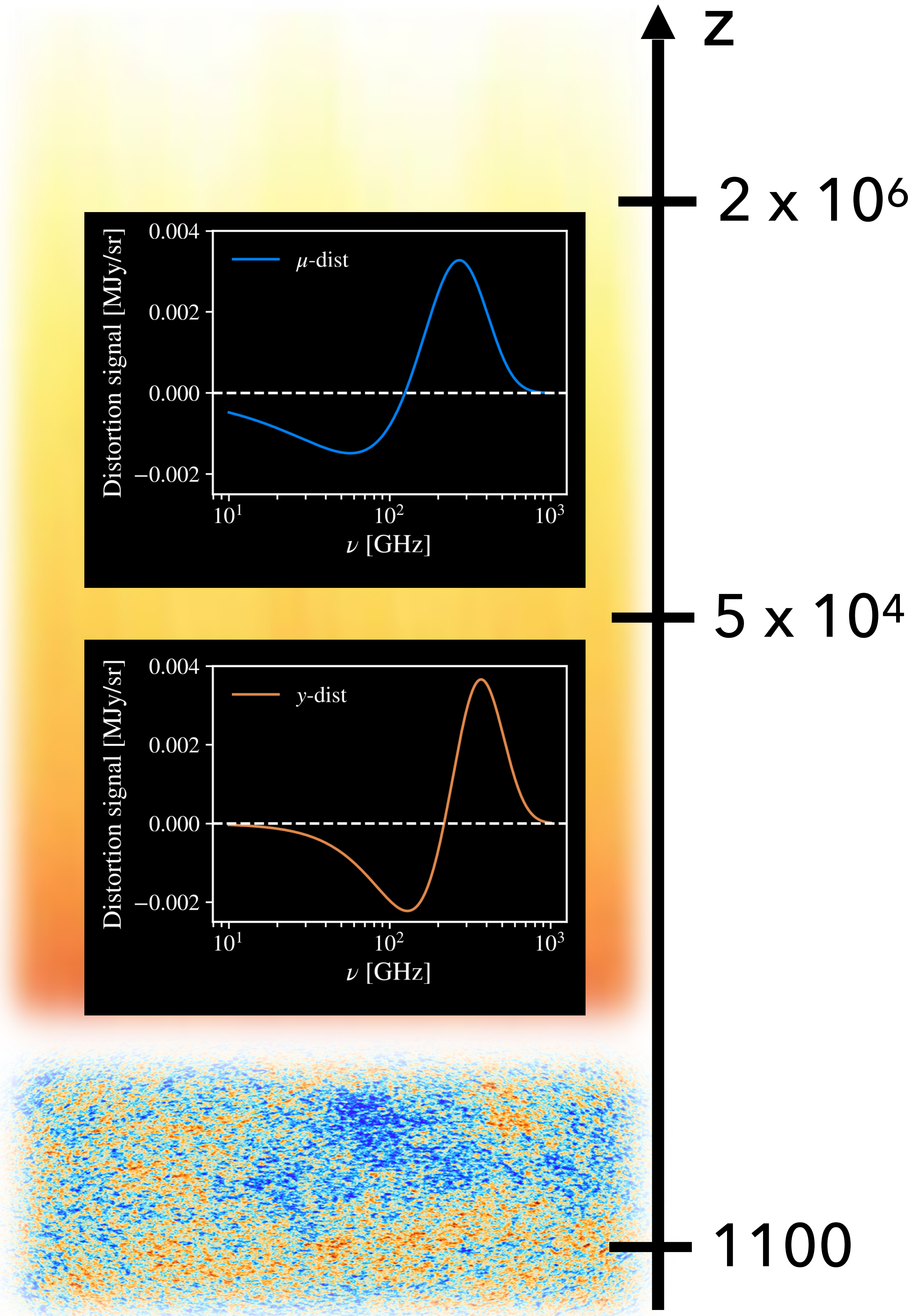
CNRS @ INSTITUTE D'ASTROPHYSIQUE SPATIAL

WITH F. BIANCHINI (STANFORD), A. SABYR, C. HILL (COLUMBIA),
C. LOVELL (KICC CAMBRIDGE), L. THIELE (IPMU)



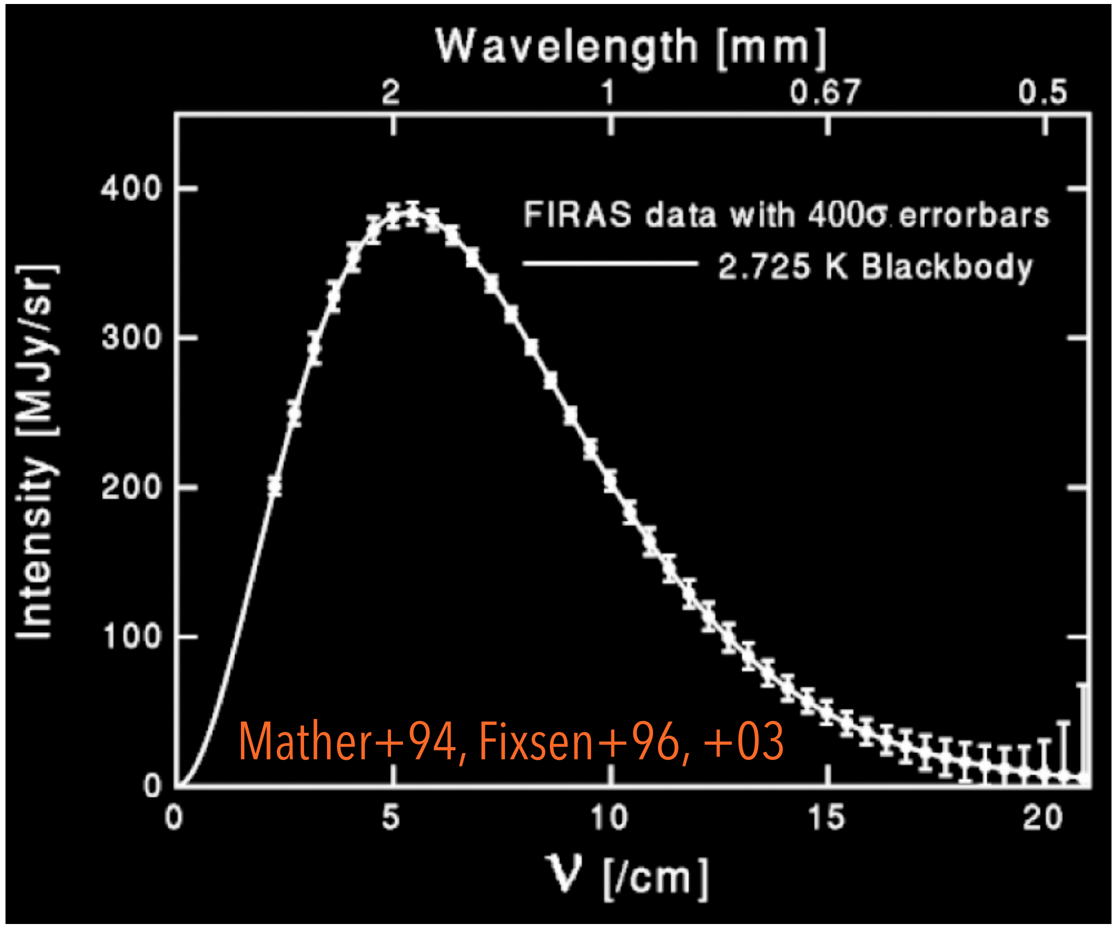
BASED ON
ASTRO-PH:2508.04593 & OUT SOON

A brief thermal history of the universe



- $z >> 10^6$ Compton scattering and brehmsstralung establish thermal equilibrium and perfect BB spectrum.
- After $z \sim 10^6$ energy injection in the plasma will not thermalize anymore and leave imprint in the CMB spectrum.
- μ distortions monopole will constraint energy releases, particle decays and small scale perturbations in the early universe.
- y distortions will probe reionization and structure formation from e.g. SZ power spectra.

Constraints on distortions

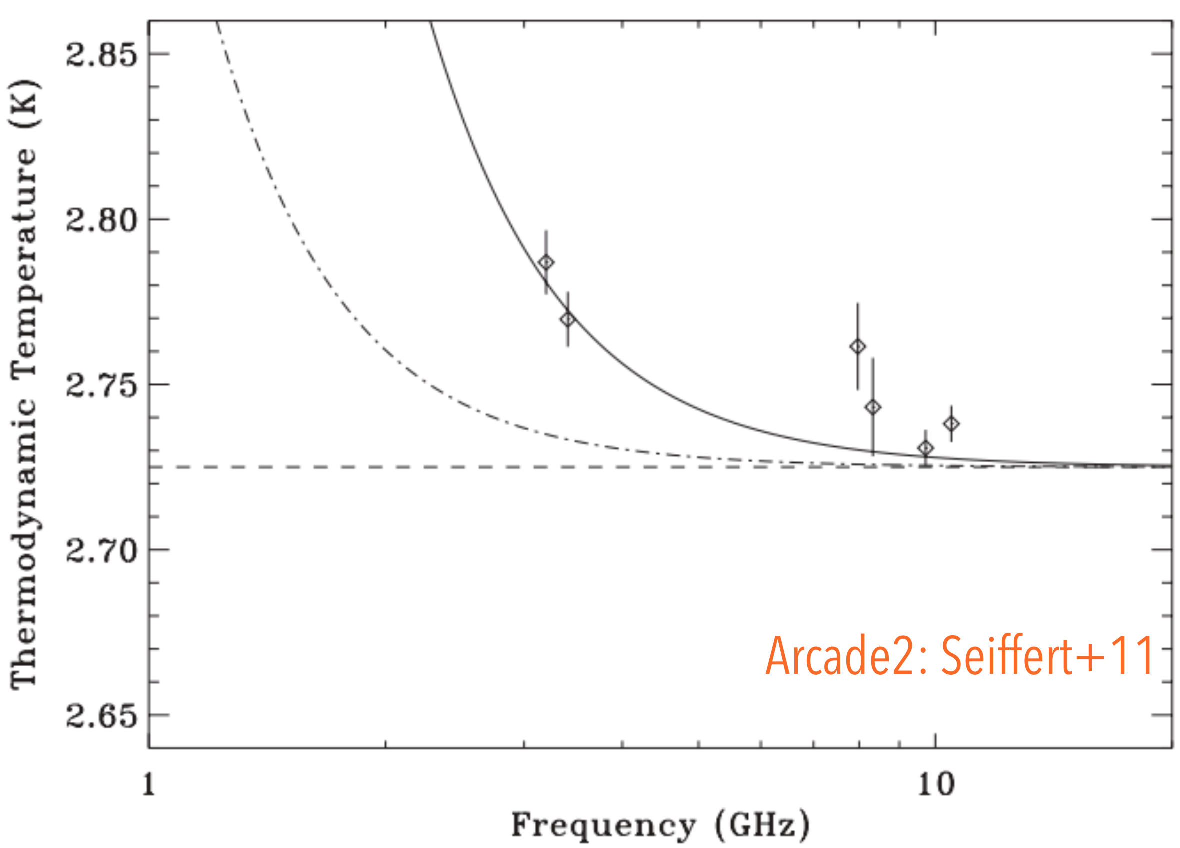


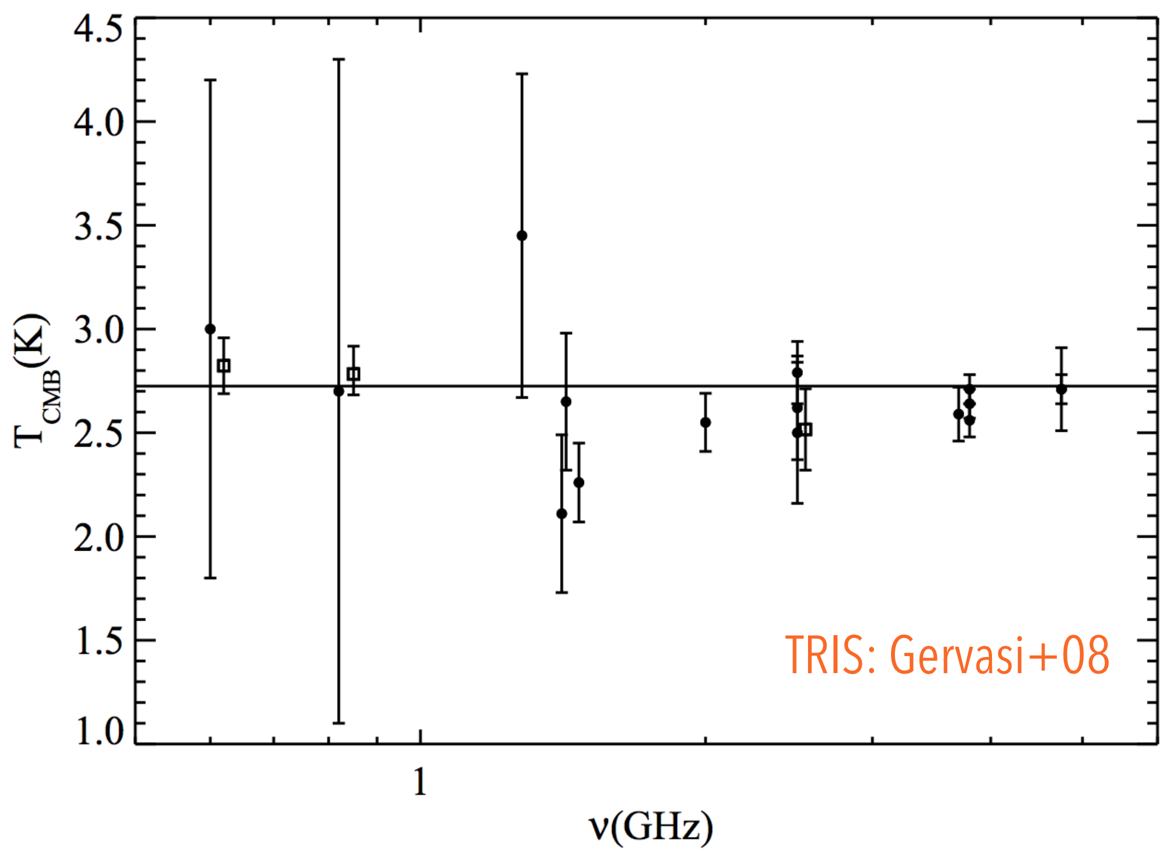
- Limited improvements after FIRAS

$$|\langle\mu\rangle| \lesssim 90\times10^{-6}, |\langle y\rangle| \lesssim 15\times10^{-6}$$

$$\langle y\rangle = (-1 \pm 6 \text{ stat.} \pm 4 \text{ syst.})\times10^{-6}$$

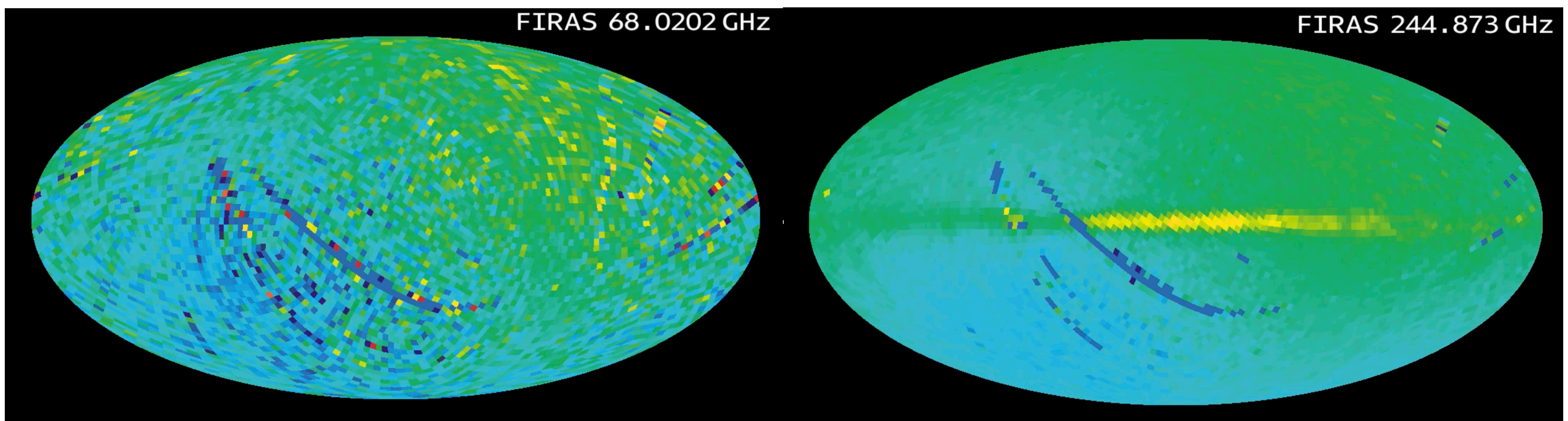
- ARCADE, TRIS: improved at $\nu \lesssim 10$ GHz questions on foreground/systematics remain.
- No new experiment: we're stuck with FIRAS!

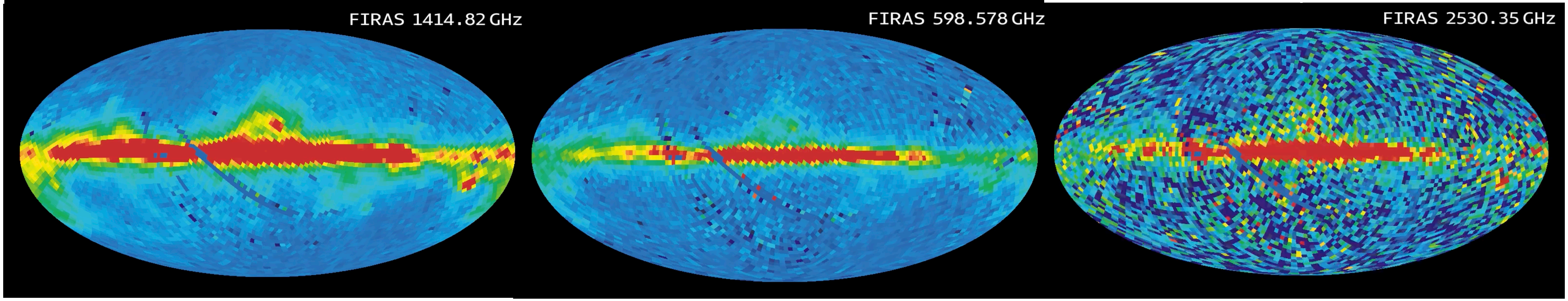




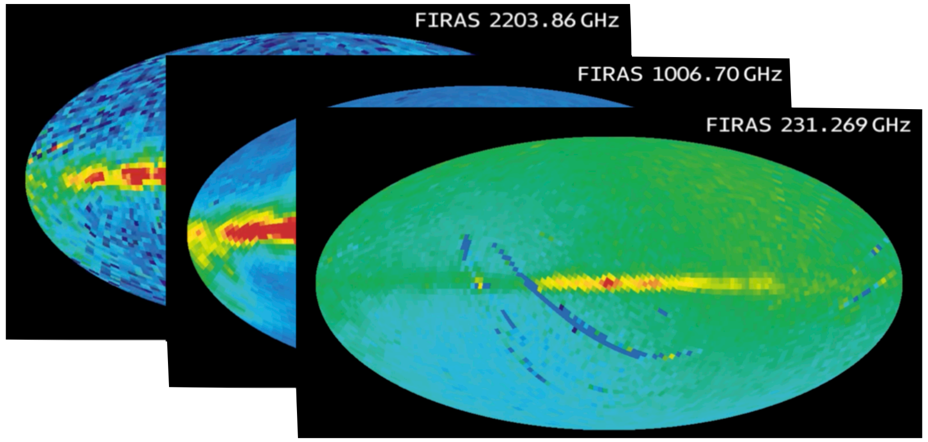
FIRAS data are more than a spectrum

- 170 frequency channels maps. Can we do a better analysis based on modern techniques and what we have learned in the meantime?





Analyzing the FIRAS data cube: FIRAS approach



Original FIRAS Fixsen+ (1996)

For each frequency

$\nu \lesssim 600$ GHz

$$I_\nu(\hat{\mathbf{n}}) = B_\nu + D_\nu \hat{\boldsymbol{\beta}} \cdot \hat{\mathbf{n}} + \sum_i A_\nu^{FG,i} I^{FG,i}(\hat{\mathbf{n}})$$

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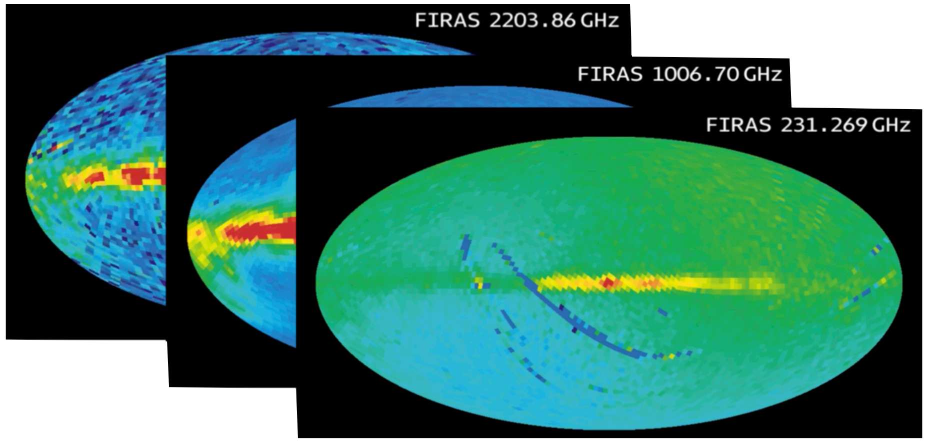

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Least-square fitting

$$B_\nu = B_\nu(T_0) + \Delta T \frac{\partial B_\nu}{\partial T} + \mu \left.\frac{\partial B_\nu}{\partial \mu}\right|_{\mu=0} + G_0 g(\nu)$$

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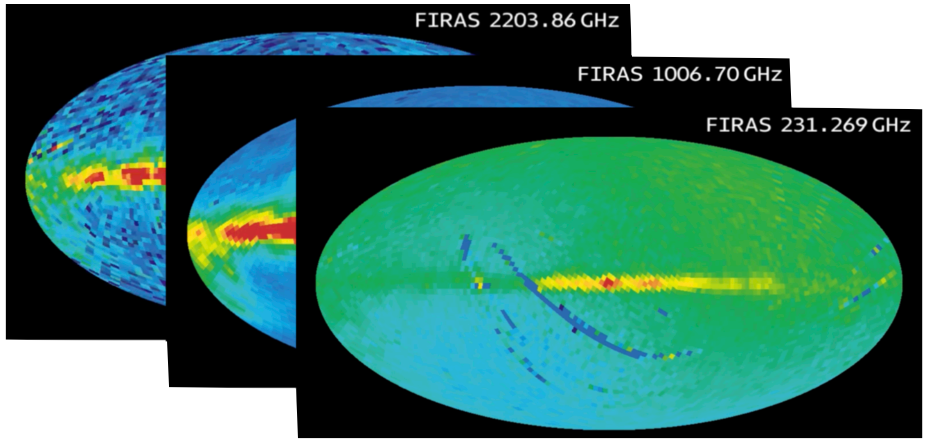

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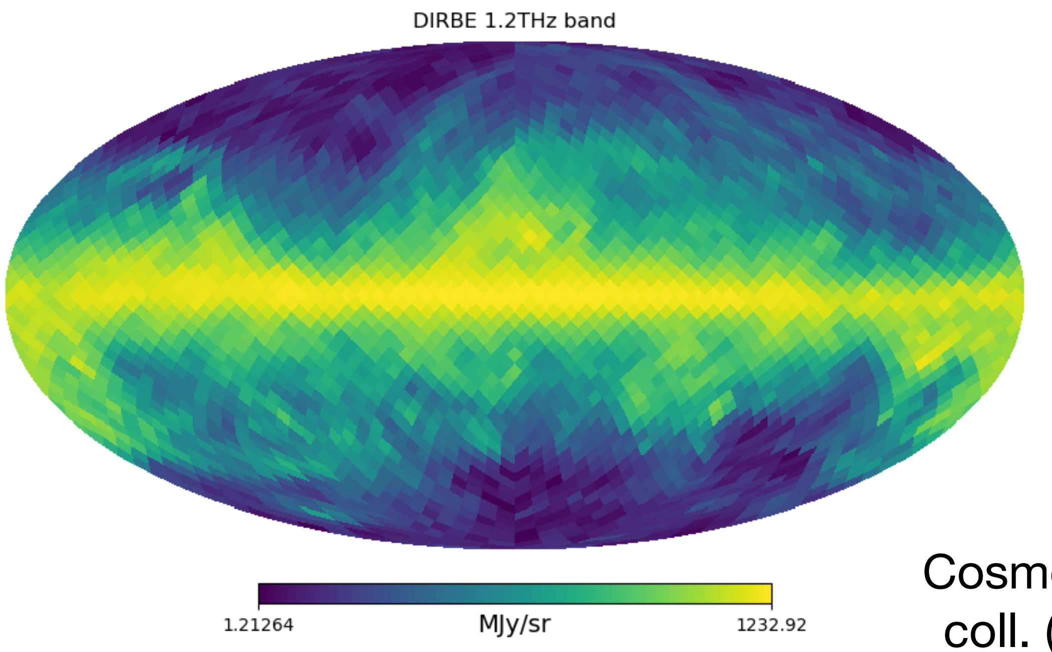
- We revisited the original FIRAS analysis trying to address several shortcomings
- Template fitting component separation: sensitive to systematics, noise and reliability.



Cosmoglobe coll. (2024)

- Linearized distortion nearly fully degenerate with other parameters (e.g. CMB).

FIRAS: a fully correlated data set

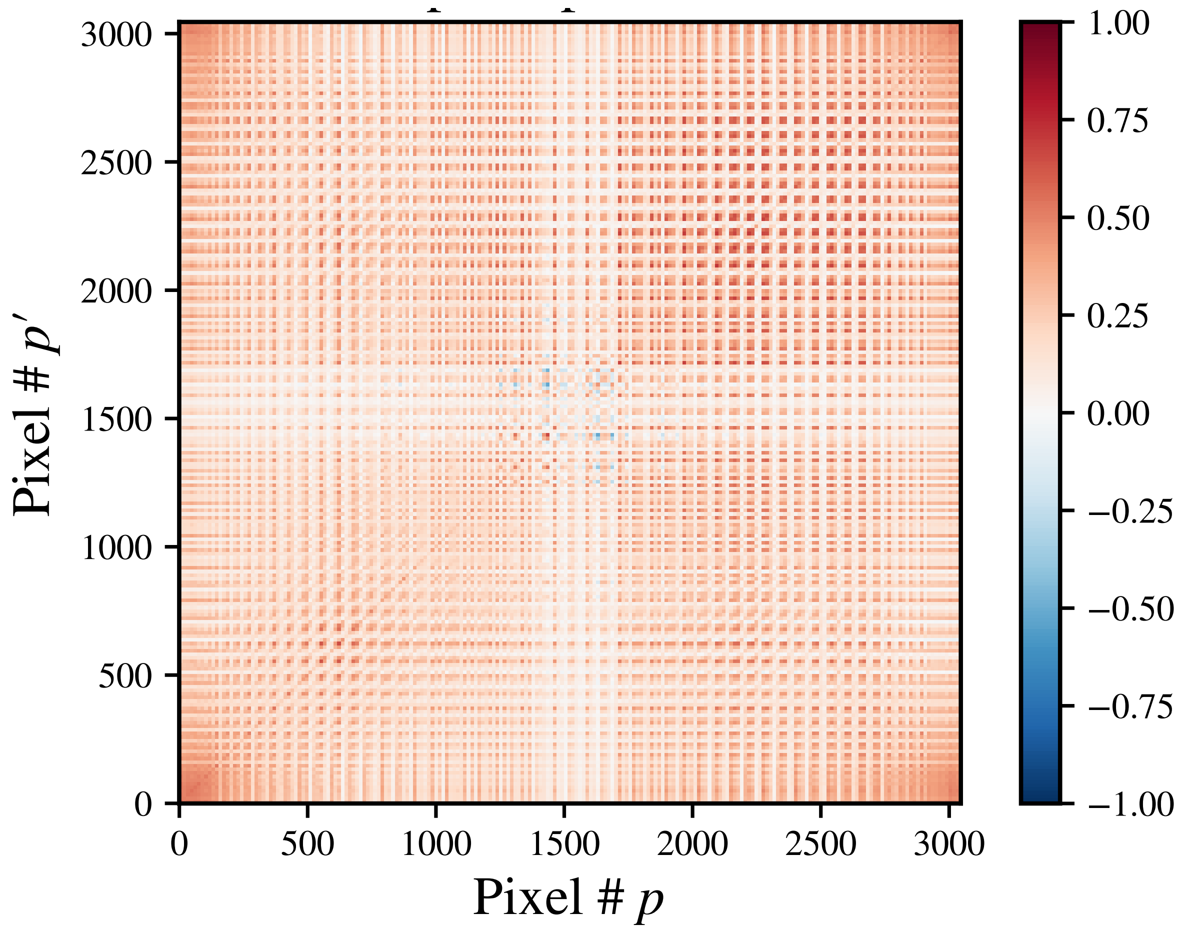
- Measurements correlated in pixel and frequency space (“unusual" regime)

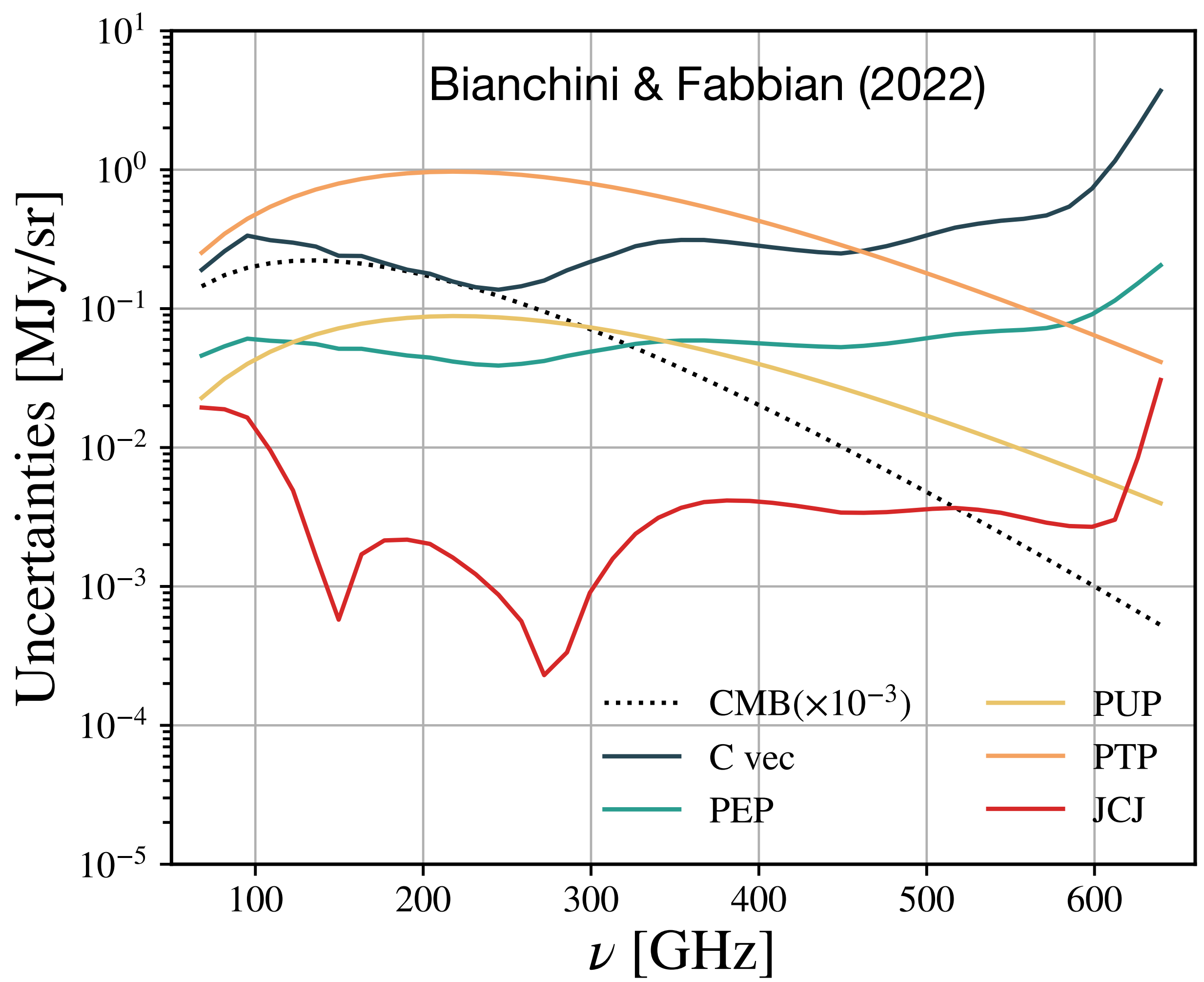
Noise correlation **Sky variation** **Calibrator emissivity**

$$\mathbb{C}^{FIRAS}_{\nu p \nu' p'} = C_{\nu\nu'} P_{pp'} + S_{p\nu} S_{p'\nu'} \left(J_\nu J_{\nu'} + G_\nu G_\nu \delta_{\nu\nu'} \right) + \partial_T B_\nu \partial_T B_{\nu'} \left(U^2 \delta_{pp'} / N_p + T^2 \right) .$$

FFT **Destriping** **Calibration errors** **Calibrator systematics**

$$P_{pp'} \equiv \delta_{pp'}/N_p + \beta^p_k \beta_{p'k} + 0.04^2,$$

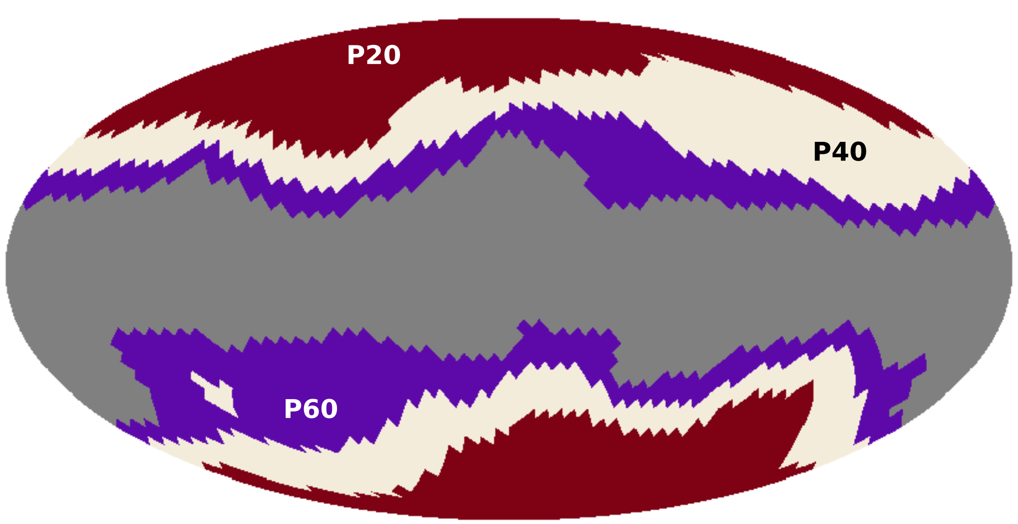




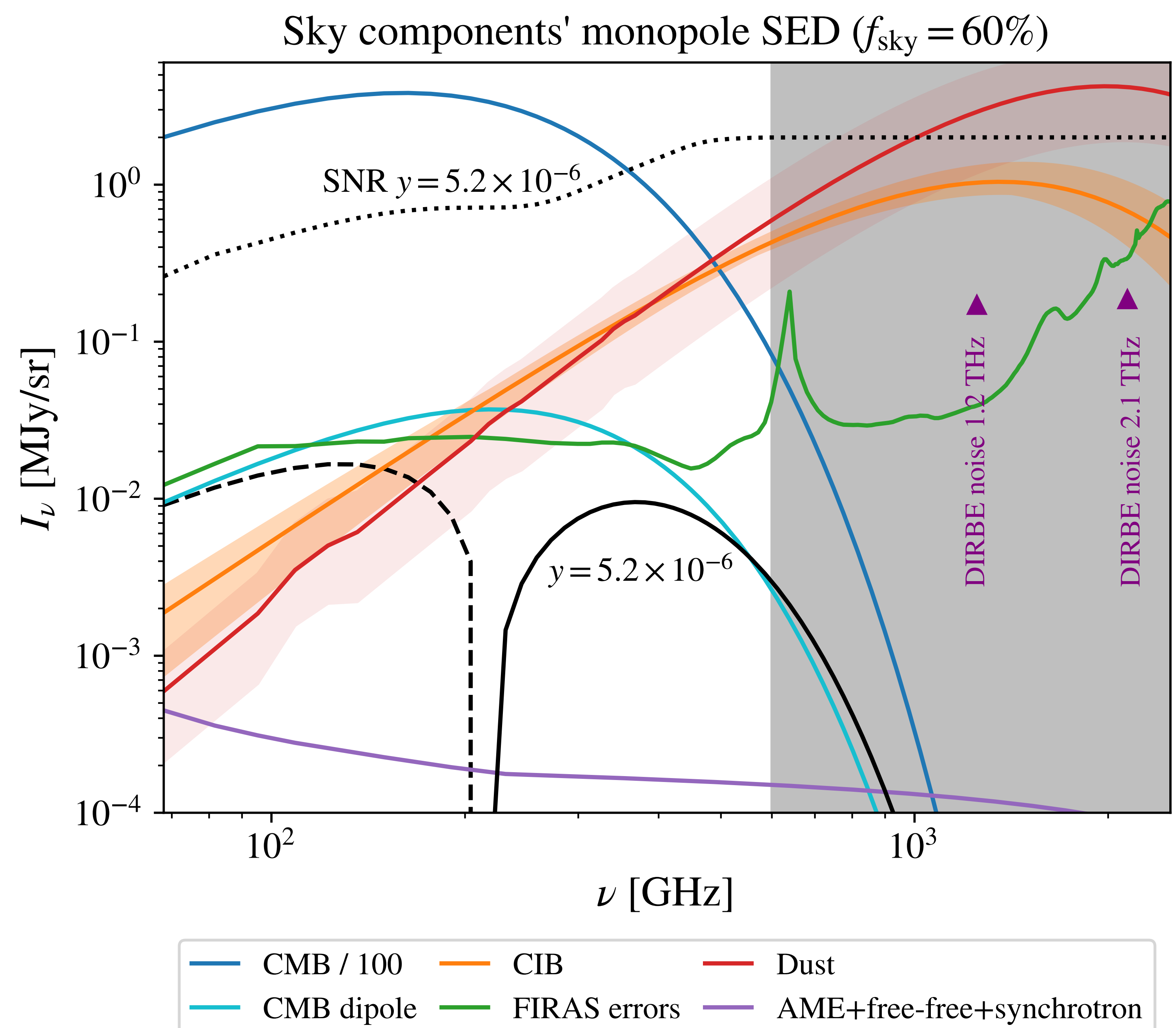
The foreground challenge

- Spectral distortions are weak and foregrounds are ~100x brighter even on clean sky regions.

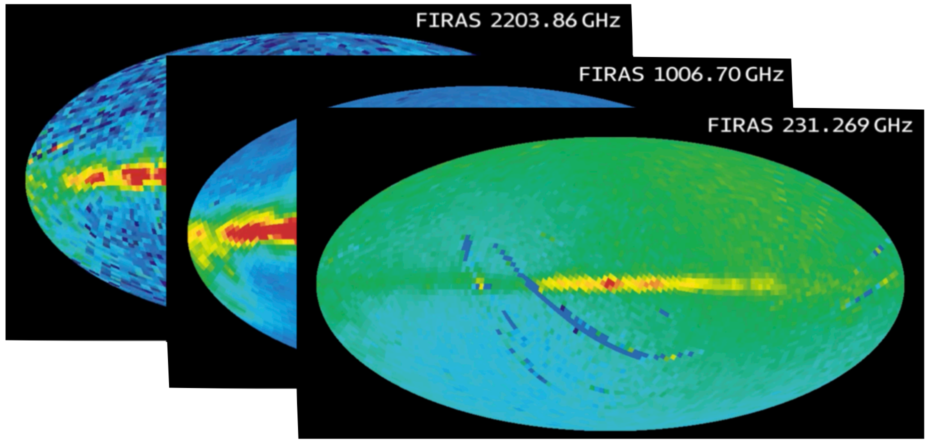
  - DIRBE noise comparable to FIRAS…



Sabyr+ (2025)
Fabbian+(2025 in prep.)
Bianchini & Fabbian (2022)



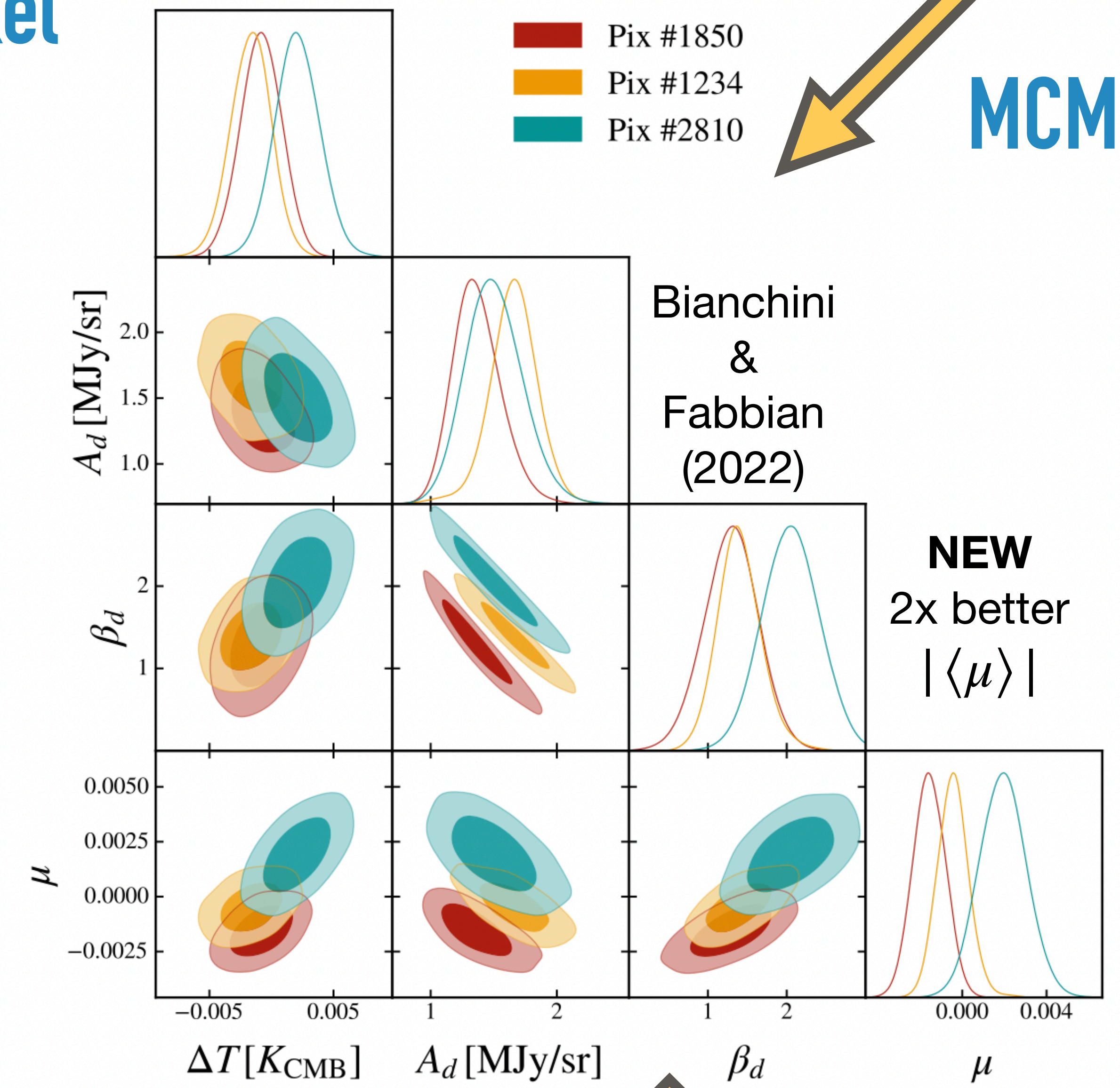
Analyzing the FIRAS data cube: our approaches



$$I_\nu(\hat{\mathbf{n}}) = B_\nu(T_0, \mu(\hat{\mathbf{n}})) + \Delta T(\hat{\mathbf{n}}) \frac{\partial B}{\partial T}\bigg|_{T_0} + I^{FG}(\boldsymbol{\theta}^{FG}, \hat{\mathbf{n}})$$

Pixel-by-pixel

MCMC



Parameters' maps $\{\langle\mu\rangle, \langle y\rangle, \ldots\}$

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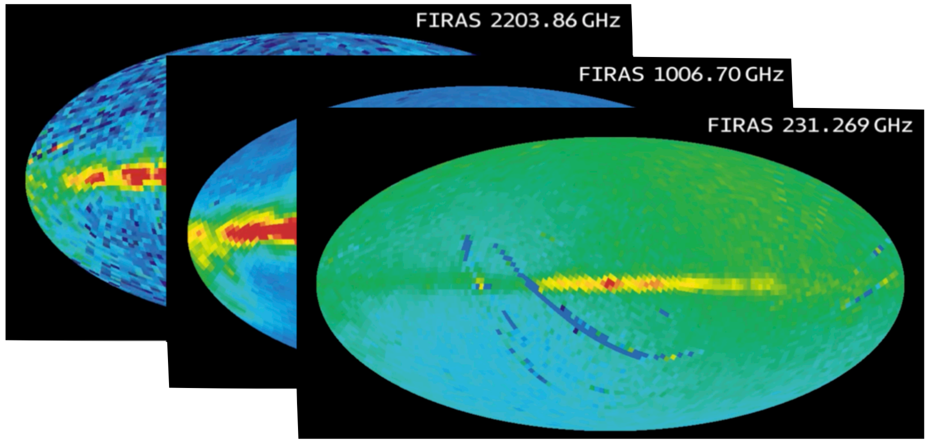

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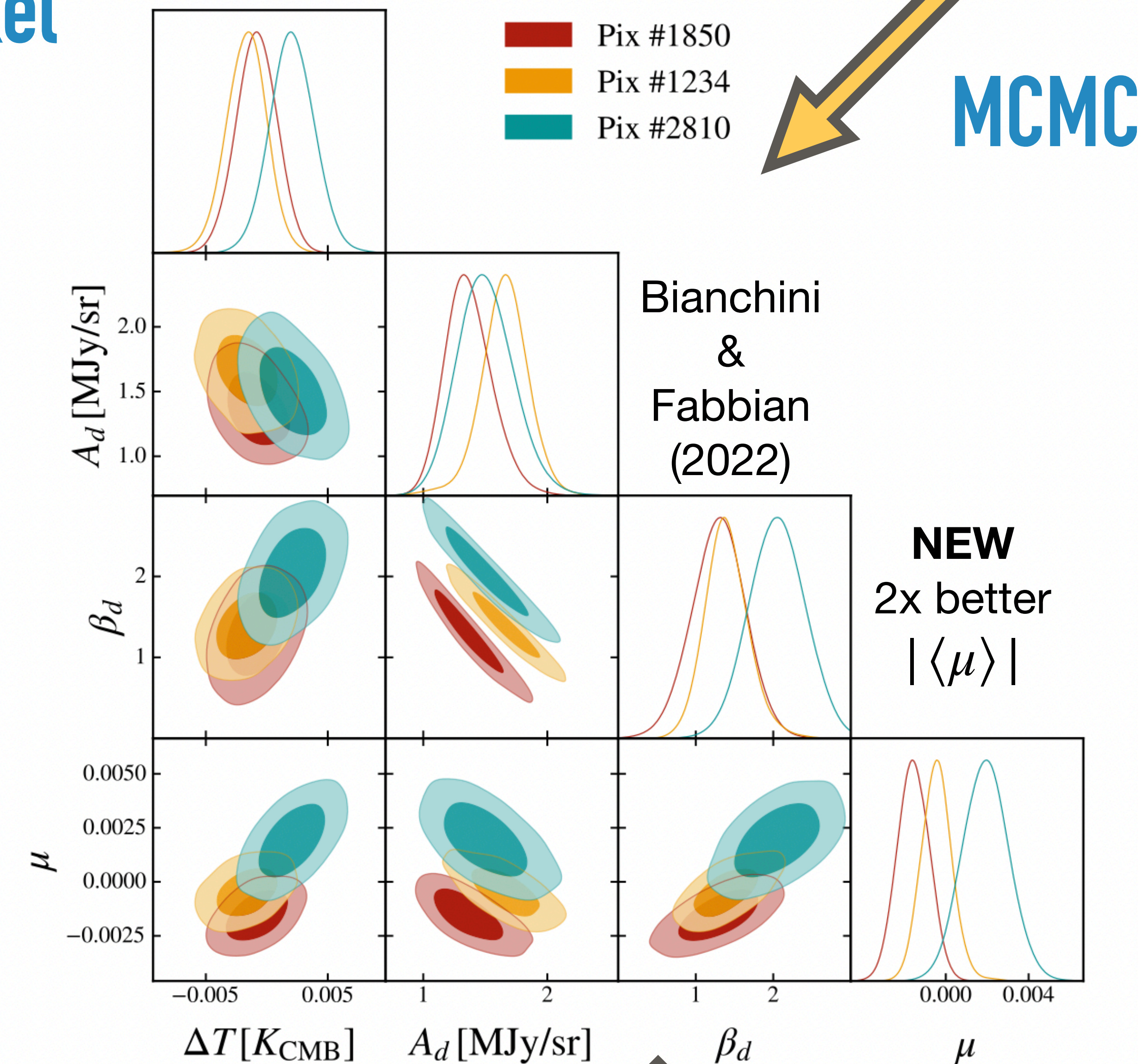


Parameters' maps → $\{\langle\mu\rangle, \langle y\rangle, \ldots\}$

Monopole modeling

Spatial mean

$$\langle I_\nu \rangle = B_\nu(T_0) + \langle \Delta T \rangle \frac{\partial B}{\partial T} + \langle I_\nu^{SD} \rangle + \sum_i \langle I^{FG,i} \rangle$$

MCMC

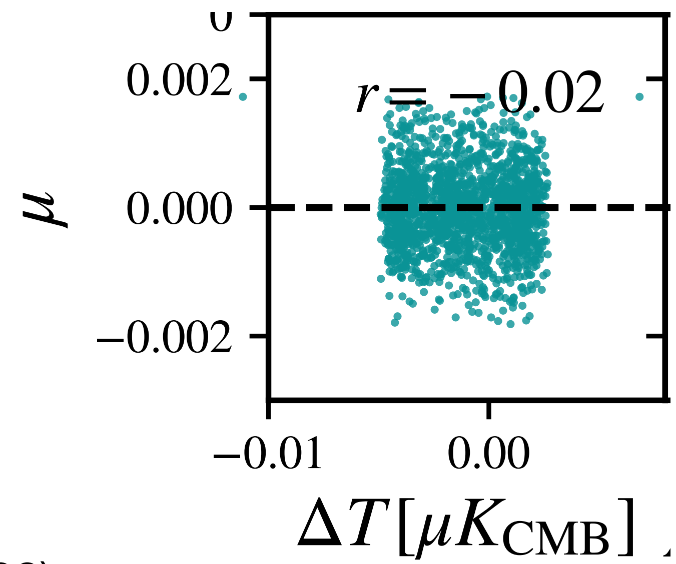
$$\boldsymbol{\theta} = \{\langle \Delta T \rangle, \langle y \rangle, \langle \mu \rangle, \ldots\}$$

Reference forecasting tool Abitbol+ (2017)

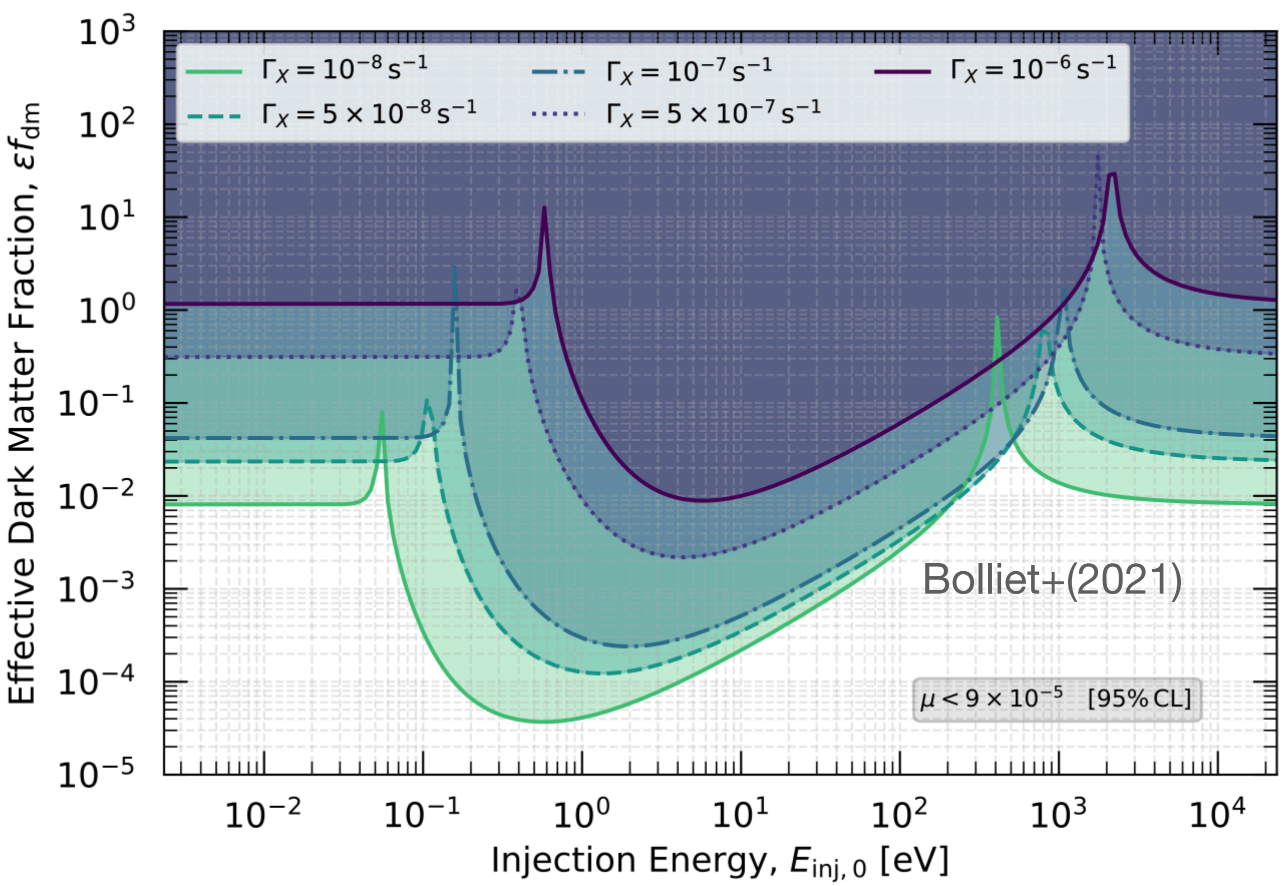
An important update!

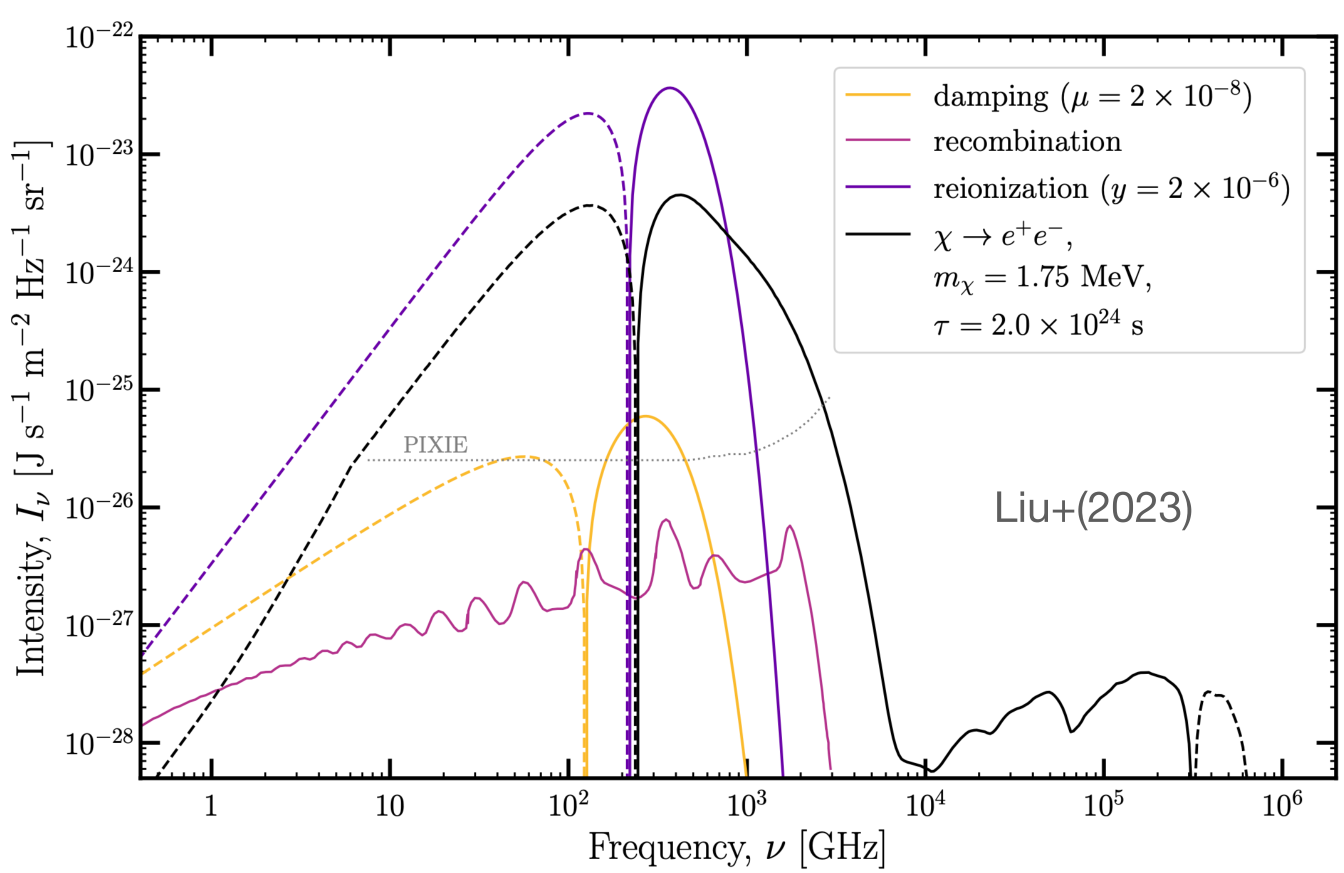
- 2x improved upper limit on the μ distortion monopole after ~25 years!

$\lvert\langle\mu\rangle\rvert < 95\%$ C.L. $[\times 10^{-6}]$	PL90	PL80	PL60	PL40	σ_{syst}
$A_d + \beta_d$	< 47	< 51	< 47	< 53	2.5
A_d, fixed β_d	< 74	< 50	< 105	< 179	48
$A_d + A_s$	$< \mathbf{252}$	< 200	< 162	< 102	54
$A_d + A_{ff}$	$< \mathbf{174}$	< 120	< 96	< 118	47
FIRAS residual	< 72	< 57	< 89	< 147	34



Bianchini, Fabbian (2022)

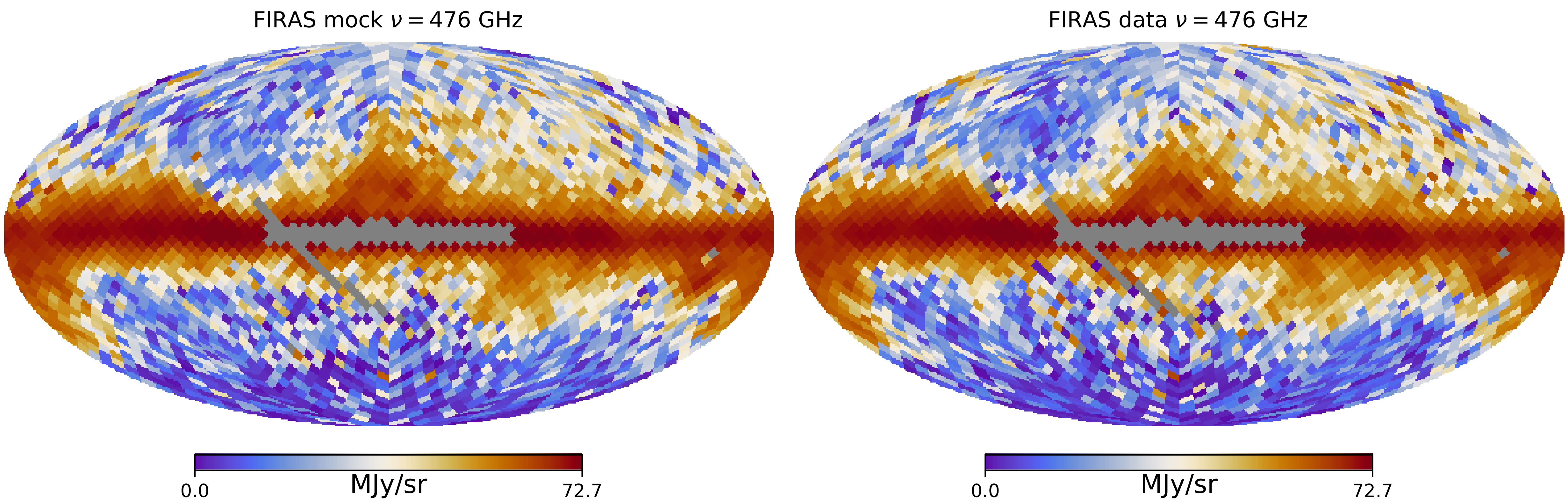




Robustness of component separation methods

- What is the best, most robust way to measure <y>?
    - CIB needs to be handled with great care.
- We built realistic mocks based on state of the art sky models.
- Compare approaches capable to exploit foreground properties and FIRAS frequency coverage.

A. Sabyr, C. Hill (Columbia),
F. Bianchini (KIPAC)

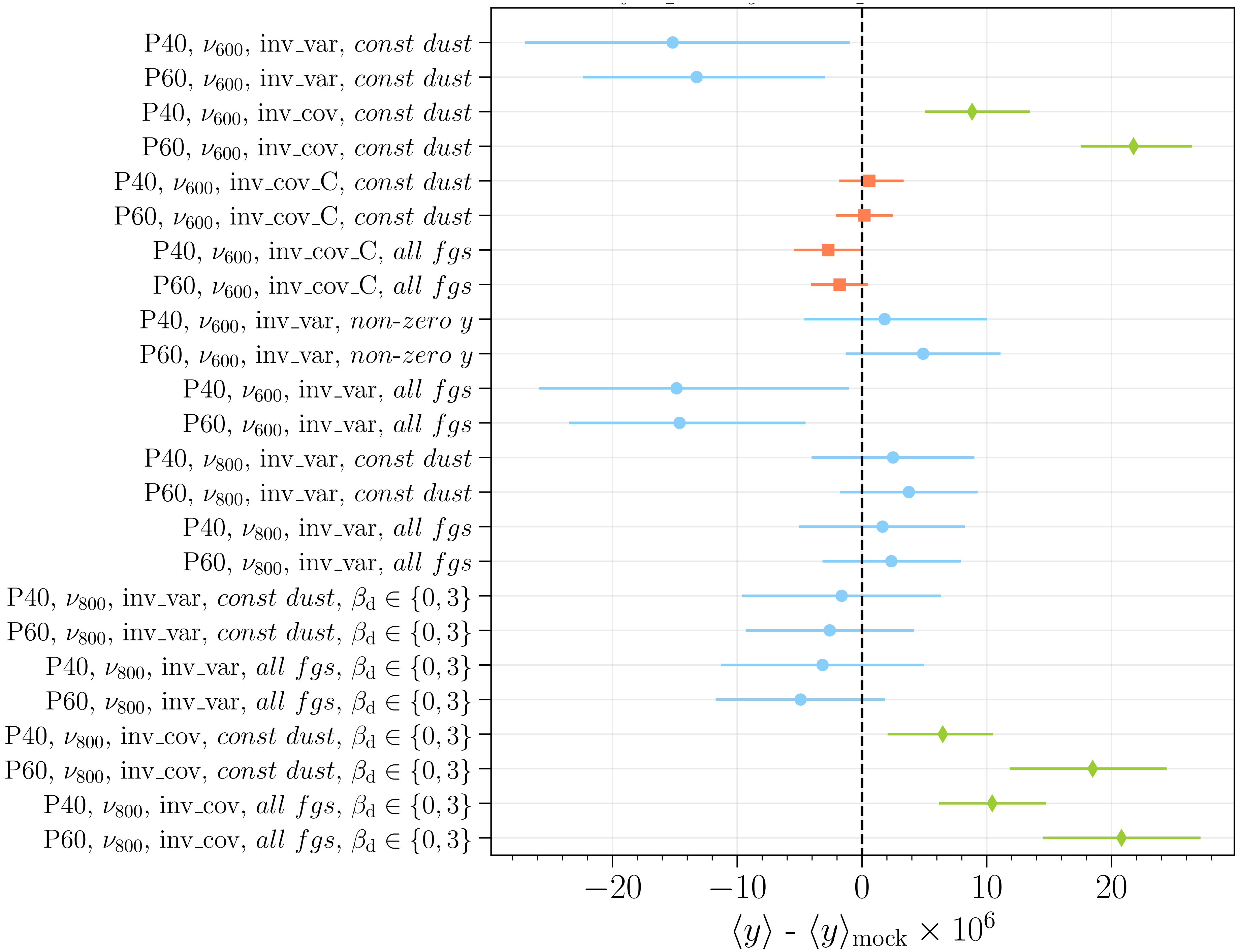


A. Sabyr, GF + (2025)

Mock data results (monopole method)

- We weight the mocks as we do with the data and investigate setup variations.

- Baseline $\{\Delta T, \langle y \rangle, A_d, \beta_d, T_d\}$, $T_d \in \{0,100\mathrm{K}\}$, different priors for β_d.



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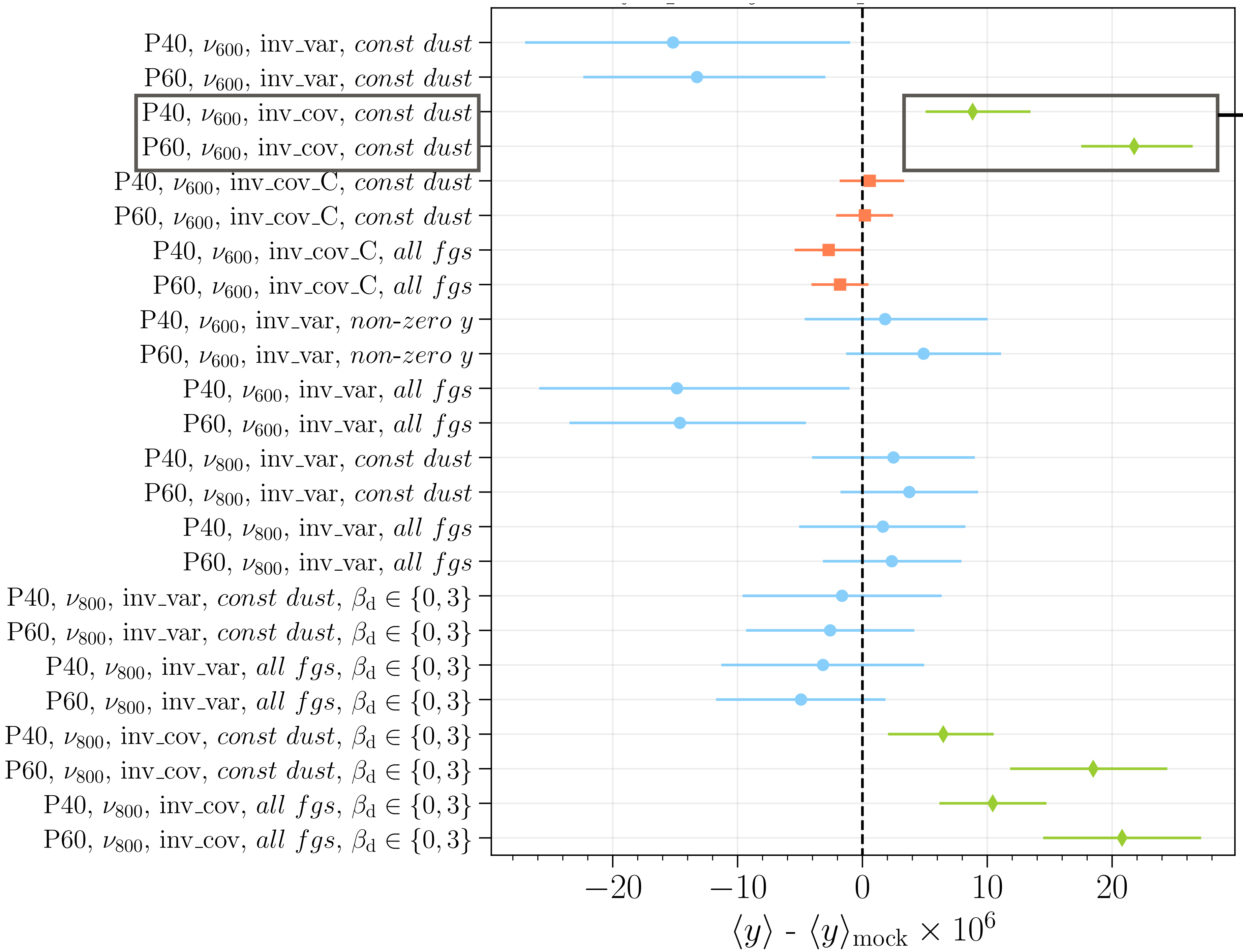

FIRAS pixel-pixel covariance is problematic

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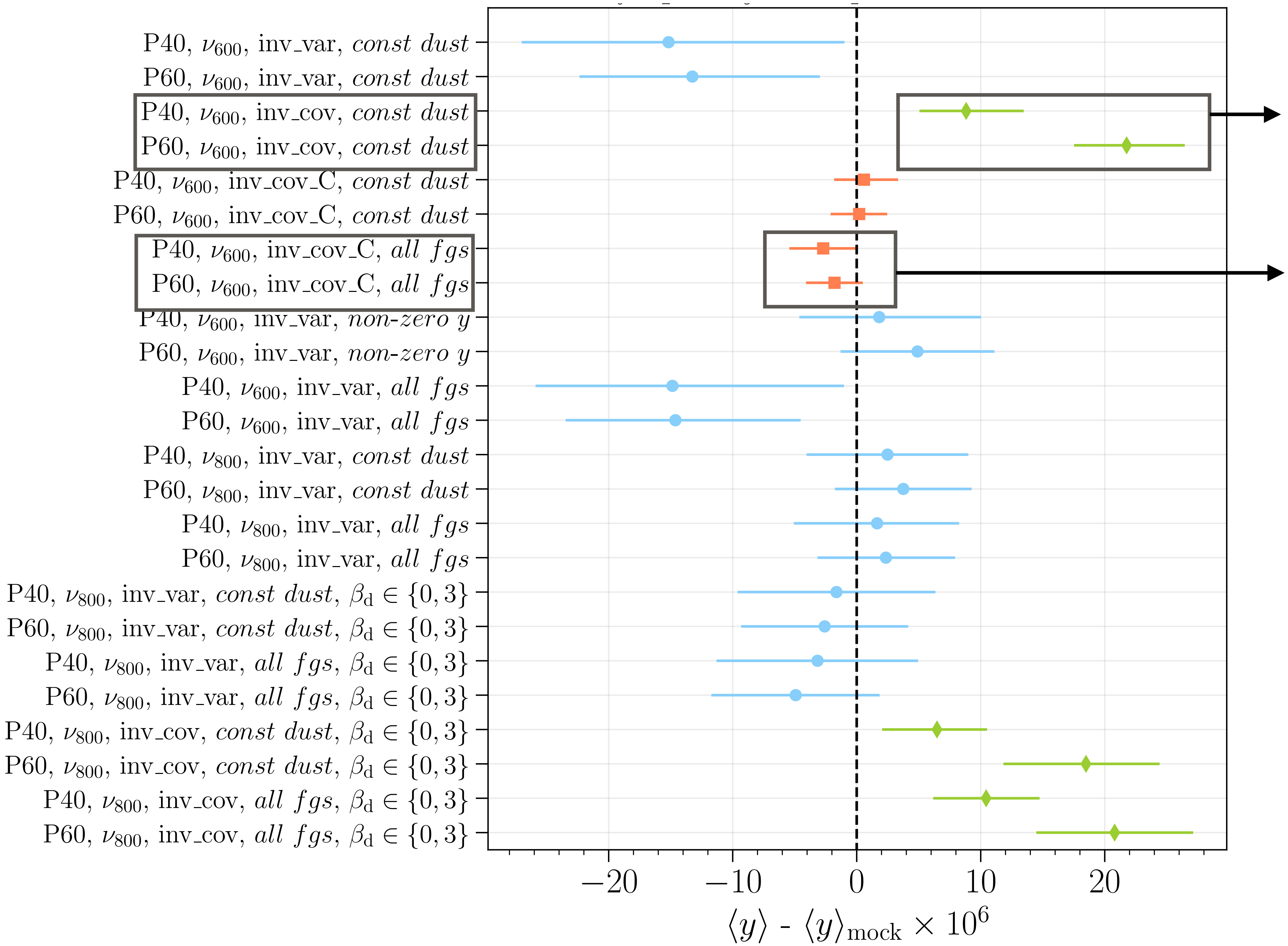

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No foreground residual with matching data model.

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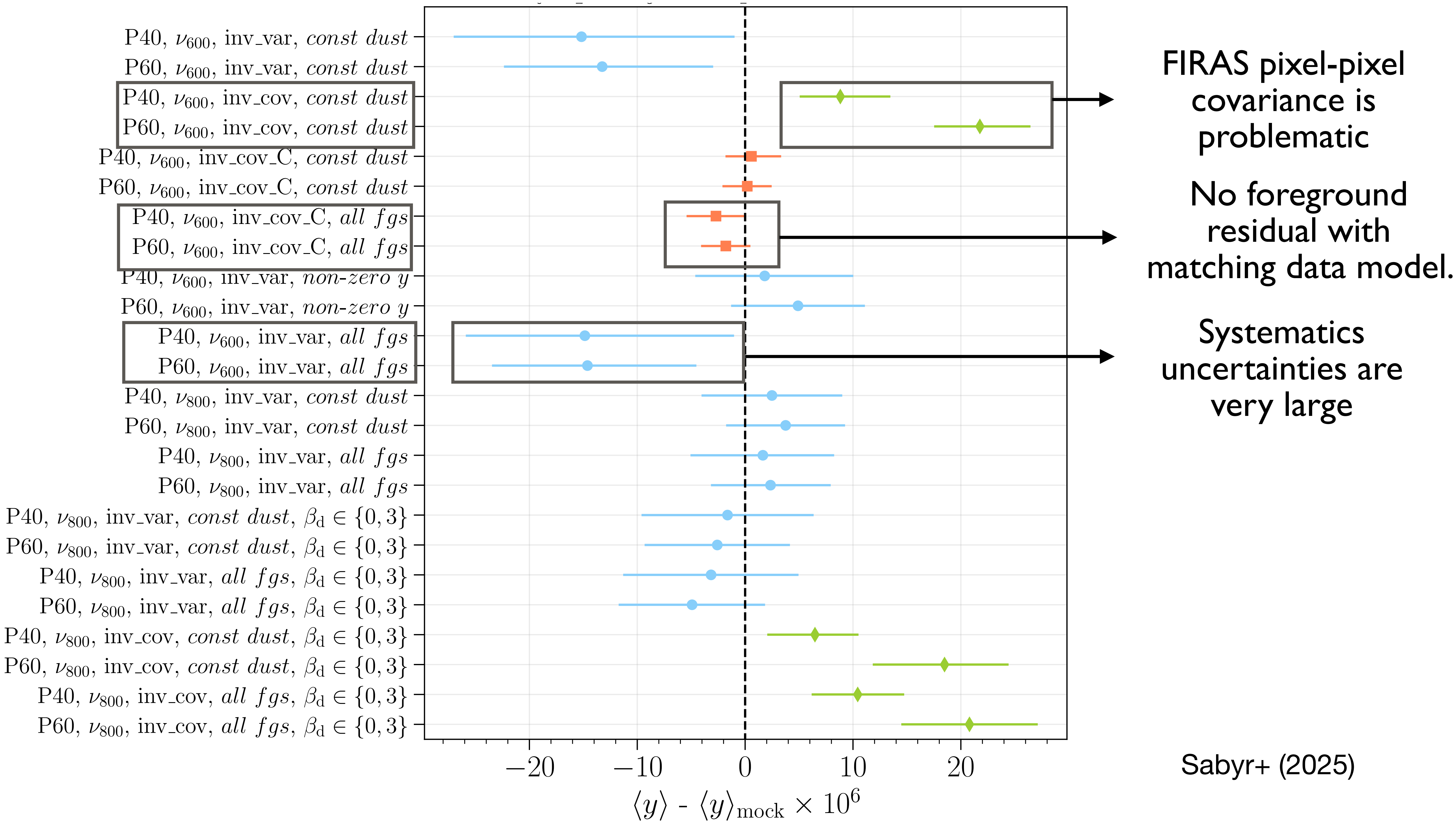

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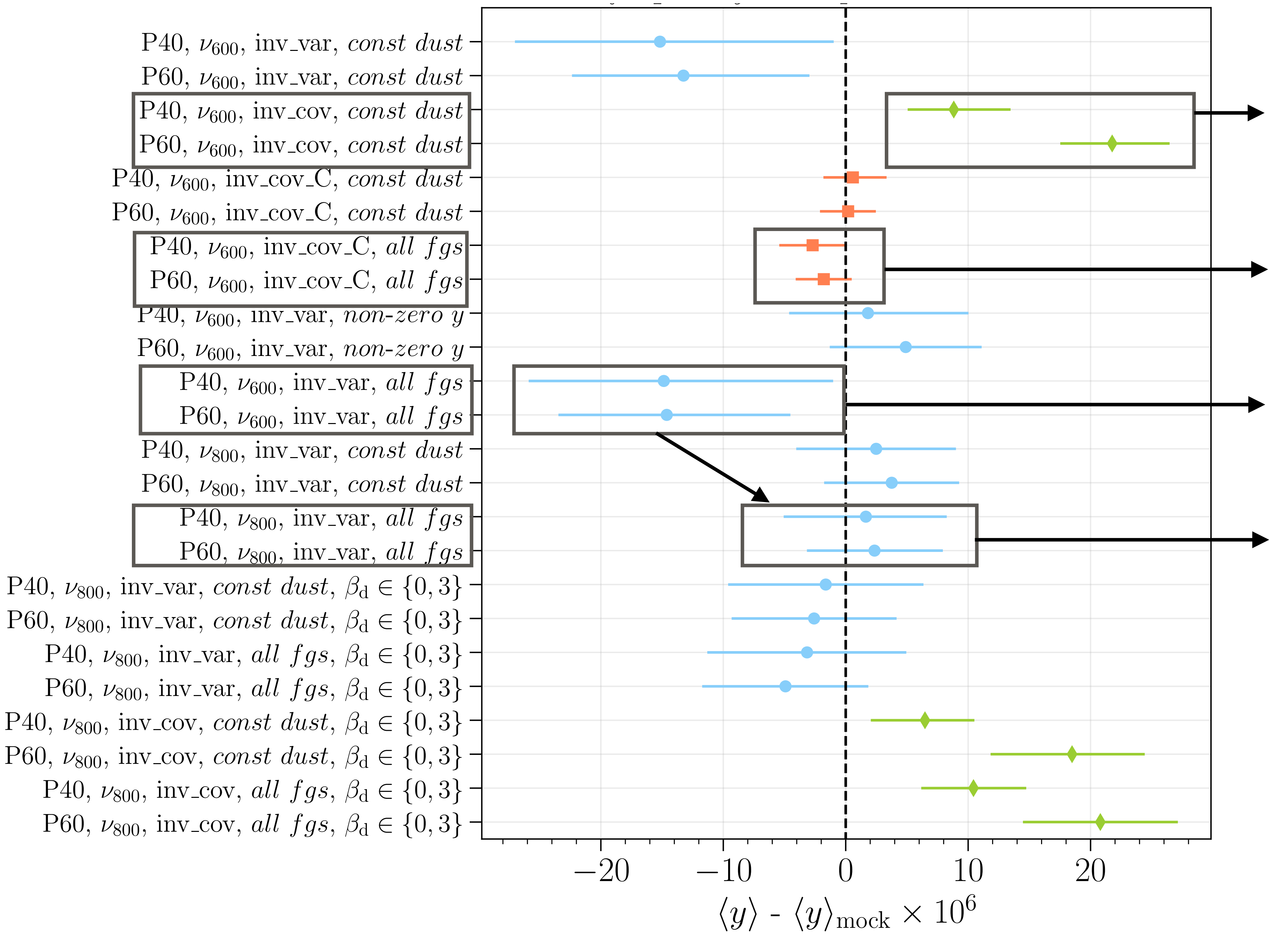

FIRAS pixel-pixel covariance is problematic

No foreground residual with matching data model.

Systematics uncertainties are very large

High-frequency can help

Sabyr+ (2025)

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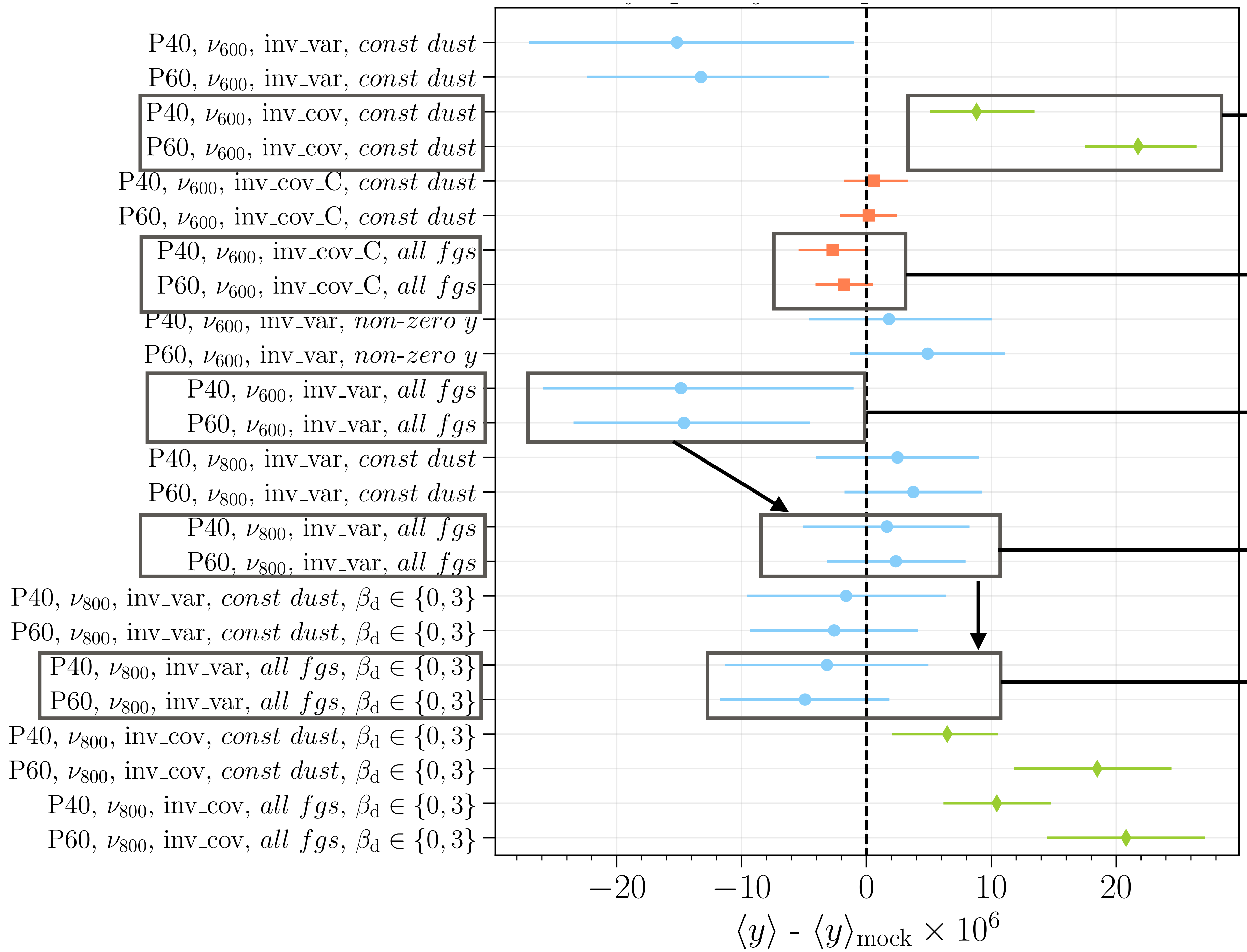

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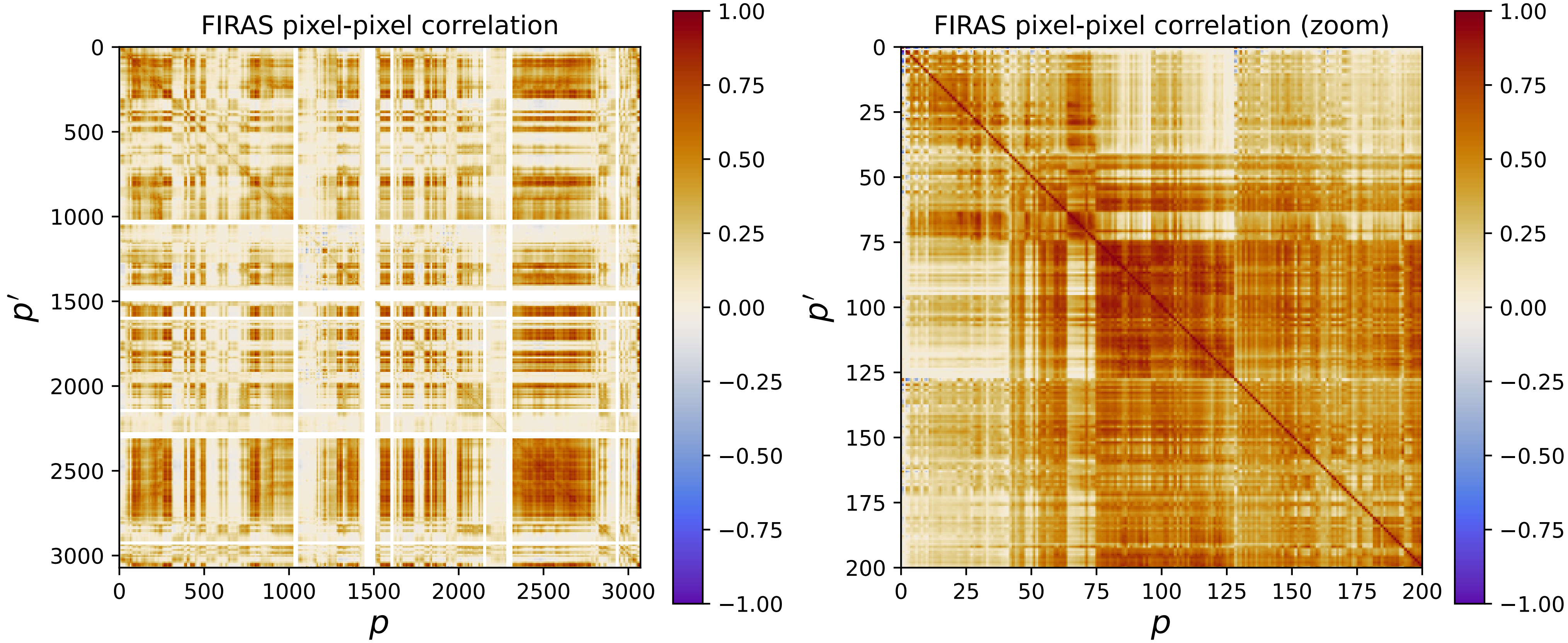
High-frequency can help

Foreground priors can be important

Sabyr+ (2025)

Pixel correlation modeling in pixel method

- Real data



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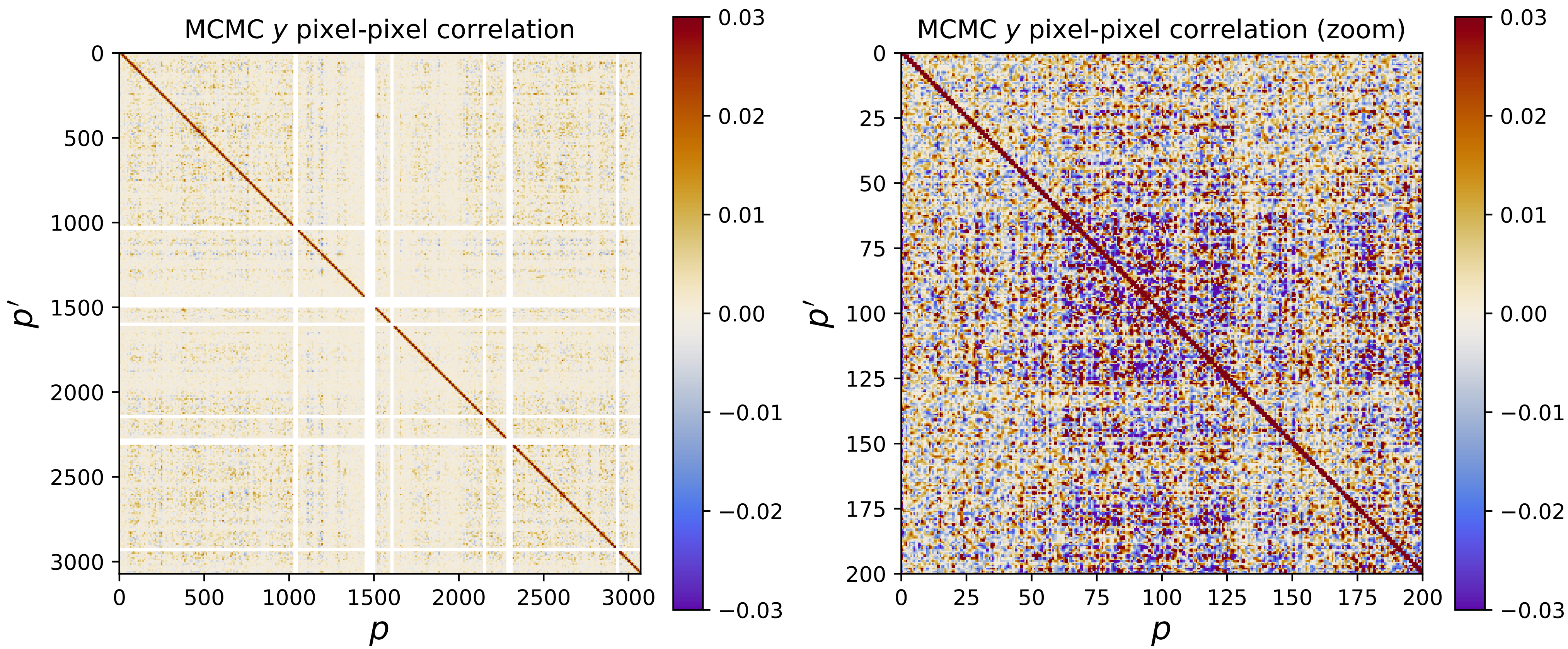

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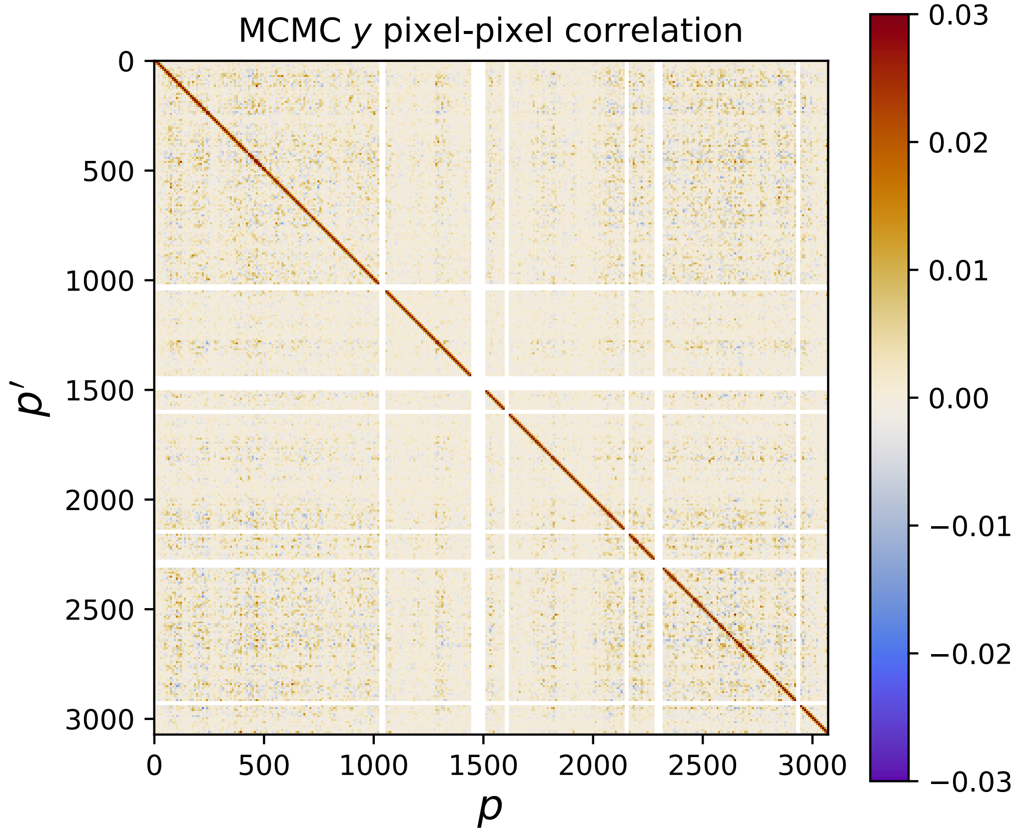

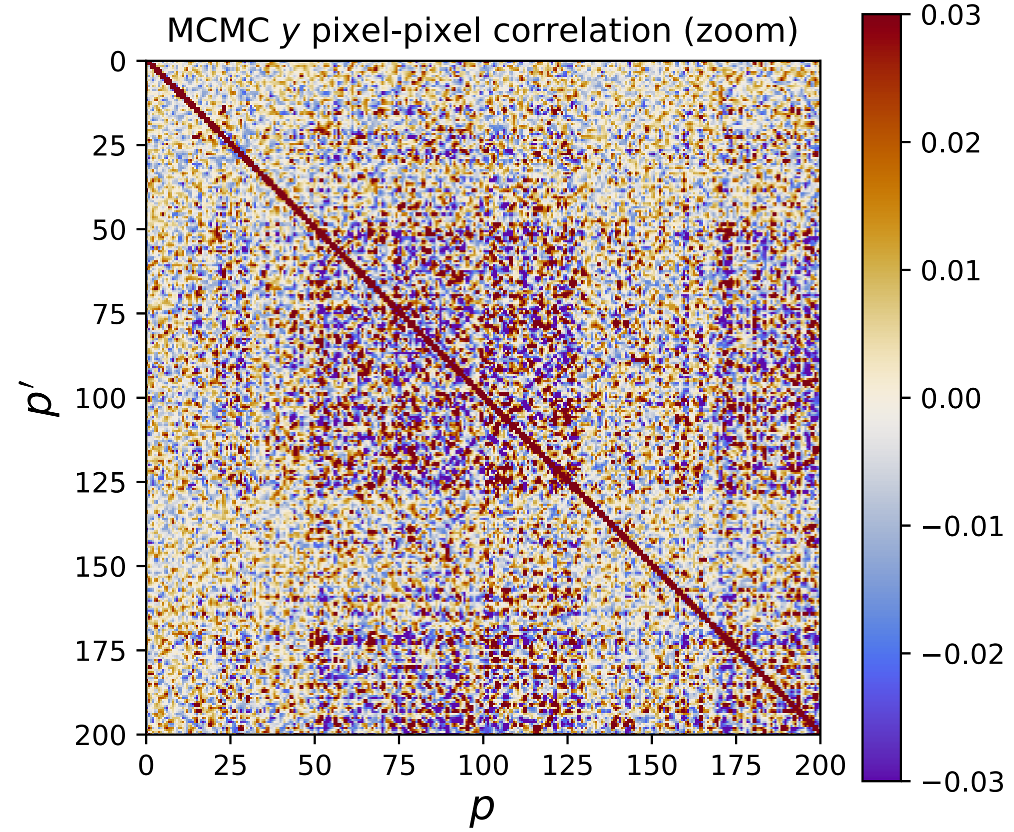

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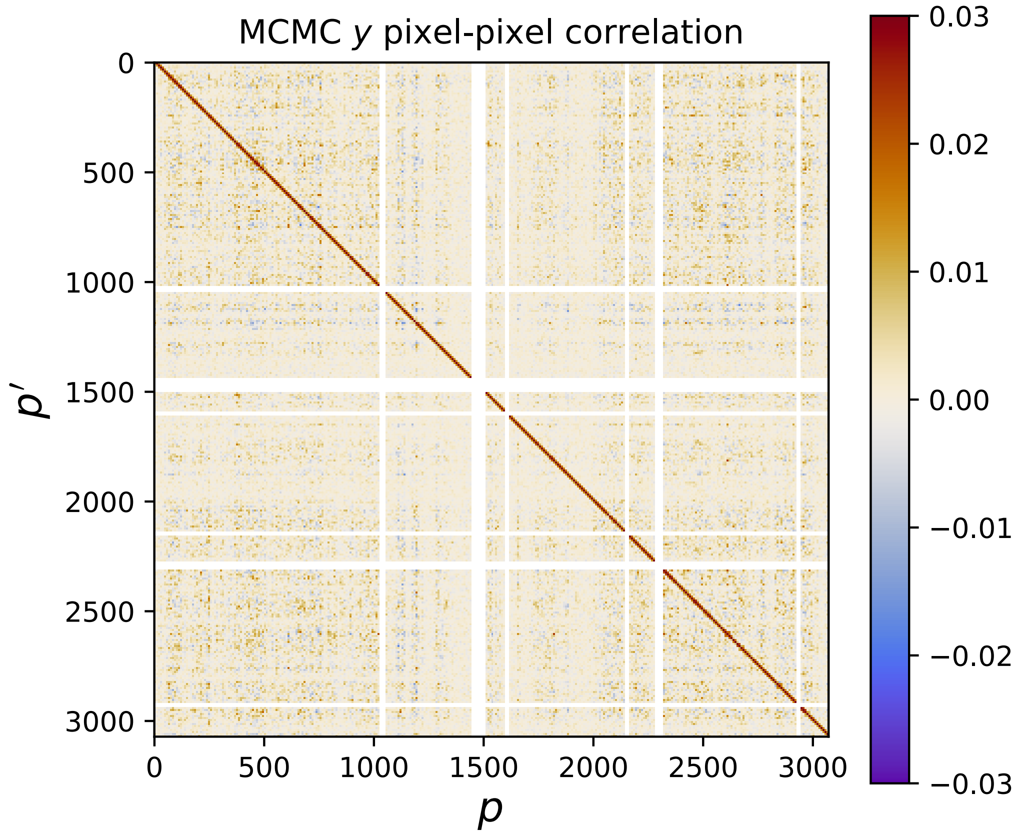
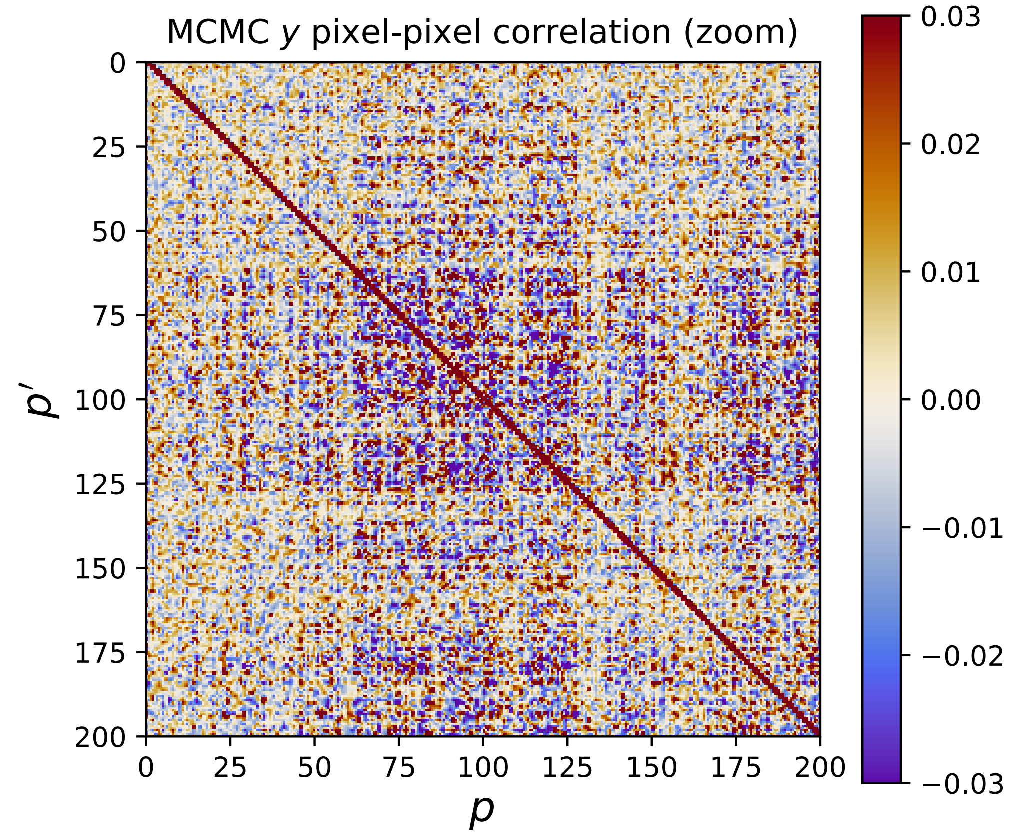
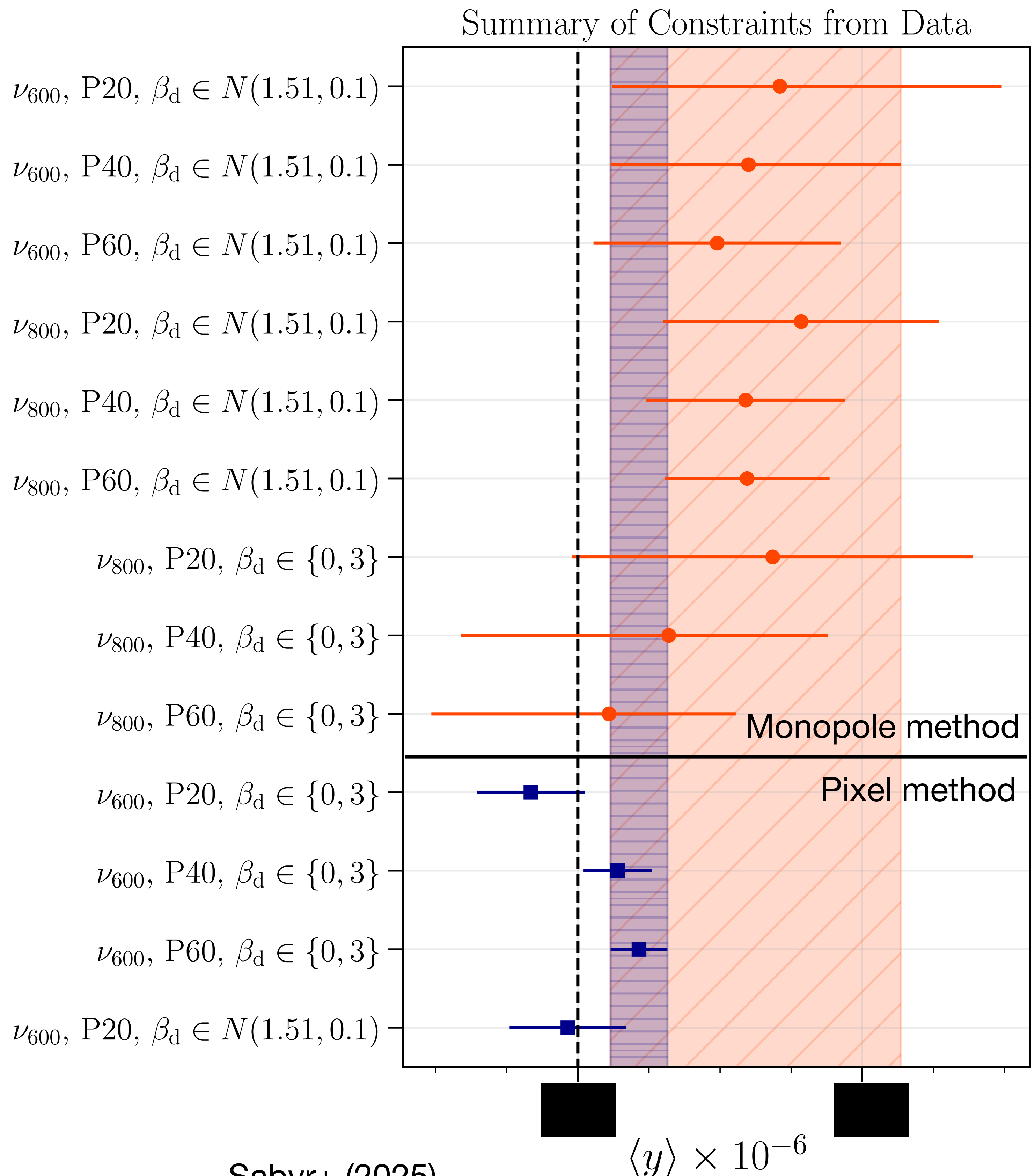




Sabyr+ (2025)

Real data results

- In line with expectations from mocks.
- Monopole method:
  - Higher frequencies help (sometimes).
  - **Agrees with Fisher forecasts expectations** (Abitbol+2017).
- Pixel method (apple to apple):
  - 3x tighter constraints.
  - Different sensitivity to priors and frequencies ranges.



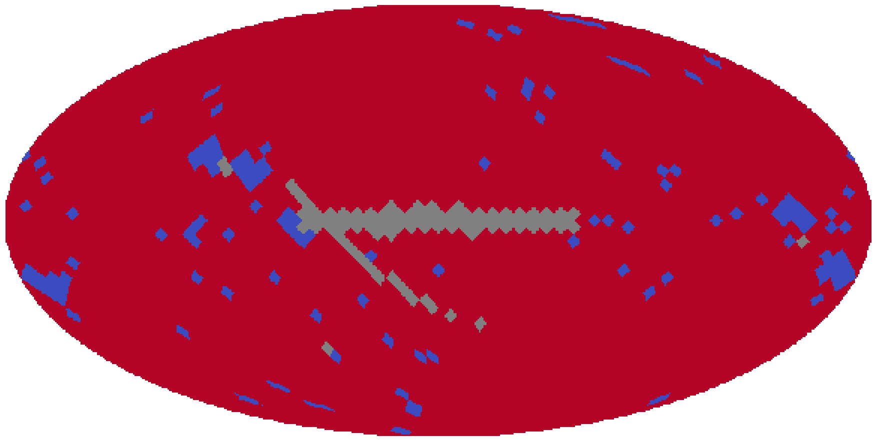
Sabyr+ (2025)

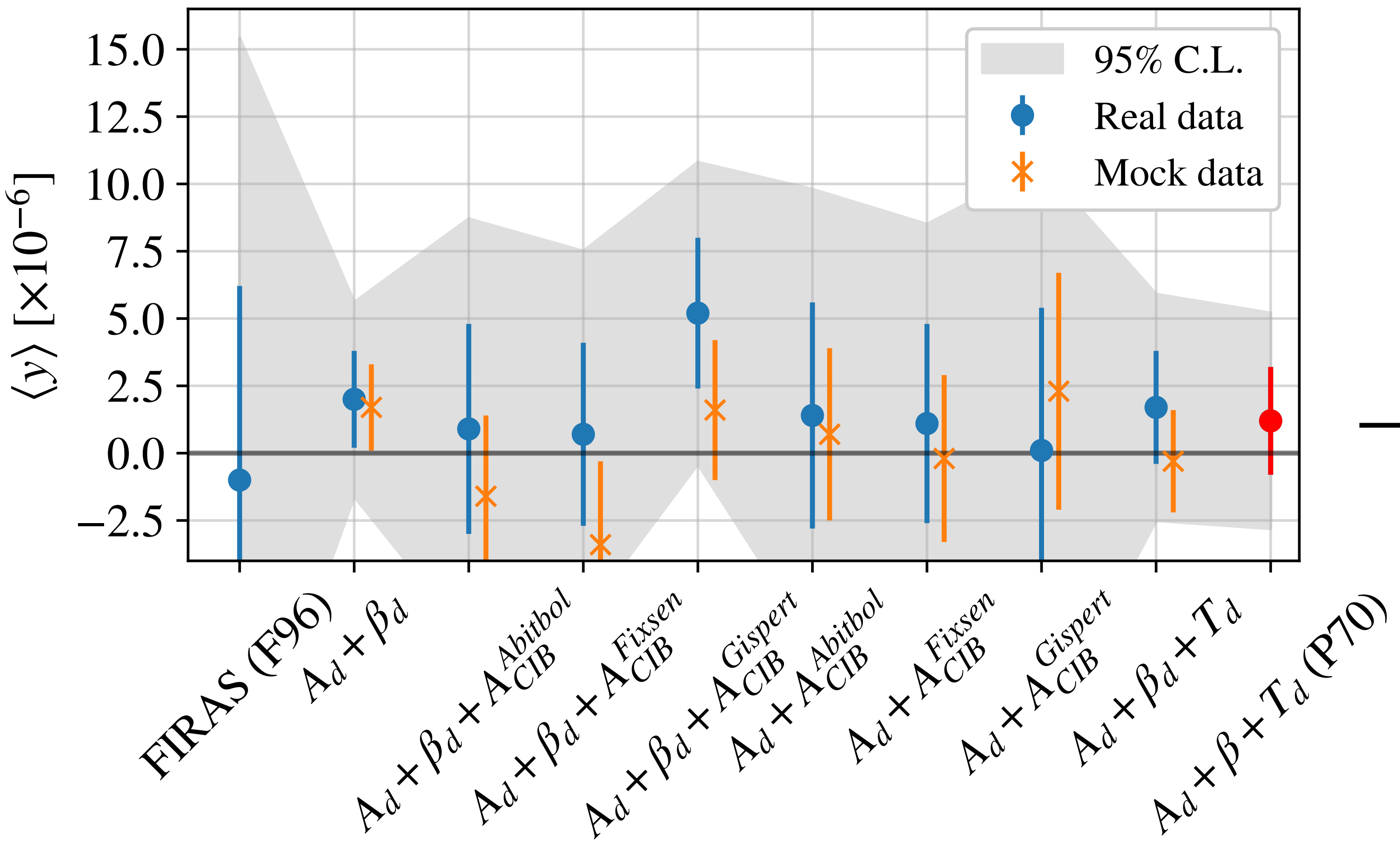
<y> measurements results

- Several models foreground models with multiple CIB removal strategies.
- Test for consistency across sky fractions and foreground models for robustness

Gratton & Challinor (2019)

$$\frac{\left|\langle y\rangle_1 - \langle y\rangle_2\right|}{\sqrt{\left|\sigma^2_{\langle y\rangle,1} - \sigma^2_{\langle y\rangle,2}\right|}} \lesssim 2$$





3x better upper limit

$$\langle y\rangle \sim (1.0 \pm 2.1) \times 10^{-6}$$

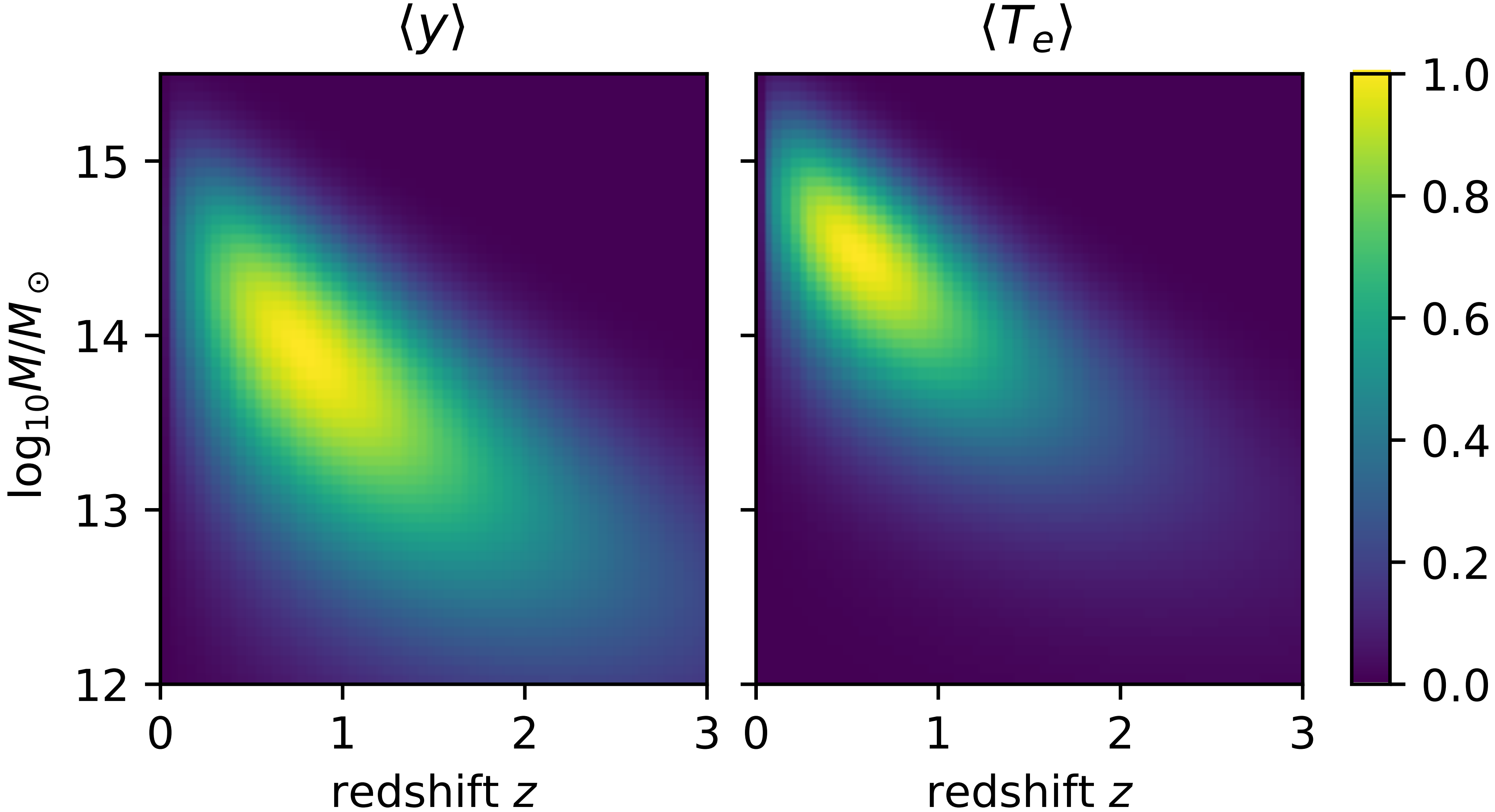
Fabbian+ (in prep.)

Why do we care?

- y distortions are dominated by late time gas physics: unique probe of feedback.

$$\langle y \rangle \equiv \langle y(\hat{\mathbf{n}}) \rangle_{\hat{\mathbf{n}}} = \int \frac{d\hat{n}}{4\pi} \frac{\sigma_T}{m_e} \int P_e(\hat{\mathbf{n}}, l) dl$$

$$\langle T_e \rangle \equiv \langle T_e(\hat{\mathbf{n}}) \rangle_{\hat{\mathbf{n}}} = \langle y \rangle^{-1} \int \frac{d\hat{n}}{4\pi} \frac{\sigma_T}{m_e} \int \left[T_e P_e \right] (\hat{\mathbf{n}}, l) dl$$



Thiele+ (2022)

- … and also reionization (subdominant) or primordial P(k) k ~ 1-10 h/Mpc.

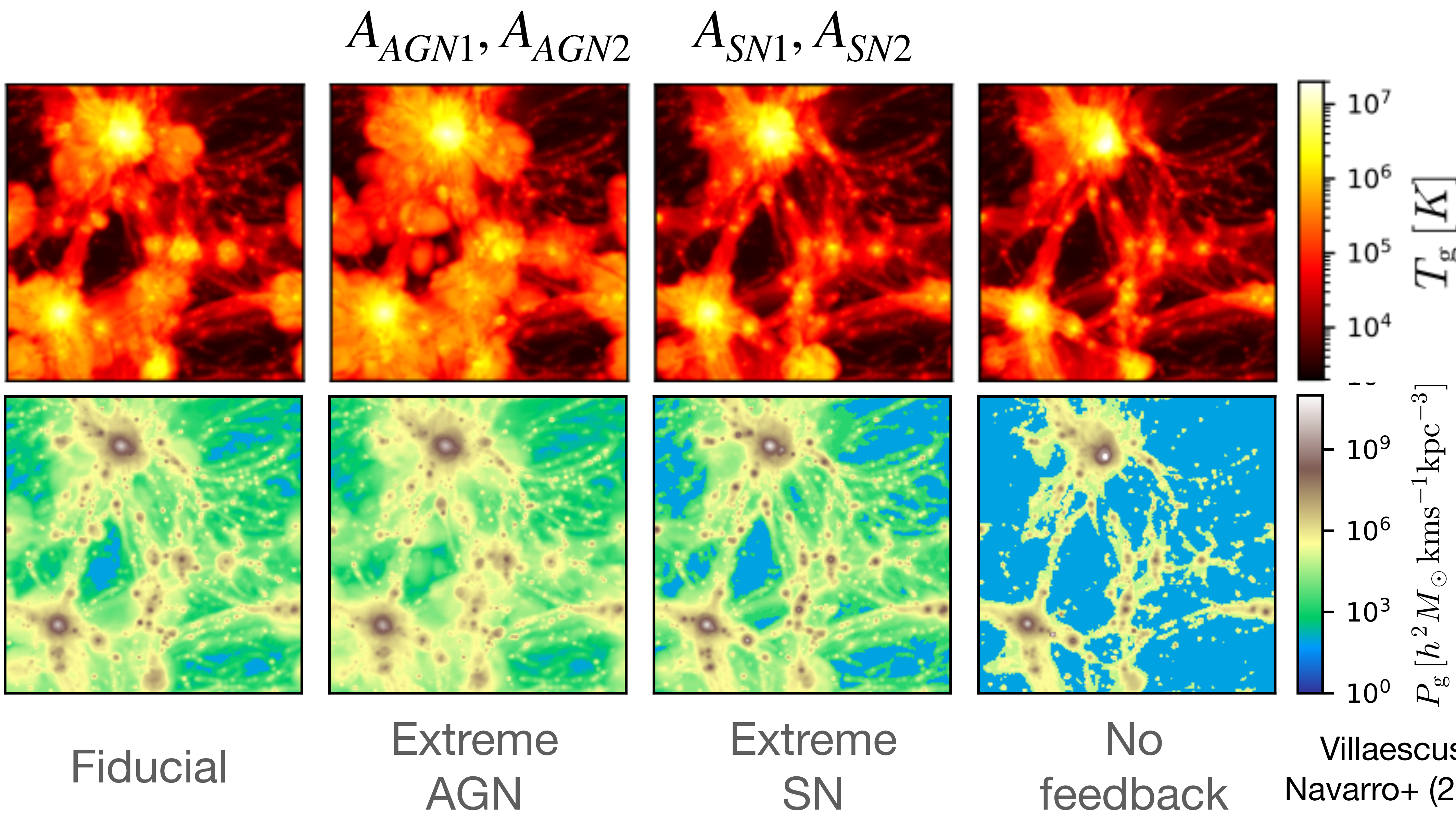
Modeling <y> in hydrodynamical simulations

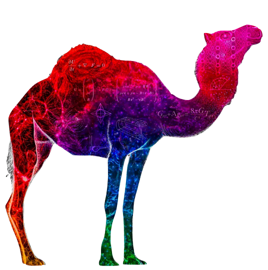
- CAMELS: over 8k hydro simulations varying cosmology, feedback recipes, codes…
- 25 Mpc/h, 2x 256³ particles: need to address volume and cosmic variance effects

$$x_i \sim f_i^c(\sigma_8, \Omega_m, \ldots) f_i^b(\{A_j\}) f_i^{\rm CV}(\delta)$$

Thiele+(2022)

z = 0





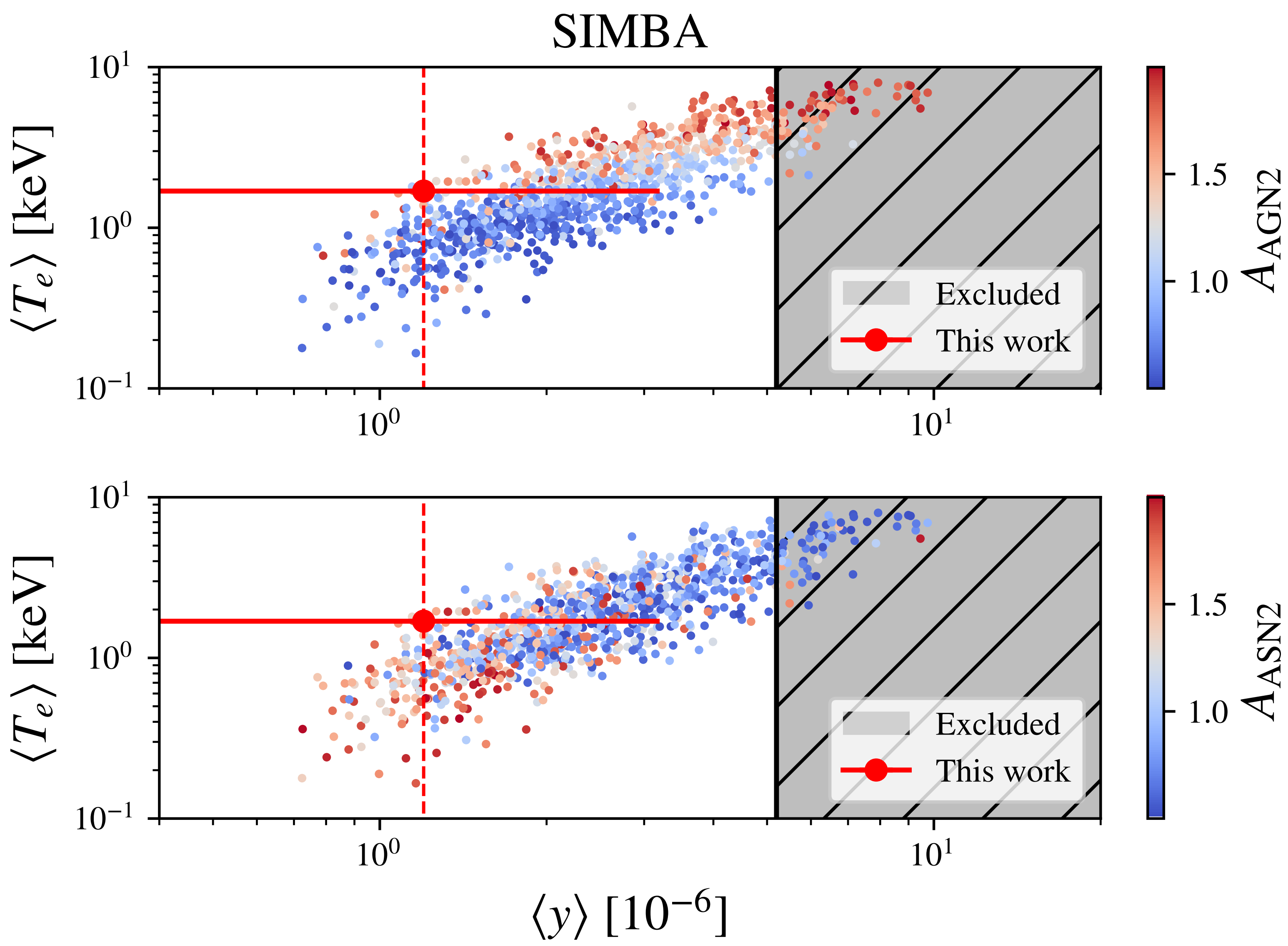
Villaescusa Navarro+ (2020)

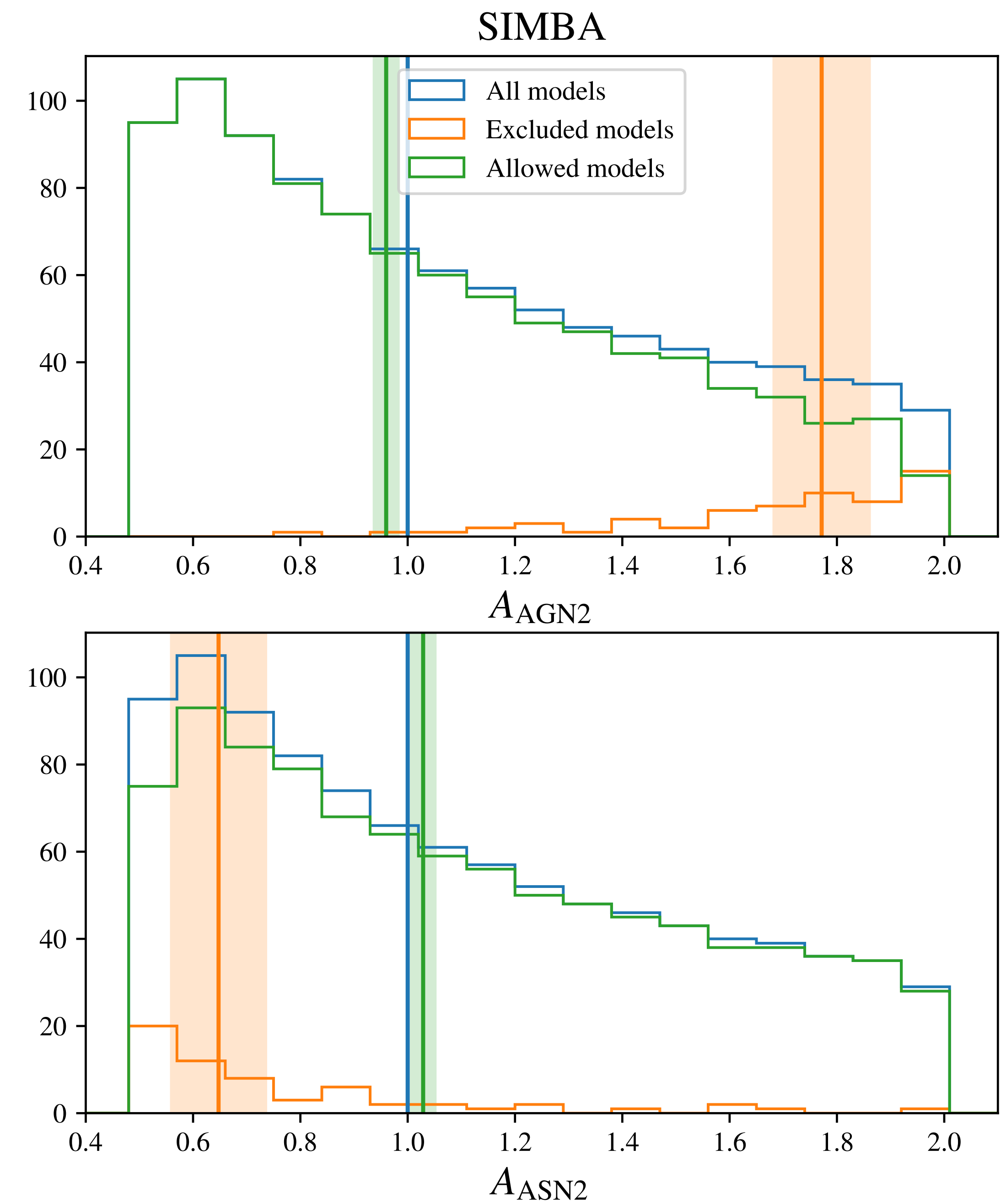
Constraining galaxy formation models

- SIMBA stronger feedback model with directional AGN jets.

- Some models start to be ruled out but arge degeneracies remains.

    - Direct constraints are weak but not hopeless: likelihood-free inference…

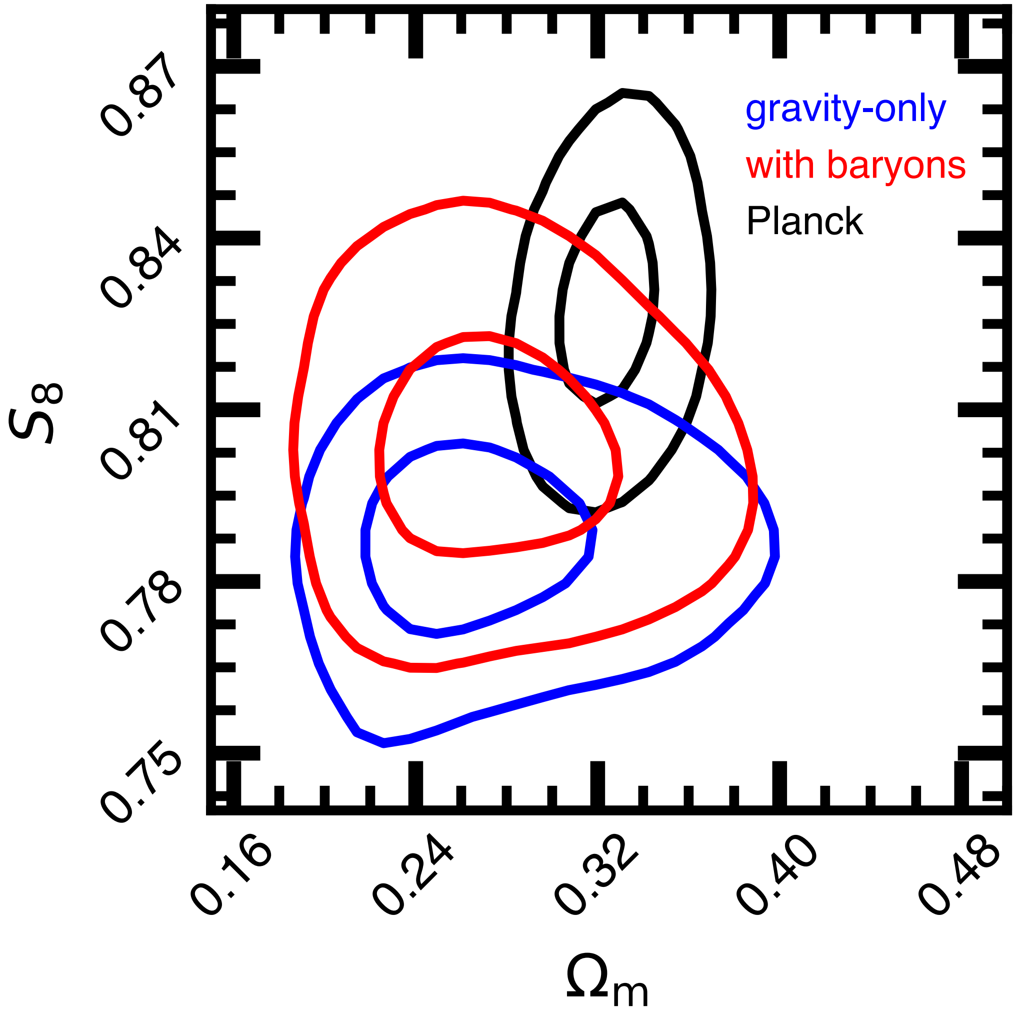




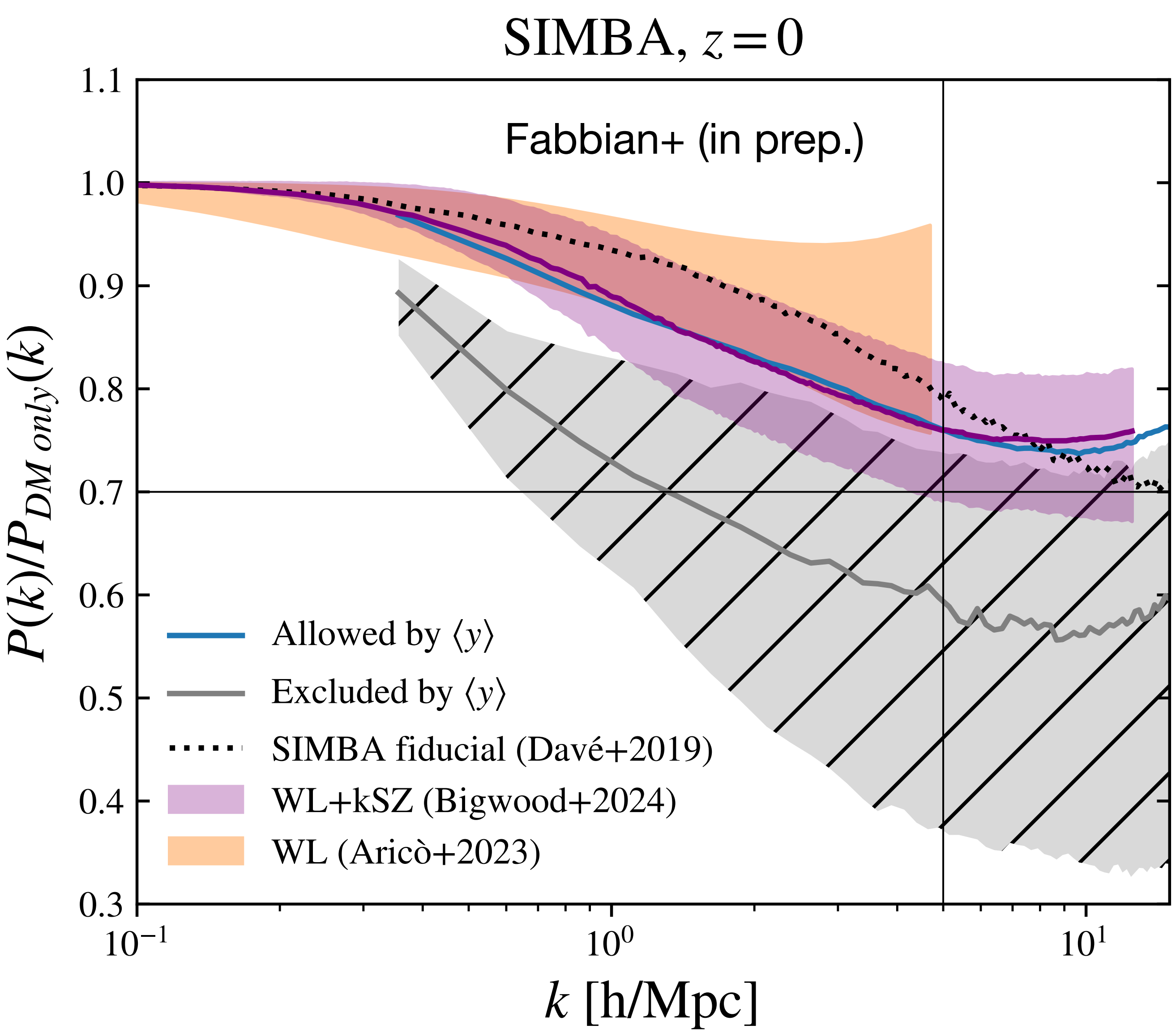
w/ C. Lovell

Implications for S8 / galaxy lensing / LSS probes

- Galaxy lensing drives the S8 tension: large uncertainties on matter distribution at small scales.
  - Weak lensing + kSZ : can reconcile current measurements with (extreme) feedback.
  - <y> constraints on baryon suppression in the ballpark of current analyses, informative probe for consistency tests!



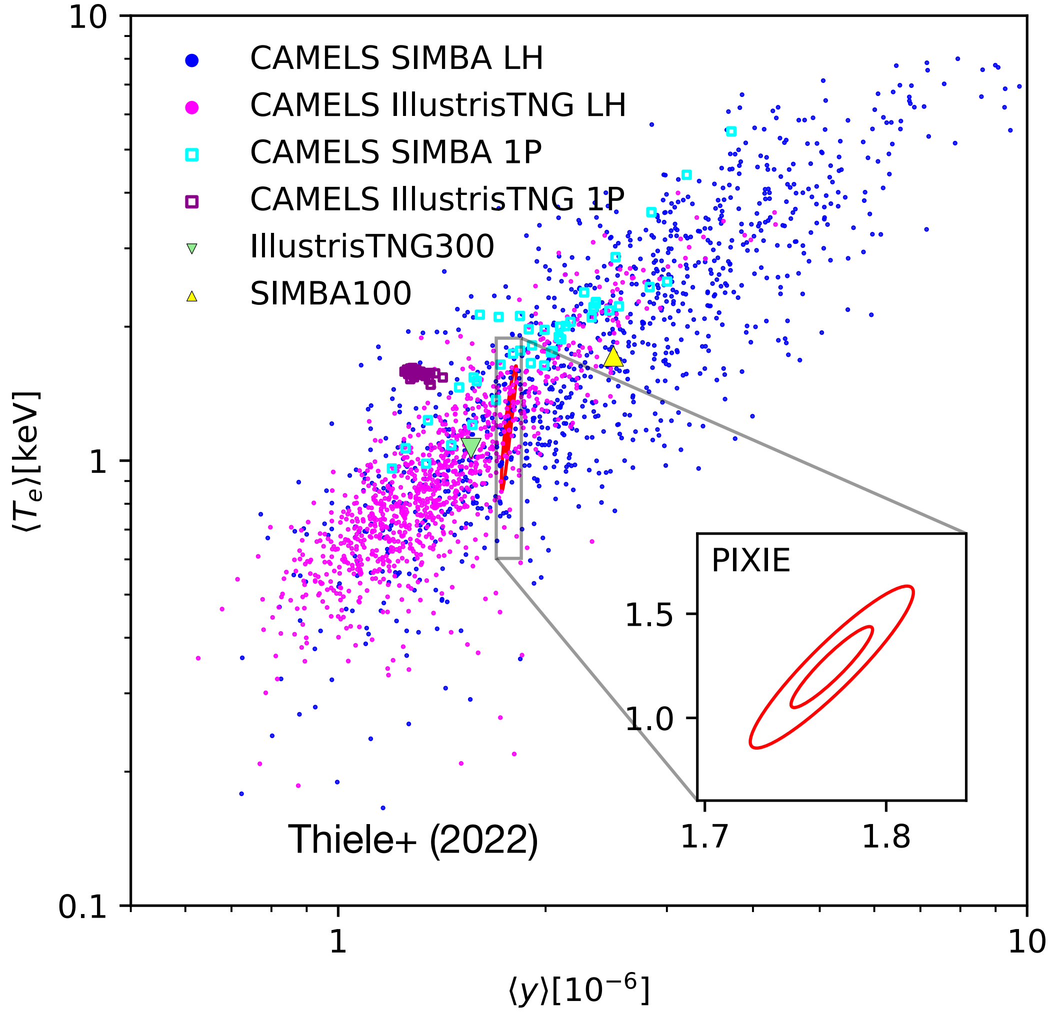
Aricò+ (2023)



Conclusions

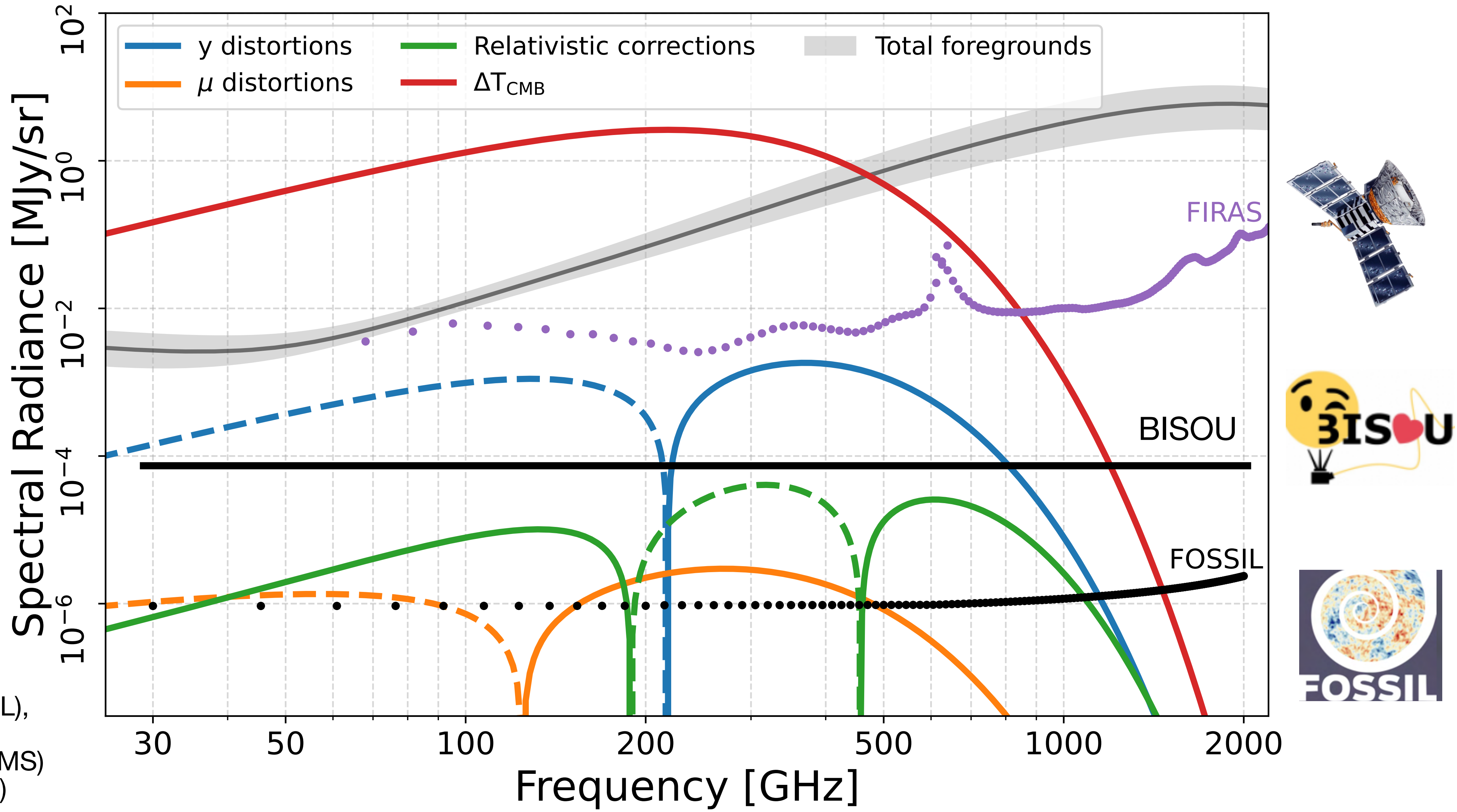
- **FIRAS data are still useful after 30 years!**
  - We can learn from from them with new approaches and prepare for the next challenges!
  - Current reanalysis of FIRAS brought us to the verge of detections of <y> (and improved <μ>!)
  - FIRAS+ hydro simulations started constraining feedback parameters!

- **Experimental spectral distortions are alive!**
  - Several planned experiments can improve FIRAS results and detect <y>!
  - $\sigma(\langle T_e \rangle) \sim 1\mathrm{keV}, \sigma(\langle y \rangle) \sim 0.1 \times 10^{-6}$ from space.
  - Previous forecasting could be pessimistic but systematics need dedicated studies.



Experimental prospects

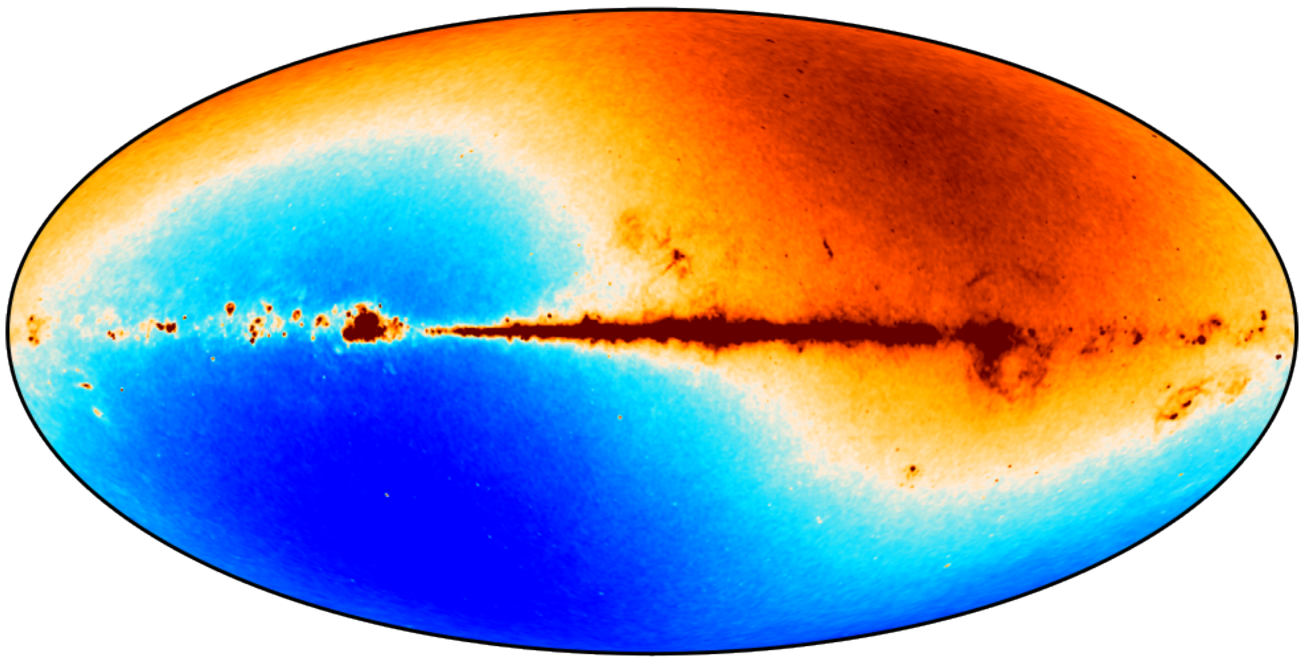
- Several instruments are being built, deployed or in phase A: transformational potential!
- Preliminary forecasts on monopole constraints (pessimistic) give us potential detection already fro BISOU!



Maffei+ (2021, BISOU),
Aghanim+ (2025, FOSSIL),
Masi+(2021, COSMO),
Rubiño-Martin+(2020, TMS)
Sabyr+(2024, SPECTER)

Why FIRAS is unique

Planck

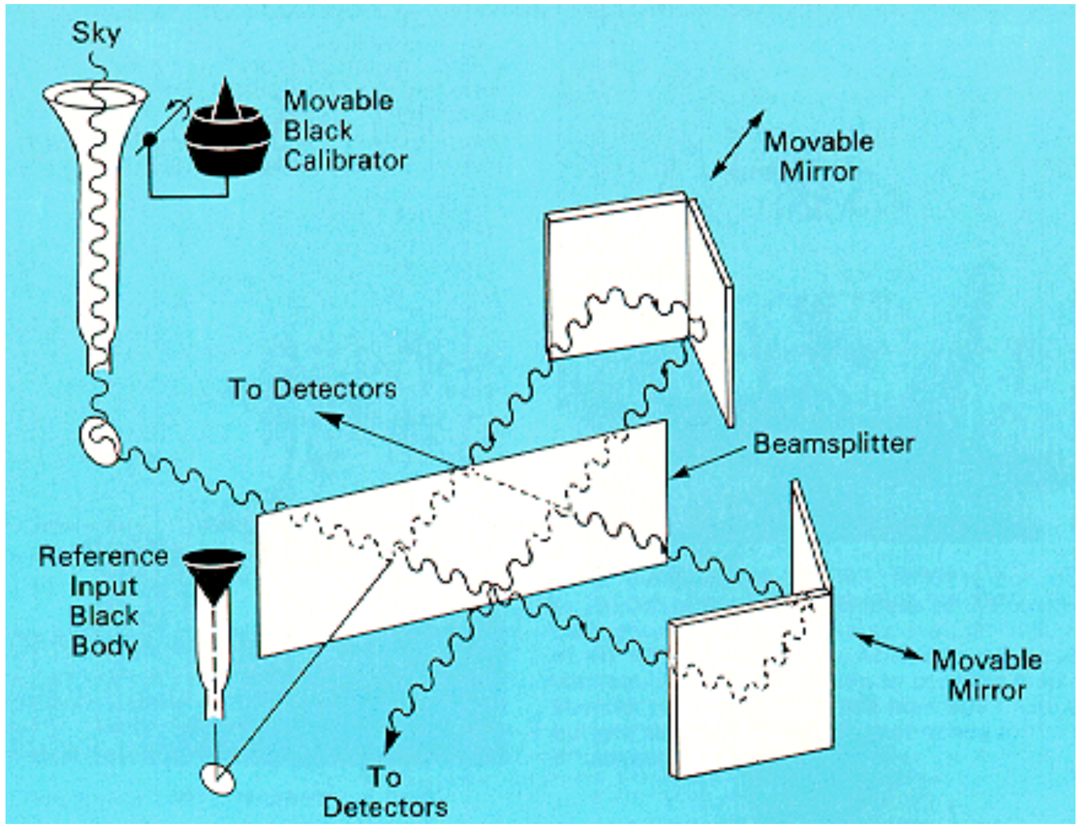


- Uses motion of satellite to calibrate

$$T(\hat{\mathbf{n}}') = \frac{T(\hat{\mathbf{n}})}{\gamma(1 - \boldsymbol{\beta} \cdot \hat{\mathbf{n}}')}$$

- Assumes T0 (from… FIRAS)

FIRAS

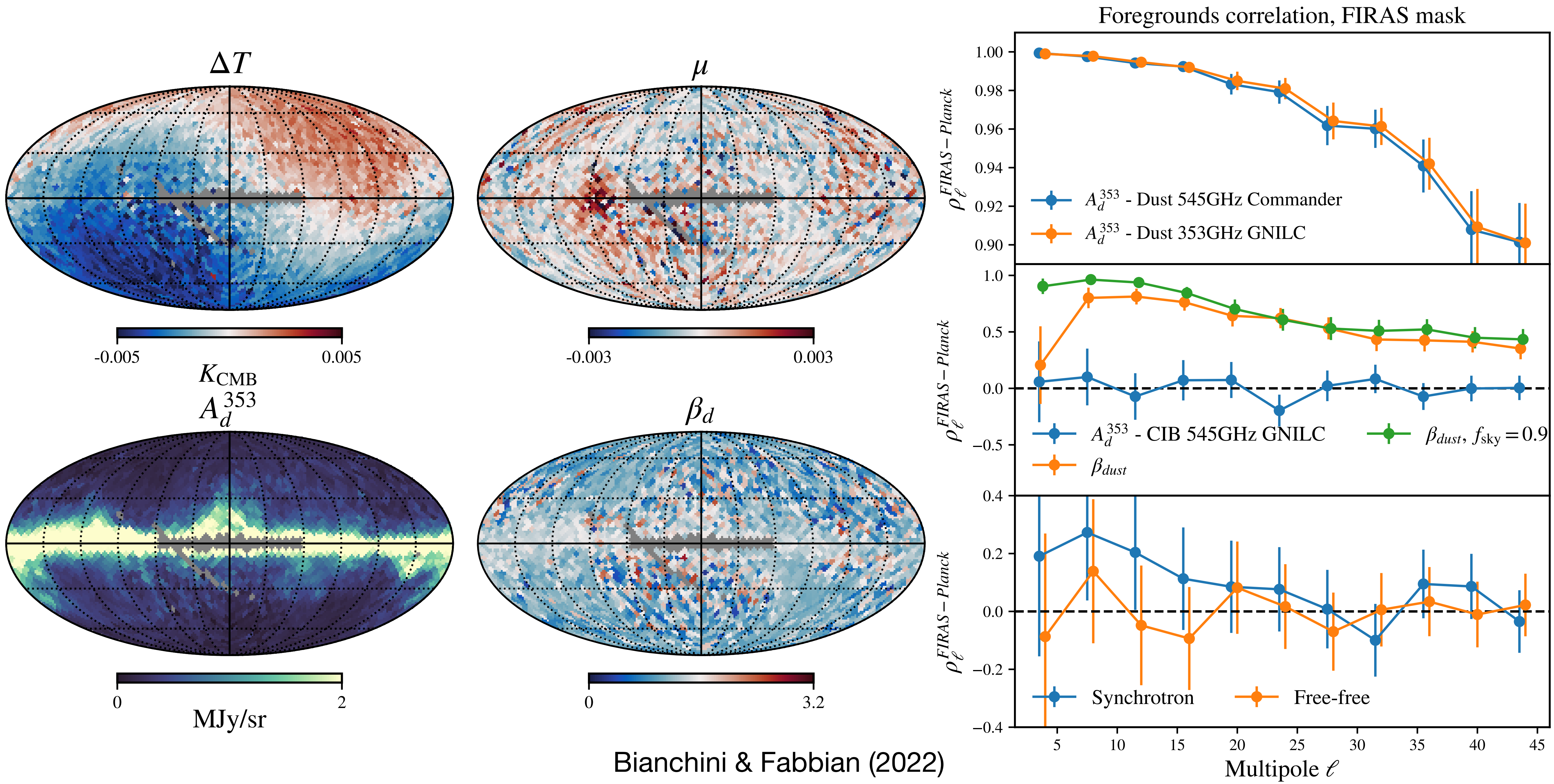


- Fourier Transform Spectrometer

- Absolutely calibrated experiment, gives true brightness temperature

Component separated maps and consistency tests

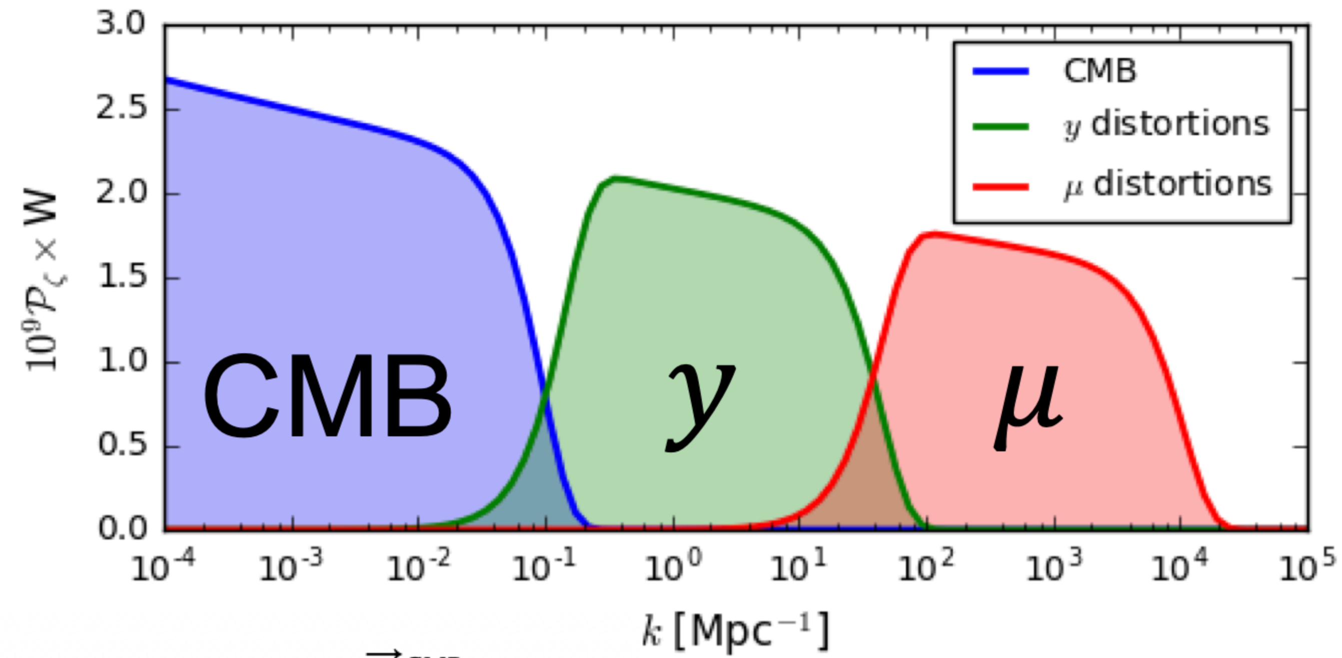
- Strong correlation with Planck-based foreground maps
- Dipole (direction and amplitude) and T0 consistent with original results.

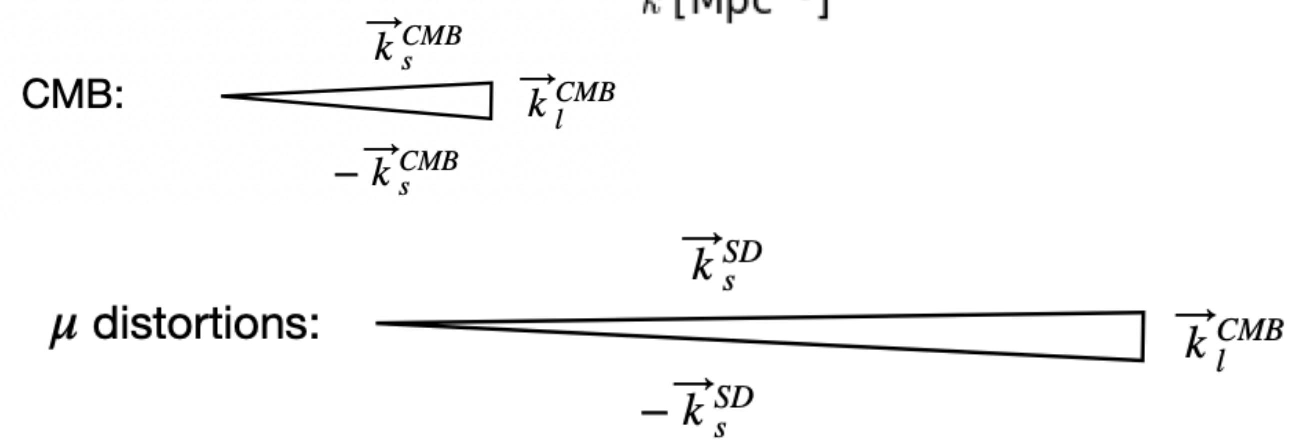


Bianchini & Fabbian (2022)

Spectral distortion and primordial non-Gaussianity

- In local PNG, the small-scale power (probed by μ) is correlated with the long-wavelength perturbations (probed by T/E)
- μ is quadratic in primordial perturbations
- μ probes smaller scales than primary CMB anisotropies
- Complementary to primary CMB bispectra!



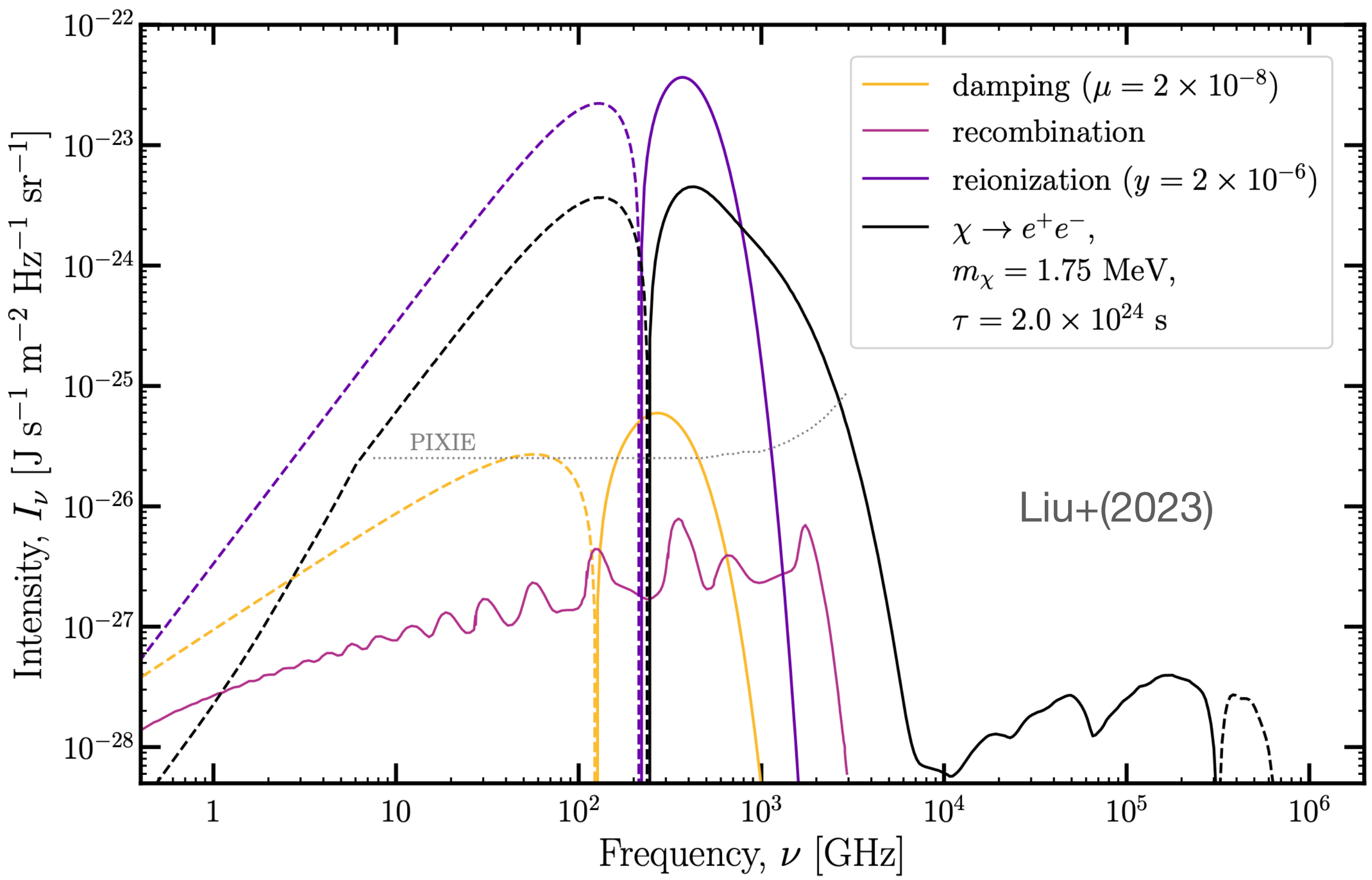


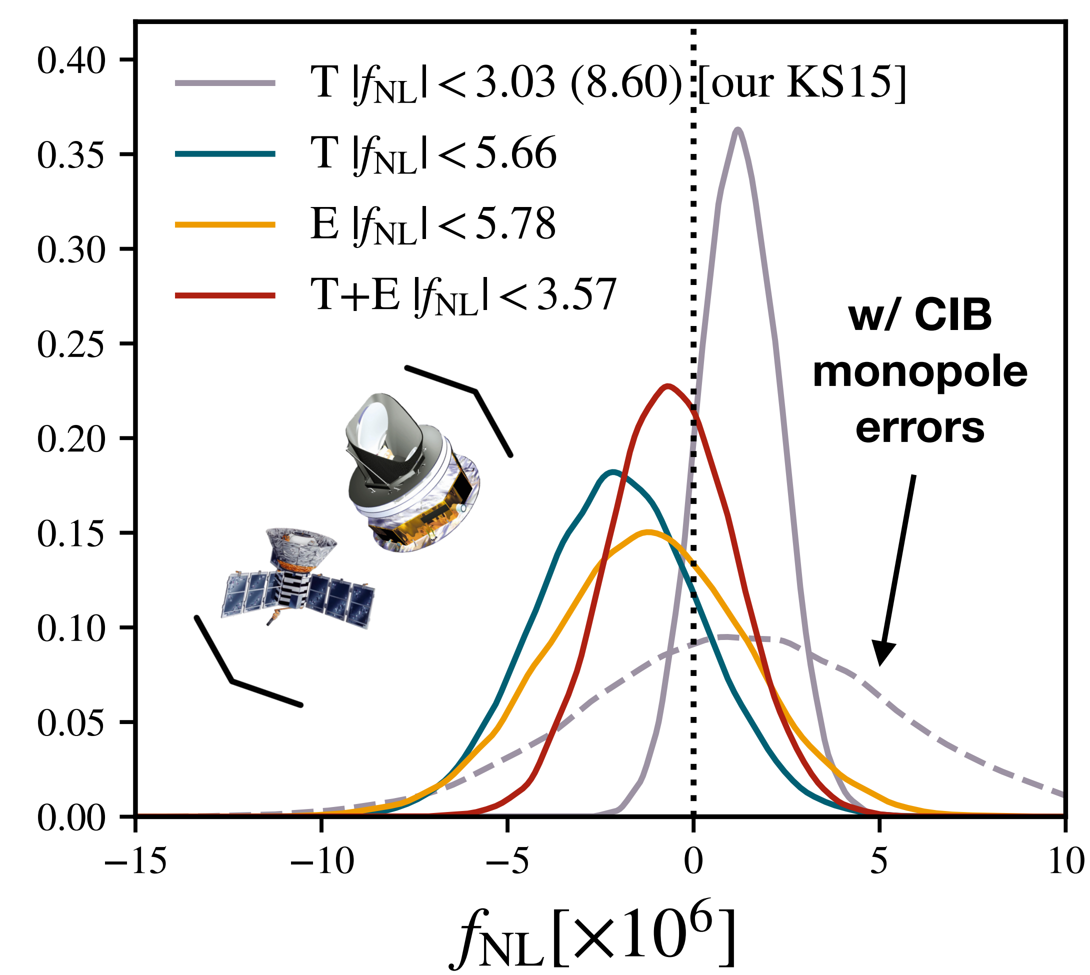
$$\Big\langle \mu T \Big\rangle \sim \Big\langle \zeta(k_s)\zeta(k_s)\zeta(k_L) \Big\rangle \approx -\frac{12}{5} f_{\rm NL} P(k_L) P(k_s) \quad C_\ell^{\mu X} \approx \frac{12}{5} f_{\rm NL} \langle\mu\rangle \int {\rm d}k\, k^2\, \frac{2}{\pi} j_\ell(k r_{\rm ls}) \mathcal{T}_\ell^{X/\zeta}(k) P_\zeta(k)$$

Pajer & Zaldarriaga (2012)

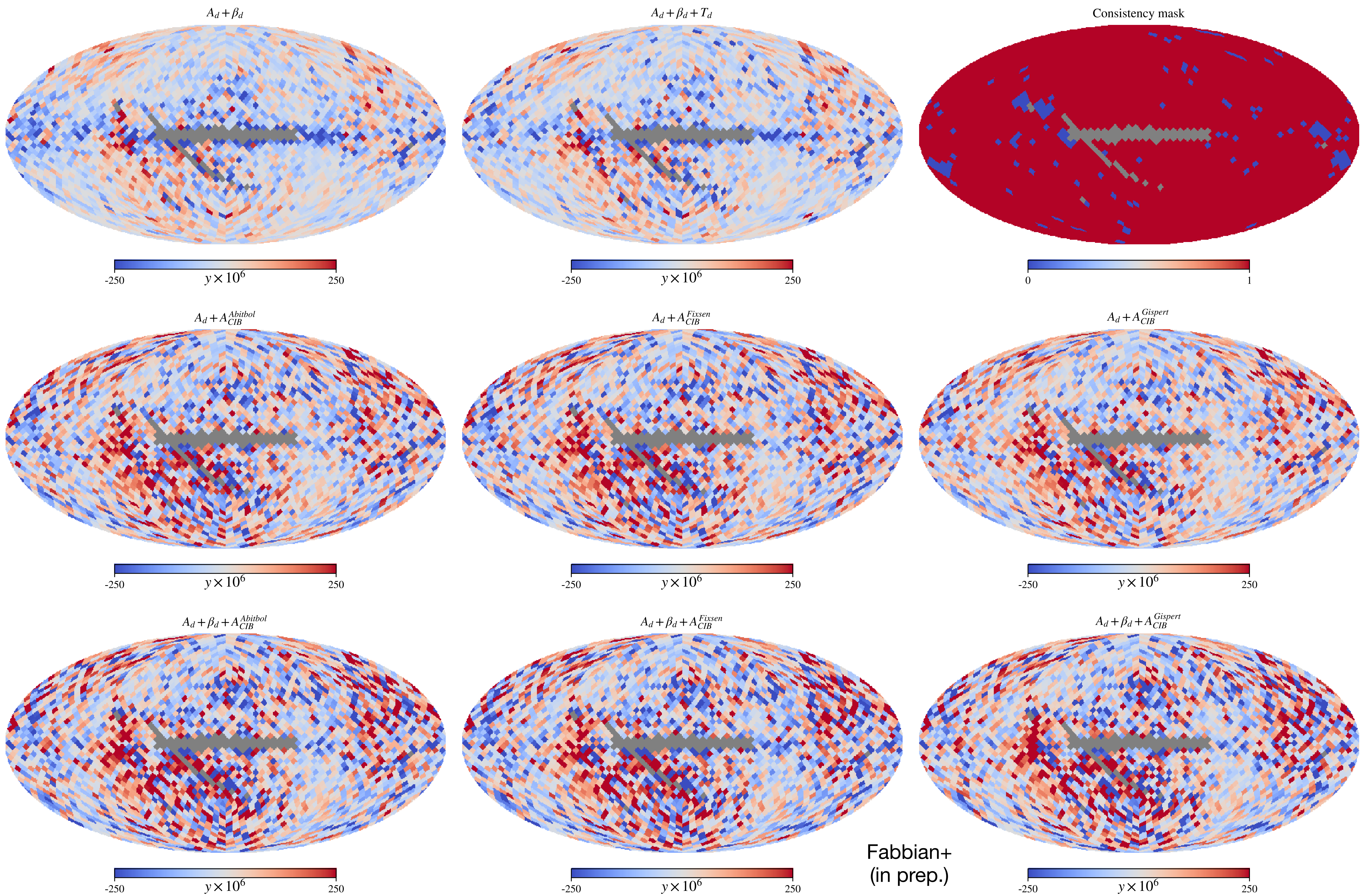
New monopole and f_{NL} constraints

- **New** $|\langle\mu\rangle| \lesssim 47 \times 10^{-6}$: major updates after ~30 years!
- **New** $f_{\rm NL} \lesssim 3.57 \times 10^6$
    - Fixed $\langle\mu\rangle \sim 2 \times 10^{-8}$ from LCDM or model independent $f_{\rm NL} \cdot \langle\mu\rangle \sim 0.07$
    - Running n_{NL} < 1.4 to satisfy CMB bispectrum anchor (f_{NL}~5 @ k ~ 0.05 Mpc^{-1})
    - For CMB-S4 we are expecting $\sigma(f_{NL}) \sim 1000$ (Zegeye, GF+2023)

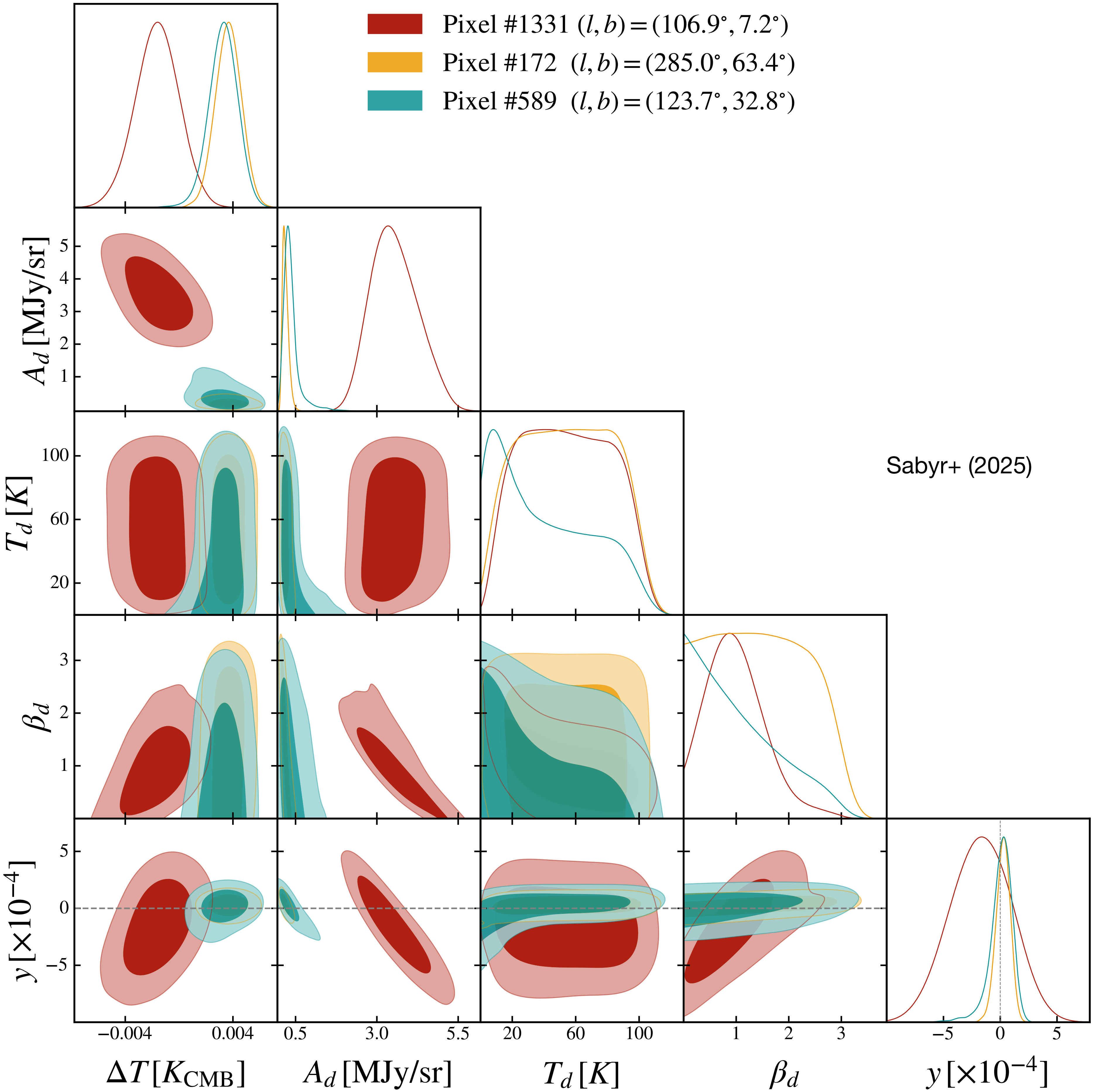




y maps



$A_d + \beta_d$
-250
$y \times 10^6$
250
$A_d + \beta_d + T_d$
-250
$y \times 10^6$
250
Consistency mask
0
1
$A_d + A_{CIB}^{Abitbol}$
-250
$y \times 10^6$
250
$A_d + A_{CIB}^{Fixsen}$
-250
$y \times 10^6$
250
$A_d + A_{CIB}^{Gispert}$
-250
$y \times 10^6$
250
$A_d + \beta_d + A_{CIB}^{Abitbol}$
-250
$y \times 10^6$
250
$A_d + \beta_d + A_{CIB}^{Fixsen}$
-250
$y \times 10^6$
250
Fabbian+
(in prep.)
$A_d + \beta_d + A_{CIB}^{Gispert}$
-250
$y \times 10^6$
250



Pixel #1331 (l, b) = (106.9°, 7.2°)
Pixel #172 (l, b) = (285.0°, 63.4°)
Pixel #589 (l, b) = (123.7°, 32.8°)
Sabyr+ (2025)
A_d [MJy/sr]
T_d [K]
β_d
y [×10^−4]
ΔT [K_CMB]
−0.004
0.004
0.5
3.0
5.5
20
60
100
1
2
3
−5
0
5