CMB spectral distortions: past and future

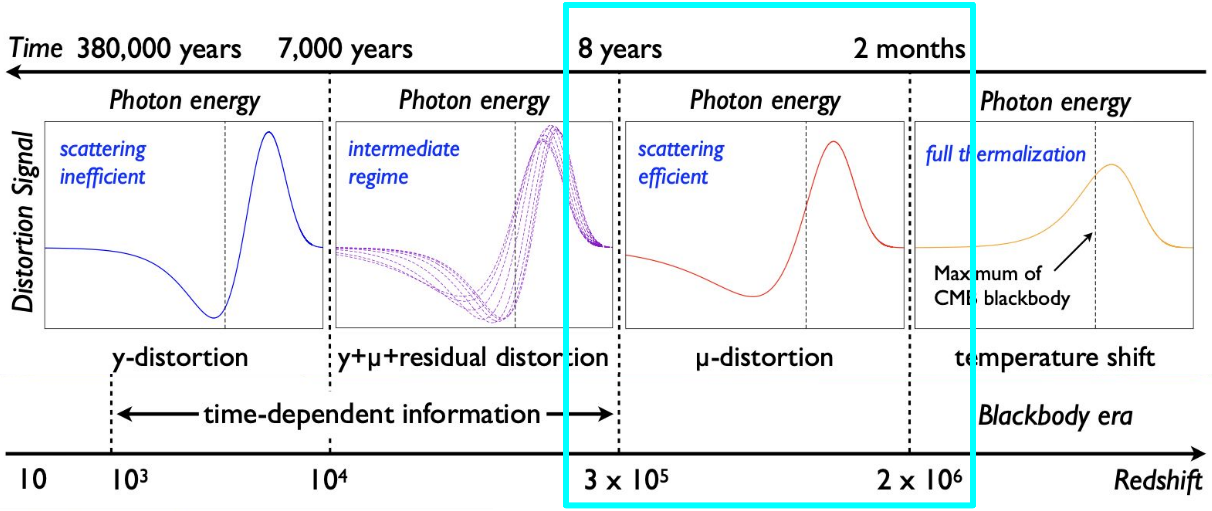
Alina Sabyr

with Colin Hill, Carlos Sierra, Jeffrey J. McMahon, Giulio Fabbian, Federico Bianchini

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

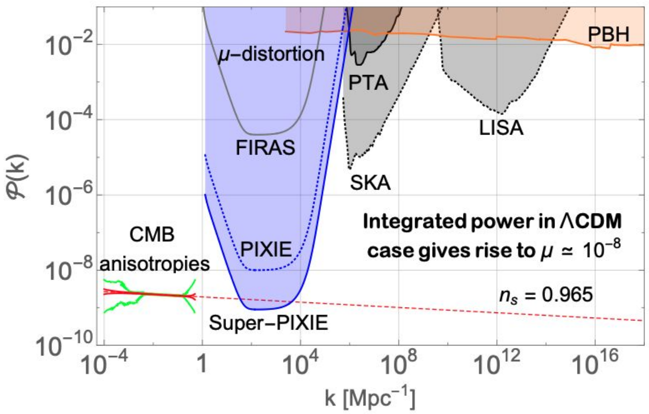
Paris-Saclay Astroparticle Workshop, 21/11/24

CMB spectral distortions: quick review



(figure adapted from Chluba+2021)

Compton scattering still efficient



Chluba+2019
Chluba+2021

μ-distortion:

➔ generated in the **early Universe** (exception: BSM models, see Chluba, Cyr & Johnson 2024)
➔ within ΛCDM: **Silk damping** & baryon cooling
➔ sensitive to primordial power spectrum on **small scales**

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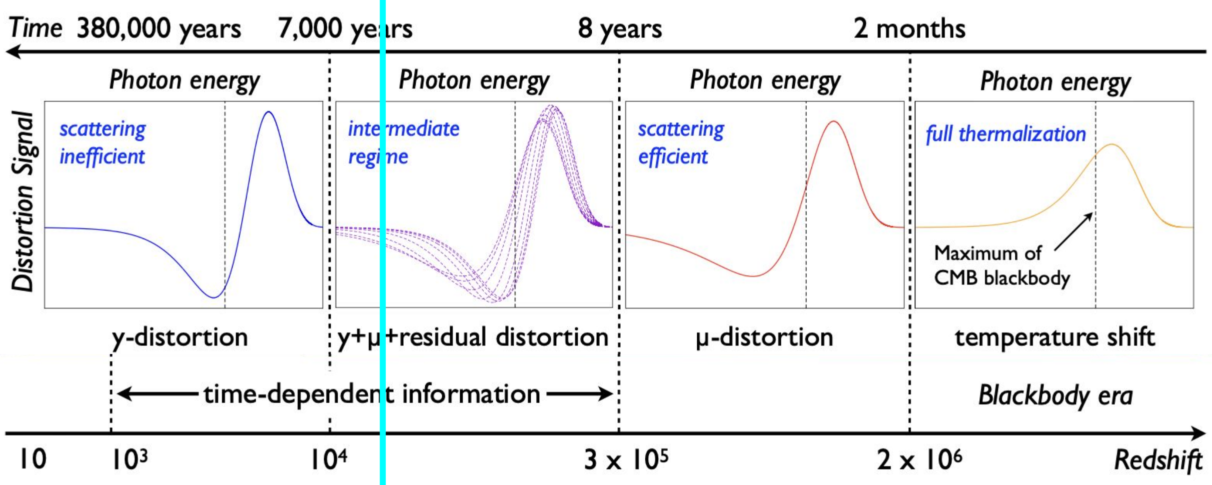
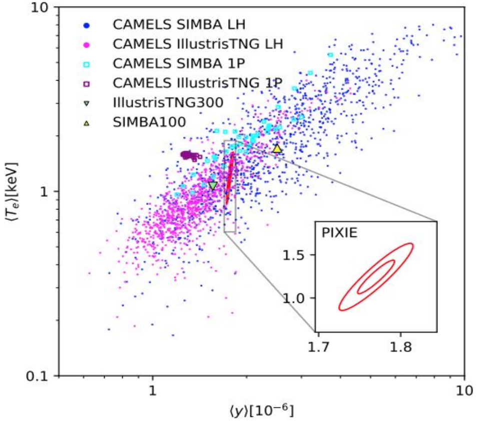


(figure adapted from Chluba+2021)

y-distortion:

- ➔ known source: thermal Sunyaev-Zel'dovich effect (**tSZ**) – inverse Compton scattering of CMB photons on free, energetic electrons, primarily in **galaxy clusters**
- ➔ **late-time Universe**
- ➔ total thermal **energy** + mean **temperature** of electrons



Thiele+2022

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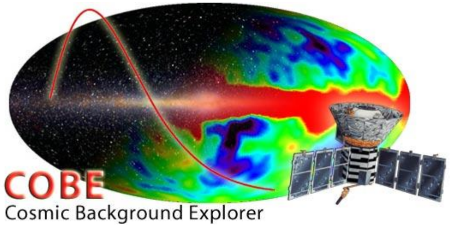
CMB spectral distortions: current status



Upper limits from *COBE/FIRAS* (flew in **1990**'s!):

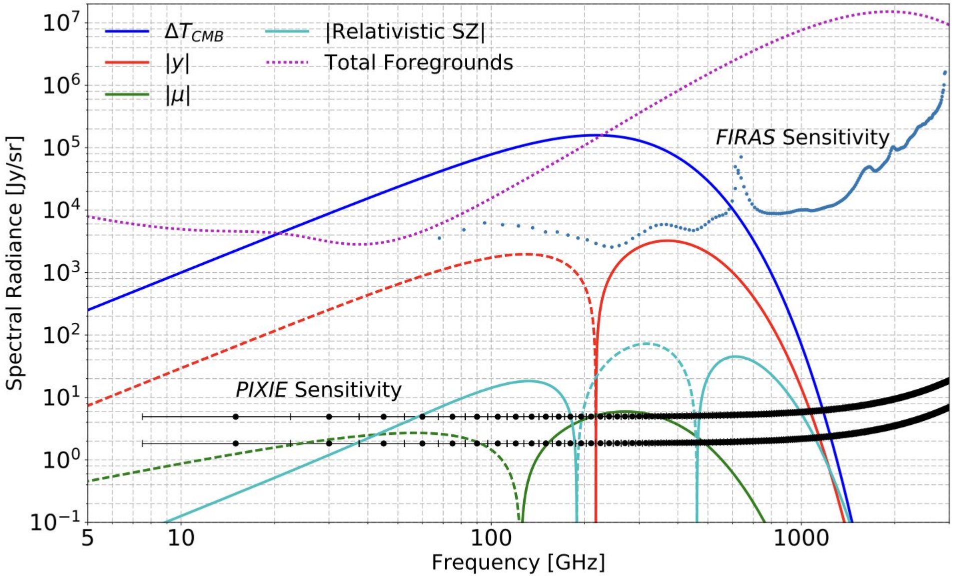
➔ ⟨y⟩ : < 15 x 10^{-6} (Fixsen+1996)

➔ ⟨μ⟩ : < 90 x 10^{-6} (Fixsen+1996), < 47 x 10^{-6} (Bianchini & Fabbian 2022)

Why are there no other direct and recent constraints?

➔ Need **absolute** temperature **calibrated** spectrum.

➔ Astrophysical **foregrounds**.



Abitbol+2017

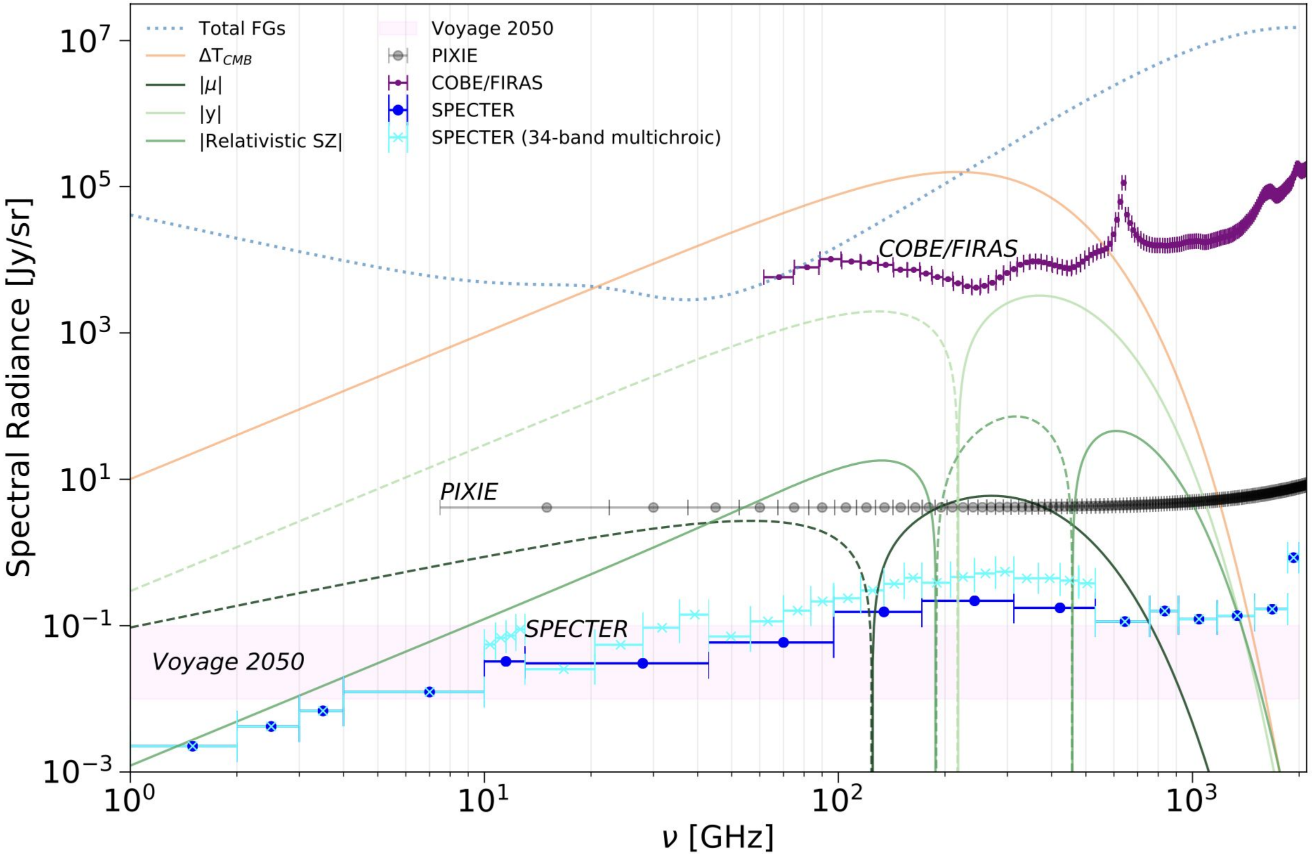
SPECTER: An Instrument Concept for a Spectral Distortion Measurement with Enhanced Sensitivity.

with Carlos Sierra, Colin Hill, Jeffrey J. McMahon

arXiv:2409.12188

<u>**Key idea:**</u>

Optimize **frequency bands** and their **individual sensitivities** to target the **μ-distortion**.



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Ingredients:

- ➔ Sensitivity calculator: **bolocalc-space**[1] *(based on BoloCalc, Hill+2018)*
  - ◆ HEMT amplifiers at ν < 10 GHz; bolometers at ν > 10 GHz.
- ➔ Fisher-forecast set-up: **sd_foregrounds_optimize**[2] (modified version of **sd_foregrounds**, Abitbol+2017)
  - ◆ CMB signals: blackbody deviation, μ-distortion, y-distortion, rel. corr. to y-distortion.
  - ◆ Foregrounds: Galactic dust, cosmic infrared background, Galactic synchrotron, free-free, spinning dust, CO.
  - ◆ Total **16 free parameters.**
- ➔ Optimization/robustness tests pipeline: **specter_optimization**[3]

*Assess the set-up via **SNR** and **area** (i.e. cost)*

All three codes publicly available on github!

[1] https://github.com/csierra2/bolocalc-space

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[3] https://github.com/asabyr/specter_optimization

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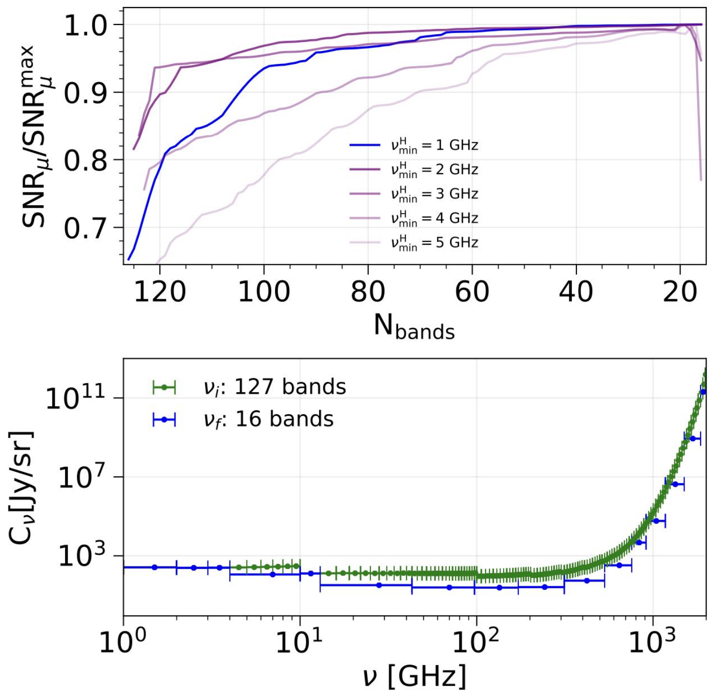
(1) Find optimal frequency bands



➔ Start with **narrow frequency bands**.

➔ **Combine** and **pick** the most **optimal** band combination.

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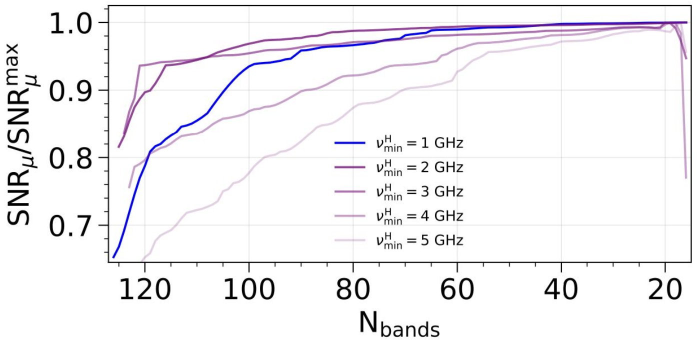
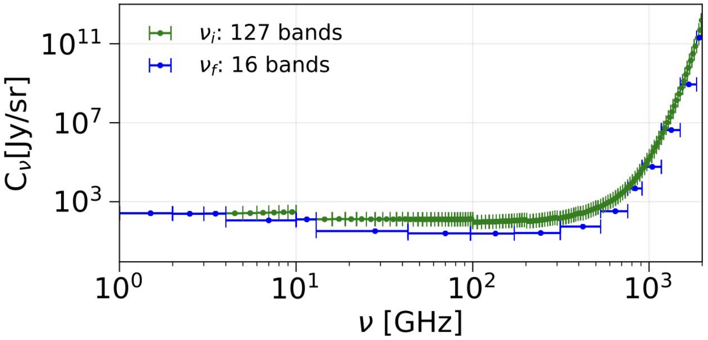


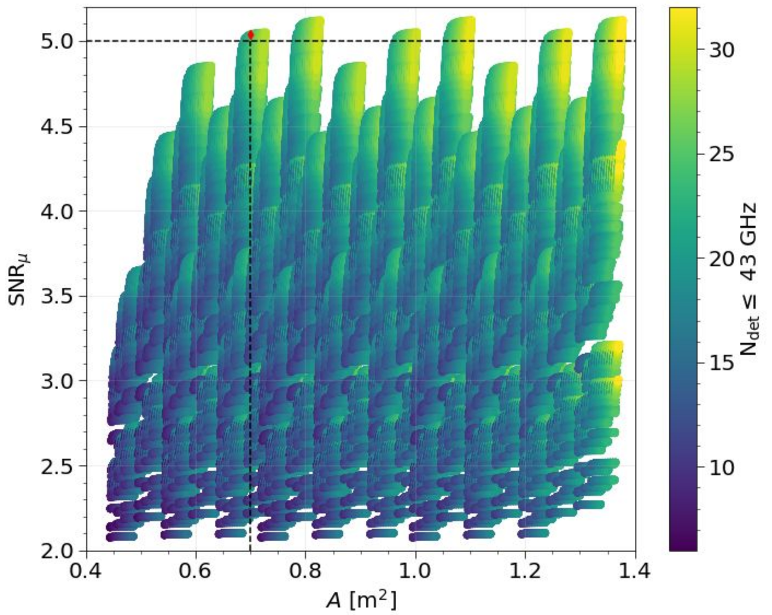


➔ Start with **narrow frequency bands**.

➔ **Combine** and **pick** the most **optimal** band combination.

(2) Optimize detector counts

>5 million Fisher calculations



➔ Optimized set-up is **not a singular** best point!

➔ Configurations **near 5σ** are the **most expensive**!

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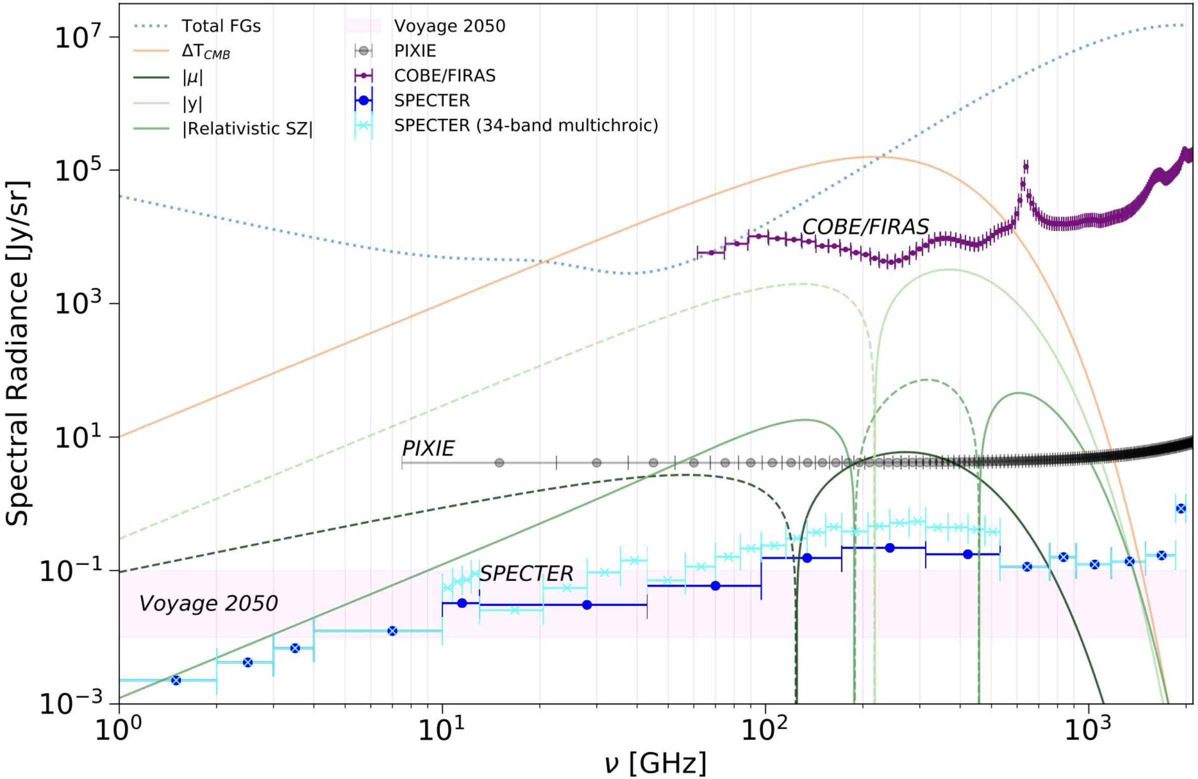
parameter & fiducial value	16-band optimized		34-band multichroic	
	SNR	σ	SNR	σ
$\Delta_T = 1.2 \times 10^{-4}$	37157	3.2×10^{-9}	30378	4.0×10^{-9}
$\mu = 2 \times 10^{-8}$	5	4.0×10^{-9}	4.5	4.4×10^{-9}
$y = 1.77 \times 10^{-6}$	955	1.9×10^{-9}	807	2.2×10^{-9}
$k_B T_{eSZ} = 1.245$ keV	33	0.037	42	0.029

TABLE III. Forecasts for the four CMB parameters using the 16-band optimized and 34-band multichroic set-ups assuming $t_{obs} = 1$ year. We list the fiducial values, SNRs, and the Fisher error bars.

parameter & fiducial value	16-band optimized		34-band multichroic	
	SNR	σ	SNR	σ
$\Delta_T = 1.2 \times 10^{-4}$	74313	1.6×10^{-9}	60757	2.0×10^{-9}
$\mu = 2 \times 10^{-8}$	10	2.0×10^{-9}	9	2.2×10^{-9}
$y = 1.77 \times 10^{-6}$	1911	9.3×10^{-10}	1615	1.1×10^{-9}
$k_B T_{eSZ} = 1.245$ keV	67	0.019	85	0.015

TABLE IV. Same as Table III, but for $t_{obs} = 4$ years.

34-band multichroic:
more frequency **resolution** at **no additional cost**!



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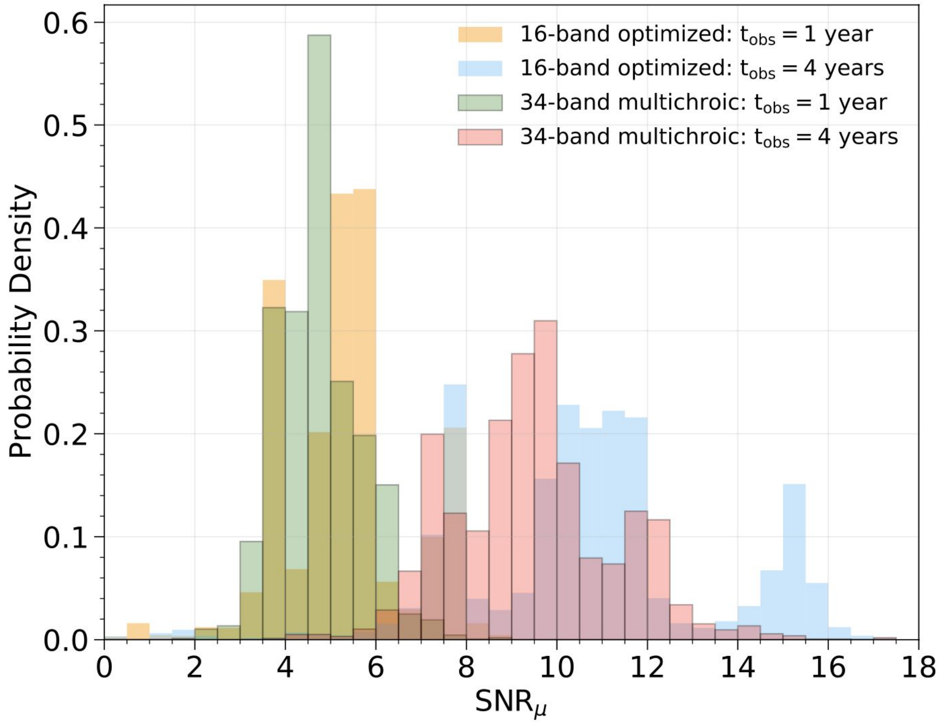
Sky model robustness:
to what extent do the results depend on the fiducial sky model?



- ➔ **Vary foreground** spectral parameters (e.g., within 20%, ~16000 combinations)
- ➔ In **<1%** of cases, SNR **< 1σ**
- ➔ Similarly likely to get a **higher** SNR!
- ➔ **Higher frequency resolution + longer observation time** → more **robust** to sky modeling assumptions
- ➔ 34-band multichroic + t_{obs}=4 years: **< 1% chance of < 5σ detection**!

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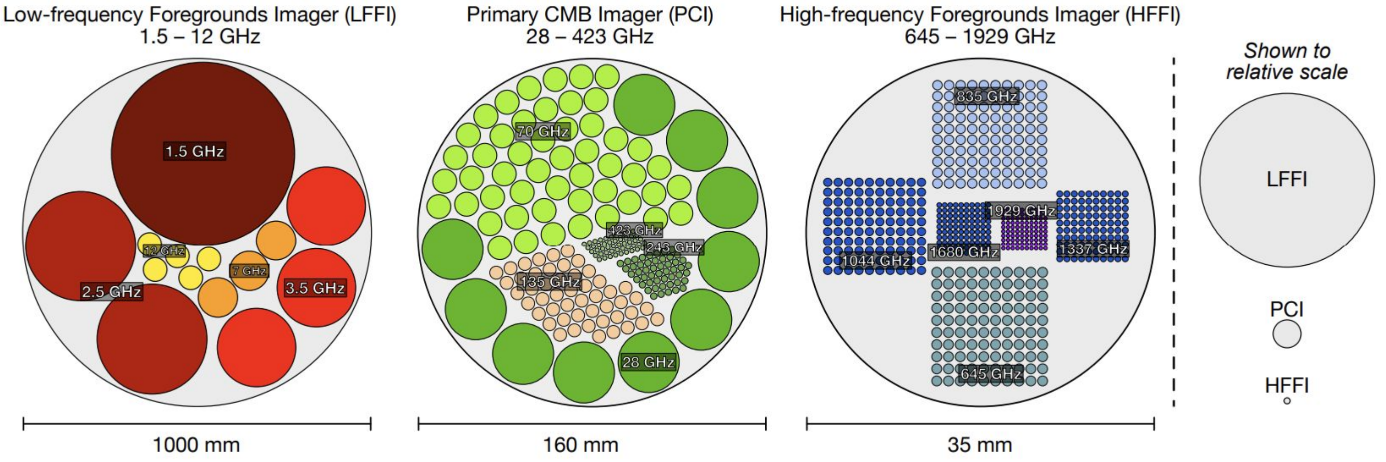
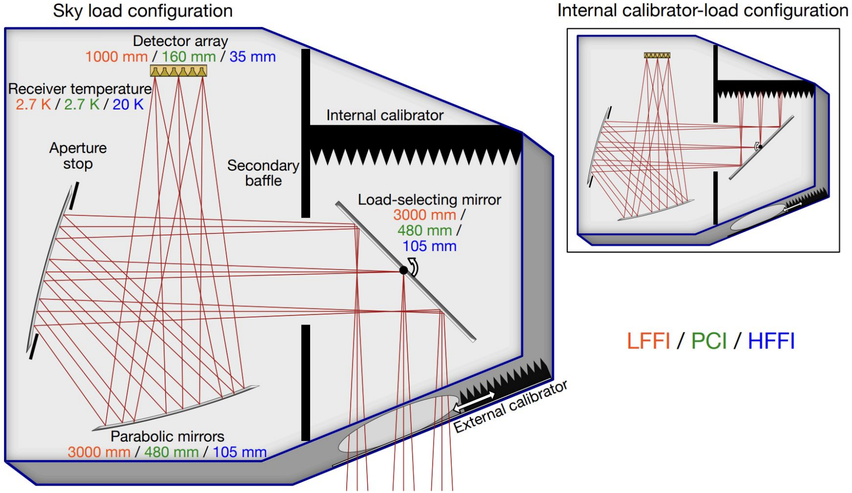
SPECTER:





Calibration requirements:

- **2-3 calibrators** are required at most.
- **~10^{-3} μK_{RJ}** calibration + can **lower the requirements for LFFI** to ~10^{-2} μK_{RJ}.

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A new constraint on the y-distortion with *FIRAS*

with Giulio Fabbian, Colin Hill, Federico Bianchini (**Sabyr**+in prep. 2024c, Fabbian+in prep. 2024)

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Motivation:

(1) validate current Fisher forecasts (e.g., *SPECTER, PIXIE, Voyage 2050*)

(2) compare analysis techniques (*pixel-by-pixel* vs. *frequency monopole*)

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(2) compare analysis techniques (*pixel-by-pixel* vs. *frequency monopole*)

Ingredients:

1. Sky model. $I_\nu^{sky} = \Delta B_\nu + I_\nu^y + I_\nu^{\rm fg}.$
2. *FIRAS* Covariance:

$$\begin{aligned} \mathbb{C}_{\nu p \nu' p'} &= {\rm Cov}(\hat{I}^{\rm FIRAS}_{\nu p}, \hat{I}^{\rm FIRAS}_{\nu' p'}) \\ &= C_{\nu\nu'}\left(\delta_{pp'}/N_p + \beta_p^k \beta_{p'k} + 0.04^2\right) \quad \textbf{noise} \\ &+ S_{p\nu} S_{p'\nu'}\left(J_\nu J_{\nu'} + G_\nu G_\nu \delta_{\nu\nu'}\right) \quad \textbf{gain error} \\ &+ P_\nu P_{\nu'}\left(U^2 \delta_{pp'}/N_p + T^2\right). \quad \textbf{systematics} \end{aligned}$$

3. *FIRAS* sky maps:

~68 GHz – 3 THz ($\Delta\nu$= 13 GHz, 210 frequency channels)

~3.5° resolution

preliminary

Frequency monopole – fitting sky-averaged spectrum

Pixel-by-pixel – fitting spectra in each pixel

Data:

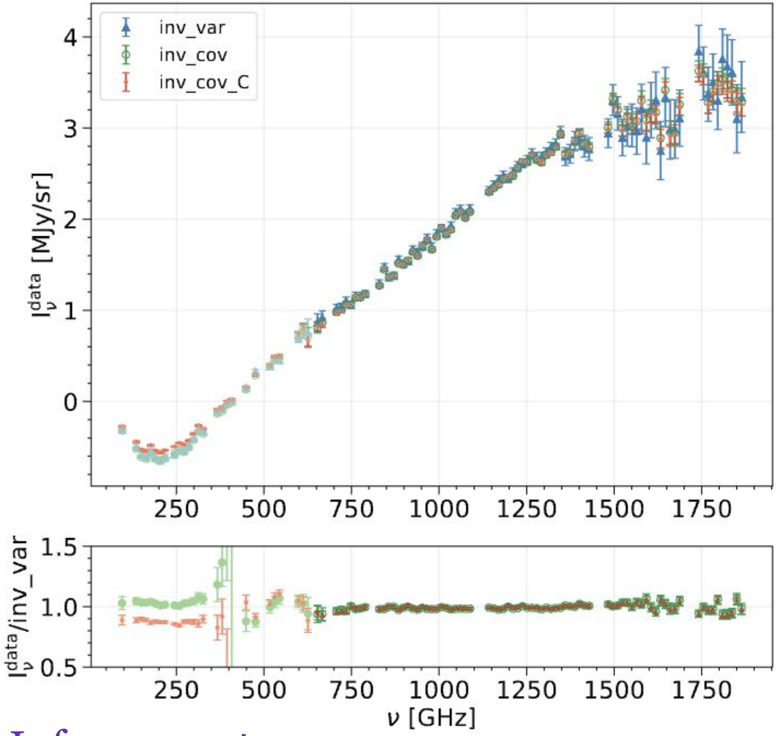
Frequency ranges:

- $\mathbf{v_{600}}$: 27 channels, 95-626 GHz
- $\mathbf{v_{800}}$: 36 channels, 95-626 GHz and 653-789 GHz

Three averaging methods for *frequency monopole*:

- **inv_cov**–inverse covariance (instrumental noise + systematics)
- **Inv_var** – inverse variance (instrumental noise + systematics)
- **inv_cov_C** – inverse covariance (instrumental noise)

Masks: P20, P40, P60



Inference set-up:

➔ Gaussian likelihood.

➔ Covariance– frequency-frequency correlation from instrumental noise

➔ NUTS + emcee

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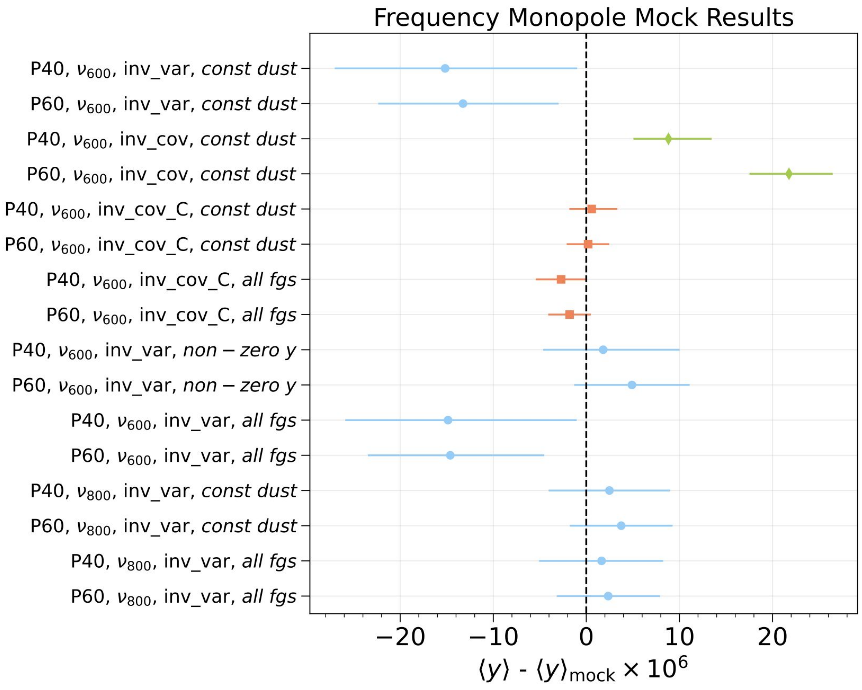
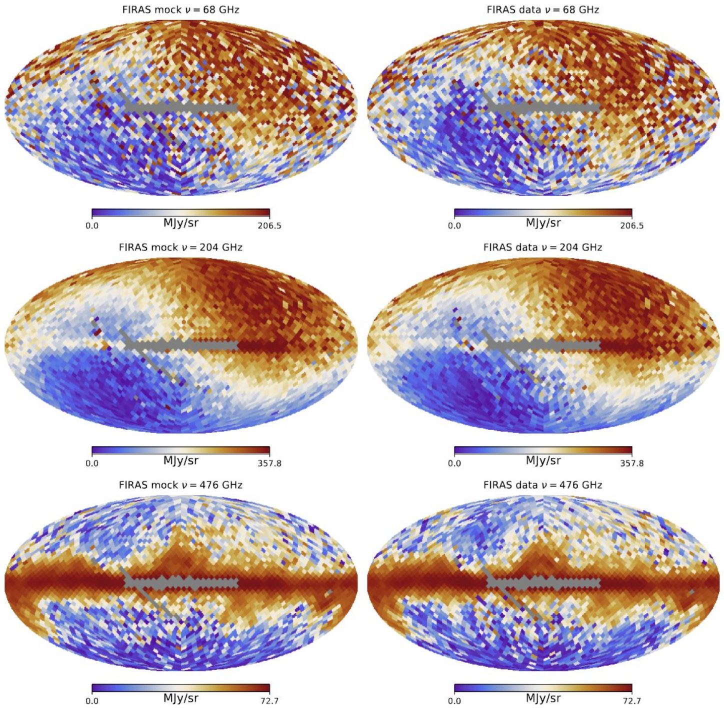
Results from Mocks



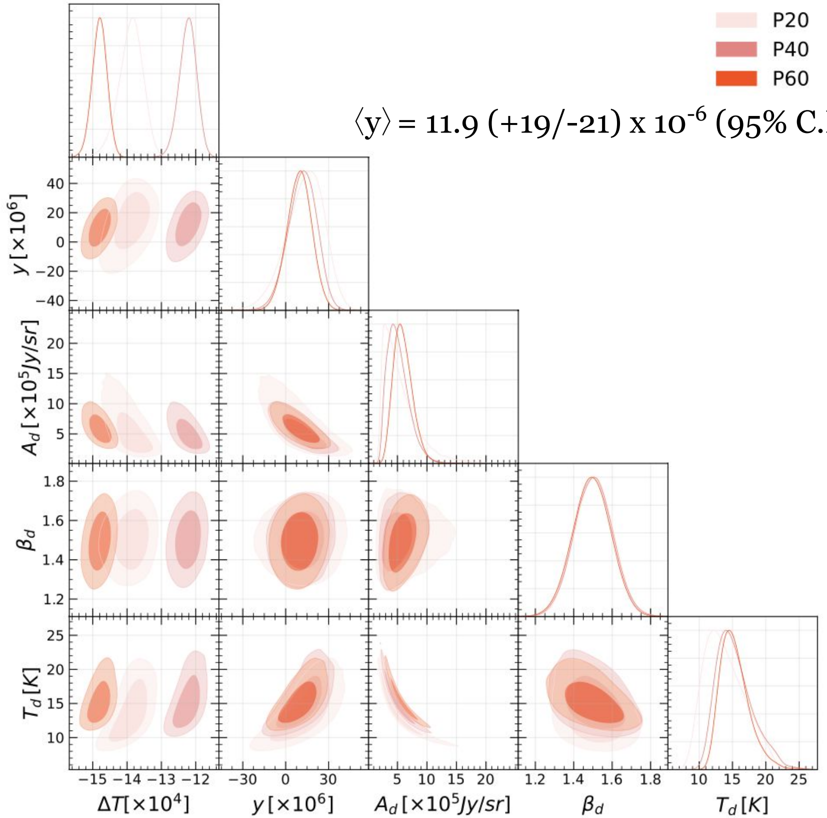


Adopt **inv_var** method for the *frequency monopole*.

Adopt flat priors for the *pixel-by-pixel* method.

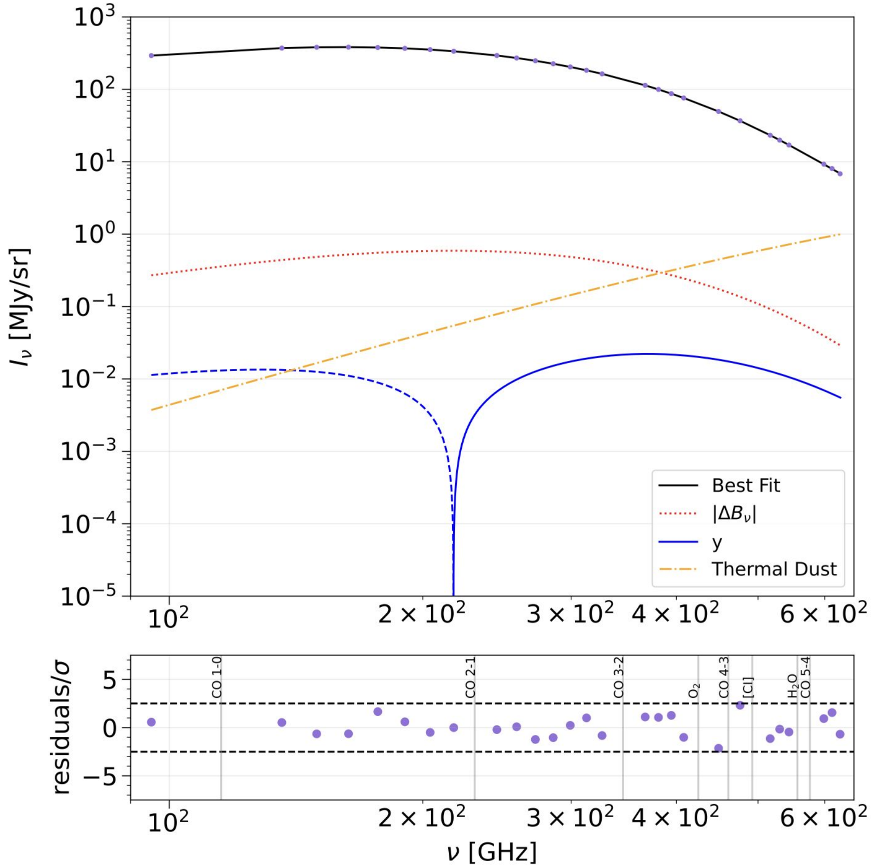
preliminary

Results from data: *frequency monopole*



$\langle y \rangle = 11.9\ (+19/-21) \times 10^{-6}$ (95% C.L.)

$$\chi^2 \approx 18.4/25.5/41.4\,(\mathrm{DOF} = 22)$$



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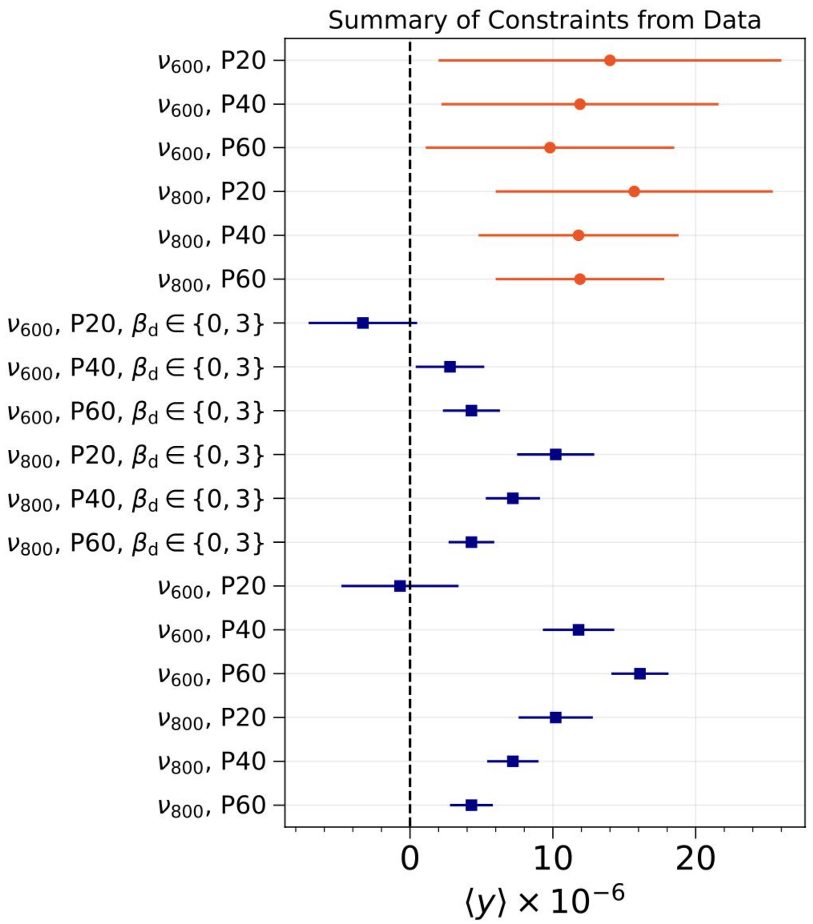
Method comparison:

***pixel-by-pixel* –**

~4x tighter constraints than from the *frequency monopole*

Fisher forecast validation:

Great agreement (within ~10%) between Fisher forecasts and the results from *frequency monopole*!

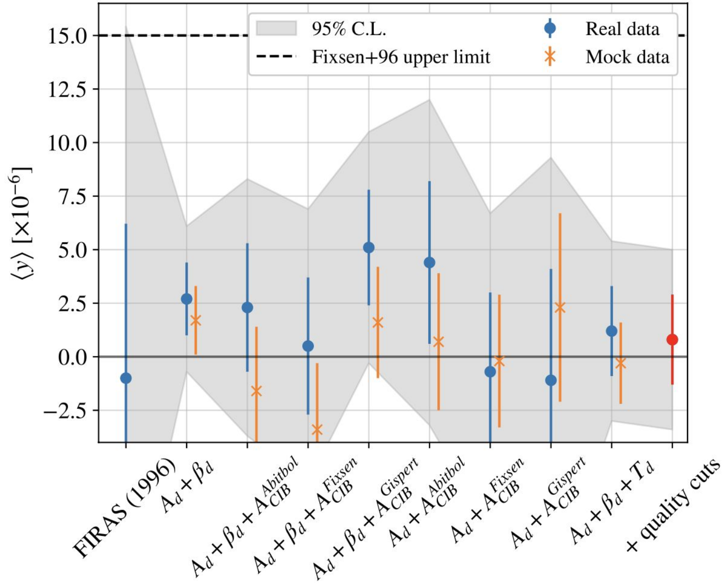


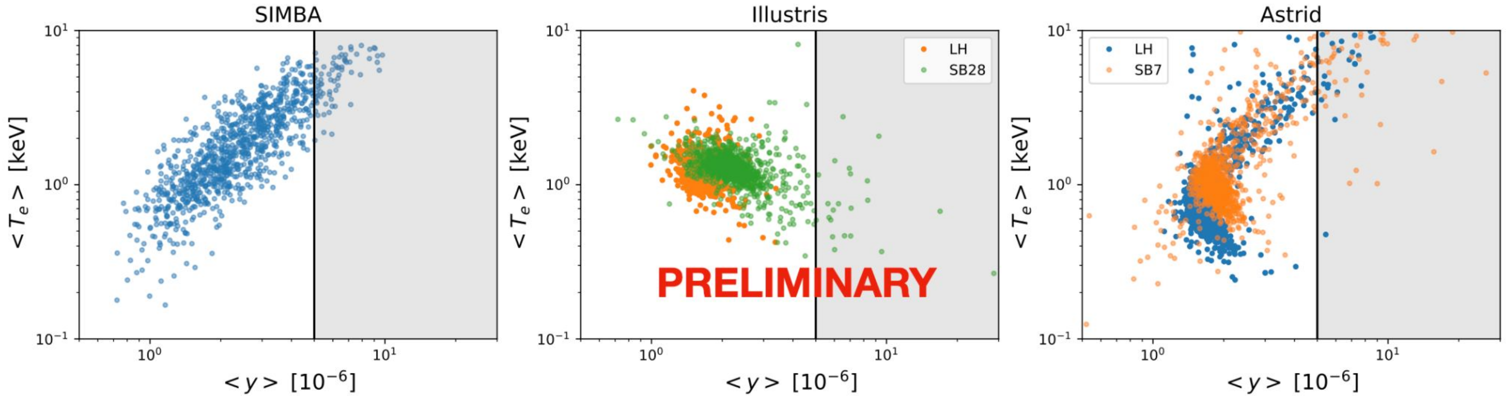
preliminary

Interpretation:

Fabbian+in prep. 2024

Stay tuned!





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Summary and future directions:

- ➔ *SPECTER* can detect **μ-distortion** at **5σ (10σ)** assuming t_{obs}=1 (4) year(s) after **marginalizing over foregrounds**!
- ➔ **16-bands** spanning **1-2000 GHz** with 1046 total detectors & three separate instruments.
- ➔ Can perform well even if the true sky differs from the fiducial (!)

- ➔ **Fisher** forecast approach **validated directly with *FIRAS*** data!
- ➔ **Better constraints** can be achieved using spatial information (i.e. ***pixel-by-pixel*** method).
- ➔ Both analysis techniques need to be applied (**robustness** & different **advantages**).
- ➔ Proof of principle: a new constraint on <y> → can rule out some hydro sims!

What next?

- ➔ The cost is driven by the **lowest-frequency bands.** Can we obtain 1.5-3.5 GHz absolute temperature calibrated observations from the **ground**?
- ➔ Further development of the **forecast set-up** (e.g. sky models).
- ➔ **Prototype** y-distortion mission.