Future cosmology with CMB spectral distortions and secondaries

Alina Sabyr

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

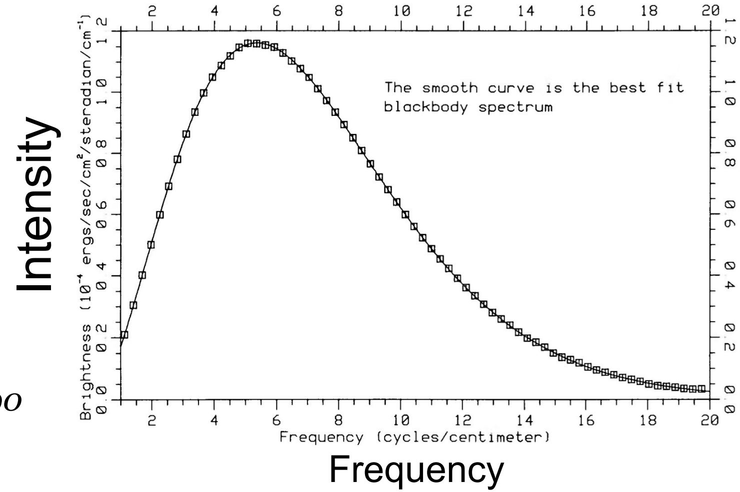
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

INPA seminar, 06/12/2024

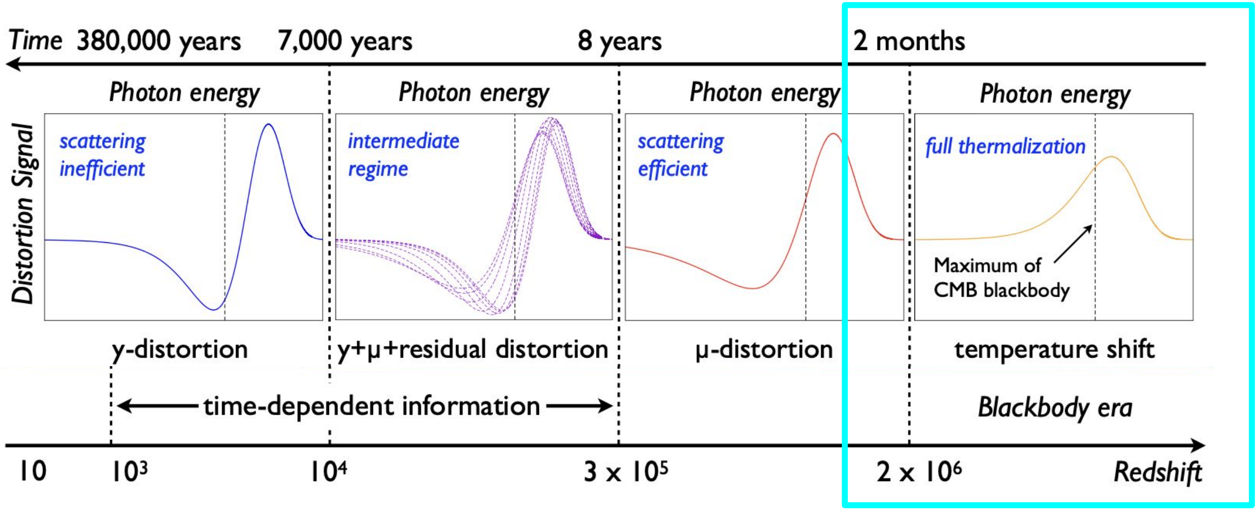
Future cosmology with CMB spectral distortions and secondaries

small deviations of the CMB energy spectrum from that of a perfect blackbody.

Mather+1990



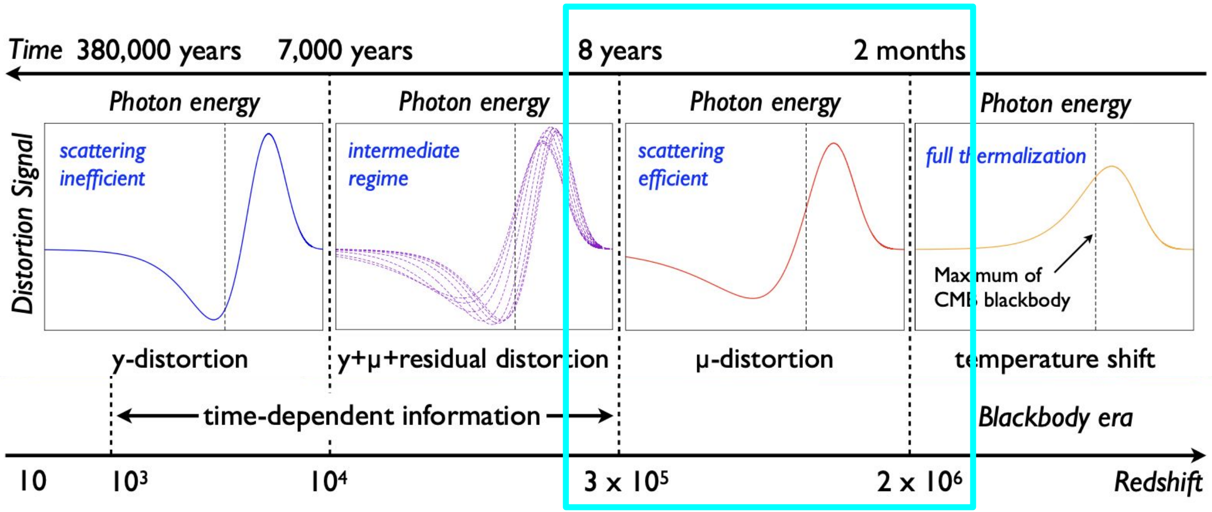
CMB spectral distortions: quick review



(figure adapted from Chluba+2021)

Compton scattering, double-Compton & bremsstrahlung emission → maintain thermal equilibrium

CMB spectral distortions: quick review



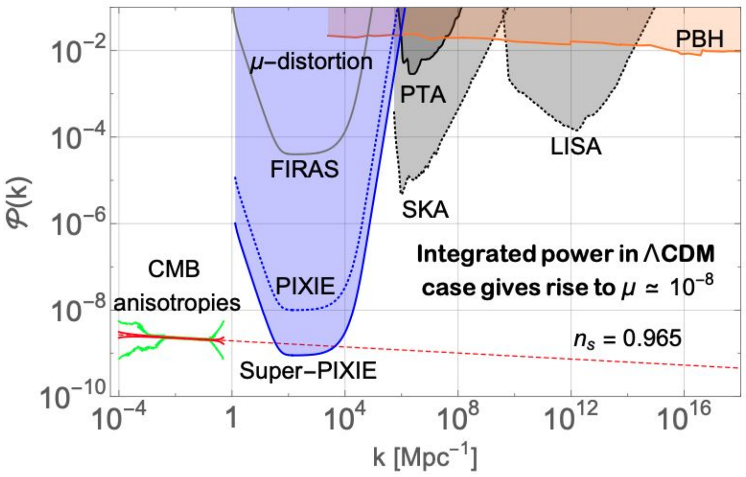
(figure adapted from Chluba+2021)

Compton scattering still efficient

μ-distortion → fundamental physics

CMB spectral distortions: quick review

μ-distortion → fundamental physics



Chluba+2019, Chluba+2021

➔ Generated in the **early Universe.**

➔ Within ΛCDM: **Silk damping** & baryon cooling

➔ Sensitive to primordial power spectrum on **small scales.**

$$\langle \mu \rangle \approx \int \frac{k^2\, \mathrm{d}k}{2\pi^2} P(k)\, W_\mu(k)$$

e.g., Chluba+2012, Chluba+2015

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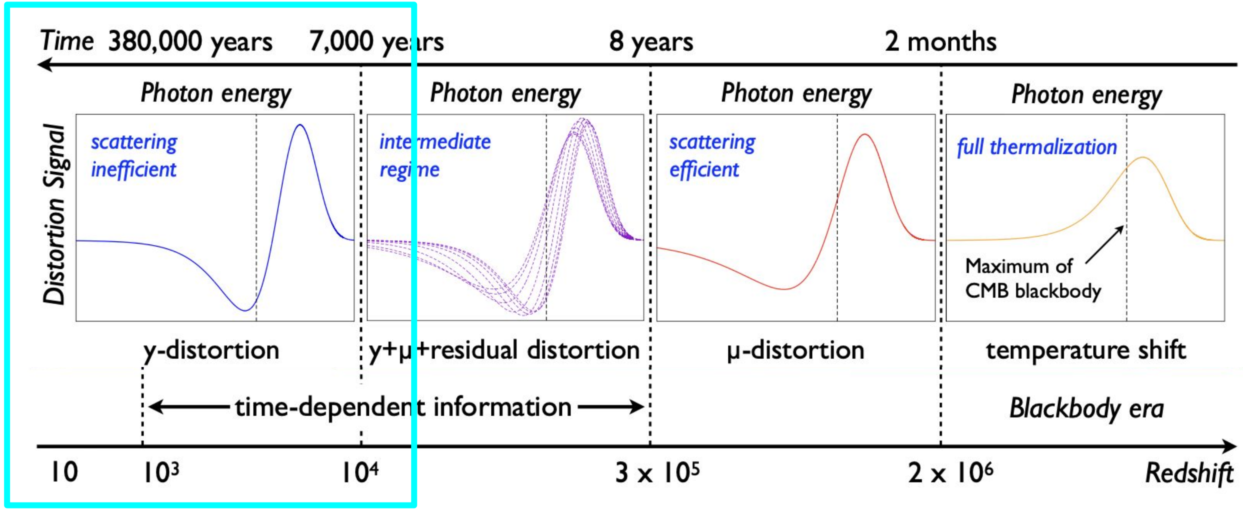
CMB spectral distortions: quick review

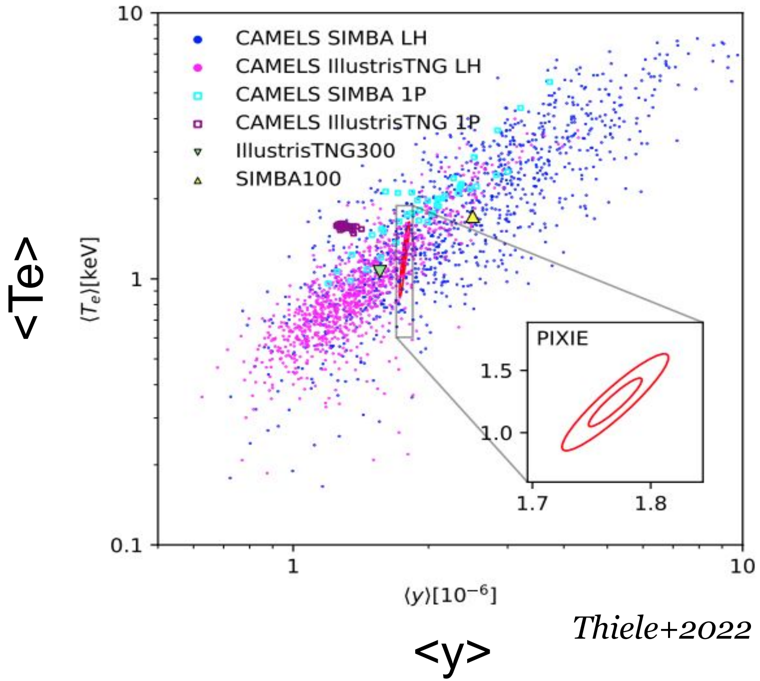


(figure adapted from Chluba+2021)

y-distortion → astrophysics

CMB spectral distortions: quick review

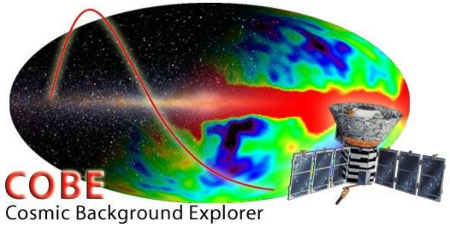
y-distortion → astrophysics



Thiele+2022

- Known source: thermal Sunyaev-Zel'dovich effect **(tSZ)** – inverse Compton scattering of CMB photons on free, energetic electrons, primarily in **galaxy groups & clusters.**
- Probes the **late-time Universe.**
- Total thermal **energy** + mean **temperature** of electrons.

CMB spectral distortions: current status

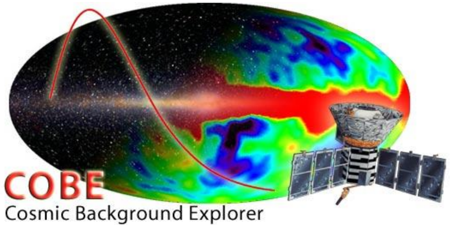


Upper limits from *COBE/FIRAS* (flew in **1990's**!):

➔ $\langle y \rangle$: < 15 x 10^{-6} (Fixsen+1996)

➔ $\langle \mu \rangle$: < 90 x 10^{-6} (Fixsen+1996), < 47 x 10^{-6} (Bianchini & Fabbian 2022)

CMB spectral distortions: current status



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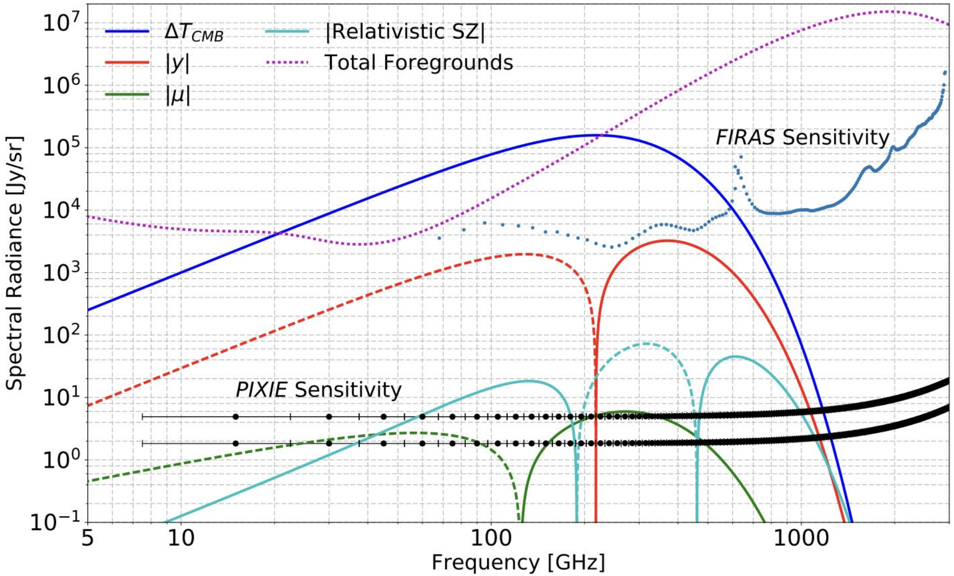
Why are there no additional direct and recent constraints?

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

➔ Astrophysical **foregrounds**.

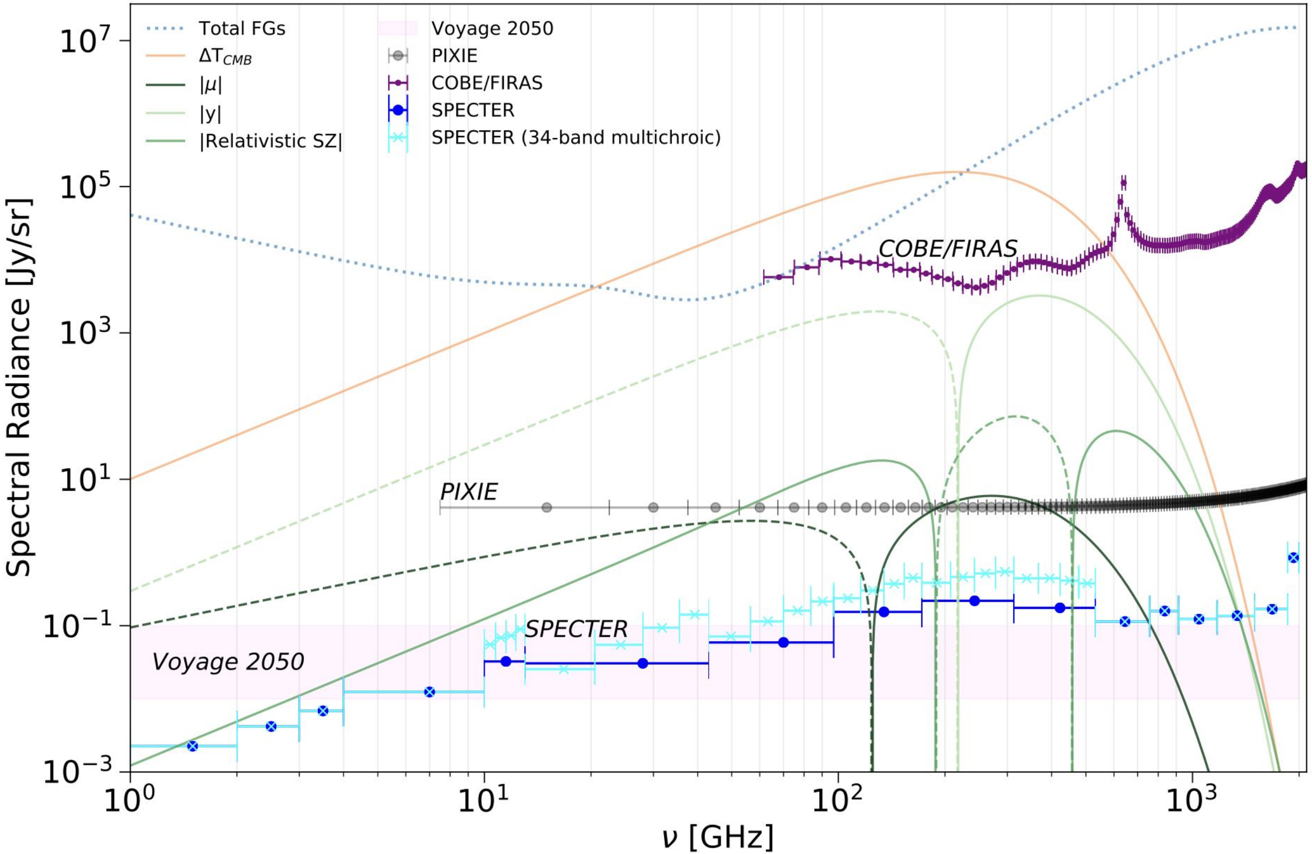


Abitbol+2017

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

with Carlos Sierra, Colin Hill, Jeffrey J. McMahon

arXiv:2409.12188



Key idea:

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

Ingredients:

- ➔ Sensitivity calculator: **bolocalc-space**[1] *(based on BoloCalc, Hill+2018)*
  - ◆ HEMT amplifiers at ν < 10 GHz; bolometers at ν > 10 GHz.

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

Ingredients:

- Sensitivity calculator: **bolocalc-space**[1] *(based on BoloCalc, Hill+2018)*
  - HEMT amplifiers at $\nu < 10$ GHz; bolometers at $\nu > 10$ 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.**

Total sky signal: $$I_\nu = \Delta B_\nu + I_\nu^y + I_\nu^{\mathrm{rel-tSZ}} + I_\nu^\mu + I_\nu^{\mathrm{fg}}.$$

Fisher matrix: $$F_{ij} = \sum_{\nu,\nu'} \frac{\partial I_\nu}{\partial p_i} C^{-1}_{\nu\nu'} \frac{\partial I_\nu}{\partial p_j}$$

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

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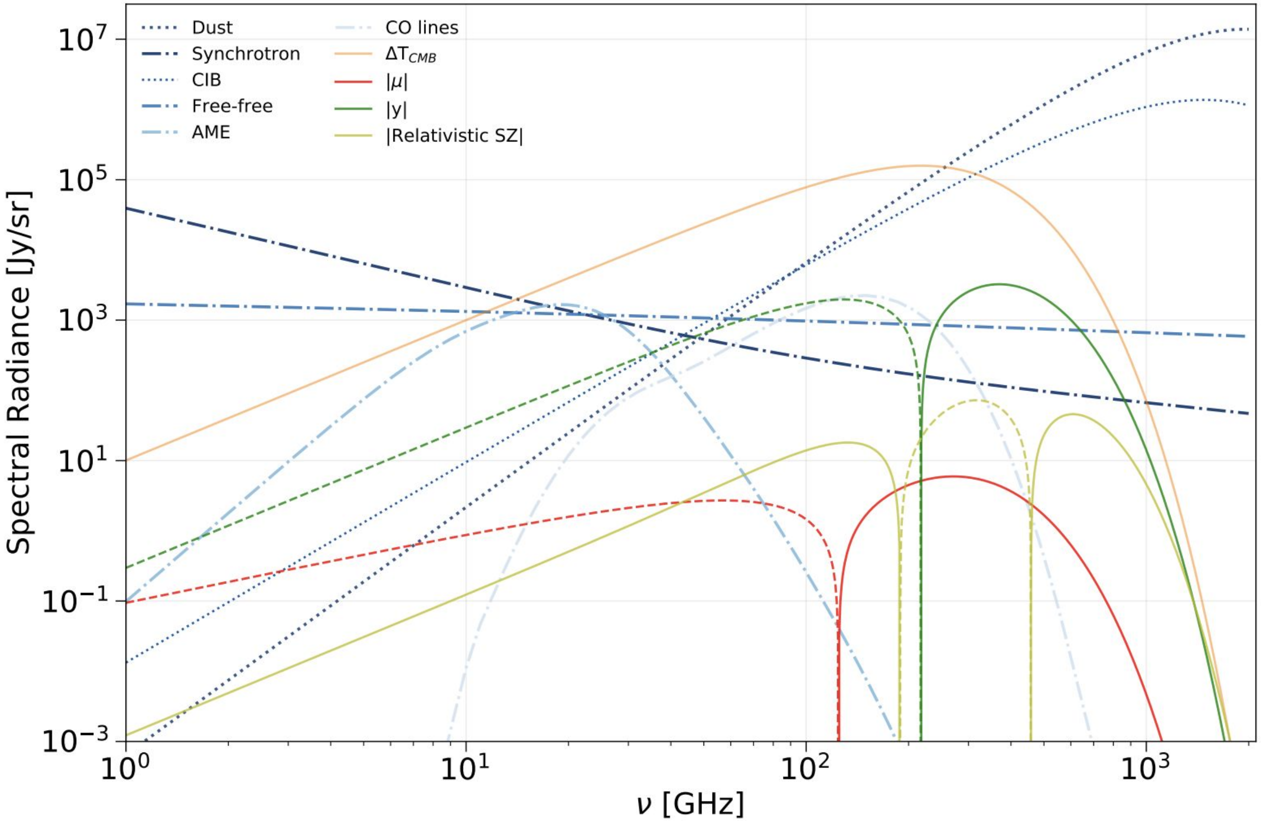
  - ◆ Total **16 free parameters.**
- ➔ Optimization/robustness tests pipeline: **specter_optimization**[3]

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

All three codes publicly available!

[1] https://github.com/csierra2/bolocalc-space
[2] https://github.com/asabyr/sd_foregrounds_optimize
[3] https://github.com/asabyr/specter_optimization



y-distortion:

$y=1.77 \times 10^{-6}$

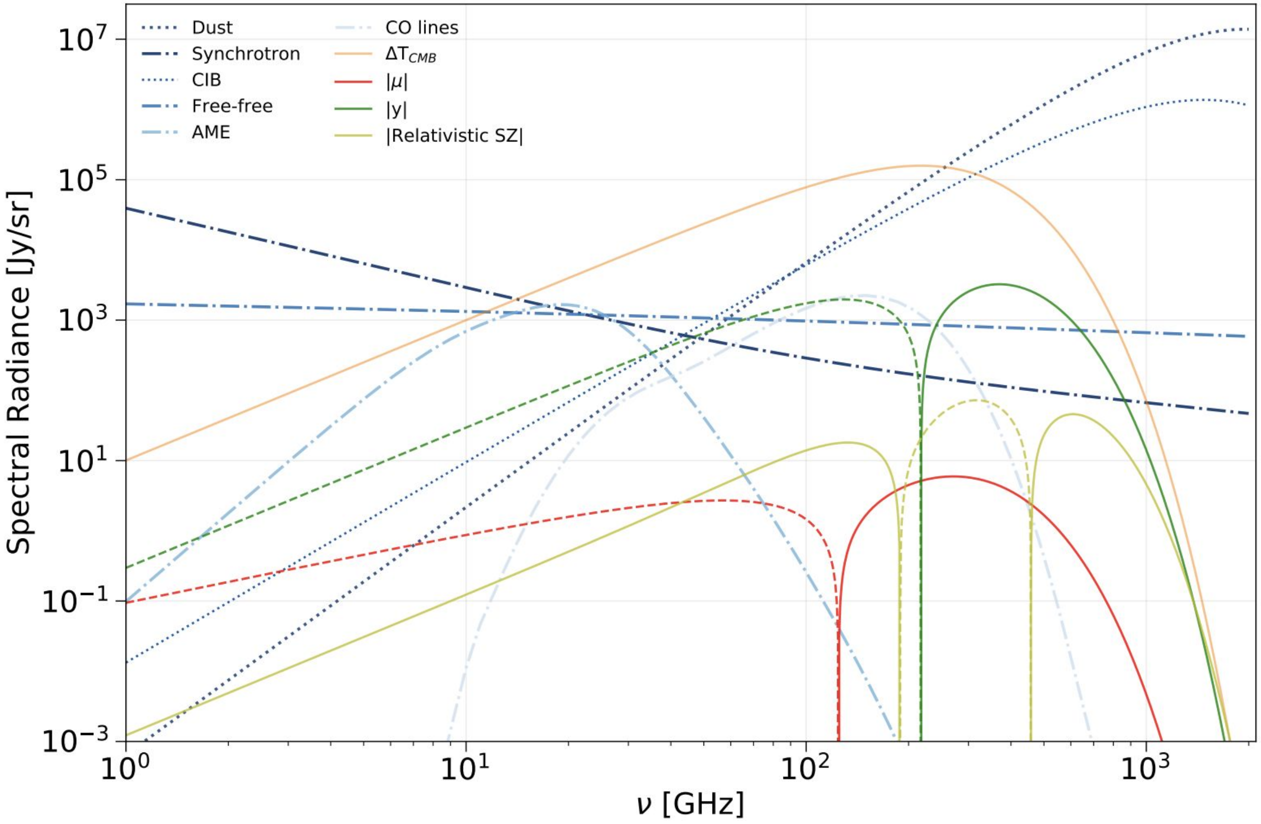
$k_B T_{eSZ}=1.245$ keV

Intracluster medium + intergalactic medium + reionization contributions based on halo model/simulations (Hill+2015).

μ-distortion:

$\mu=2 \times 10^{-8}$

Consistent with current constraints on the primordial power spectrum (e.g., Chluba+2012, Cabass+2016).



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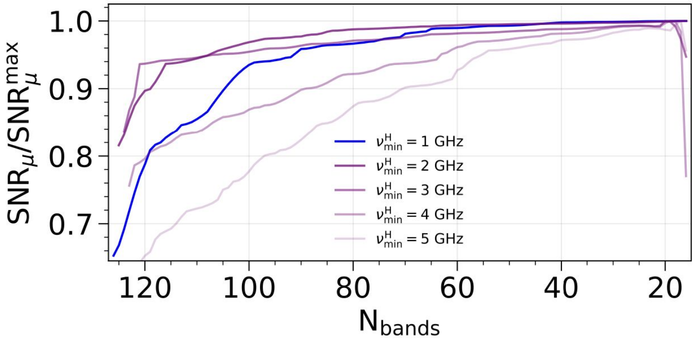
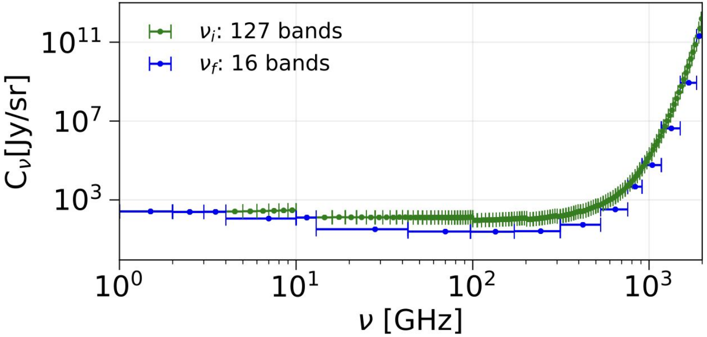
Large configuration space to explore!

(1) Find optimal frequency bands

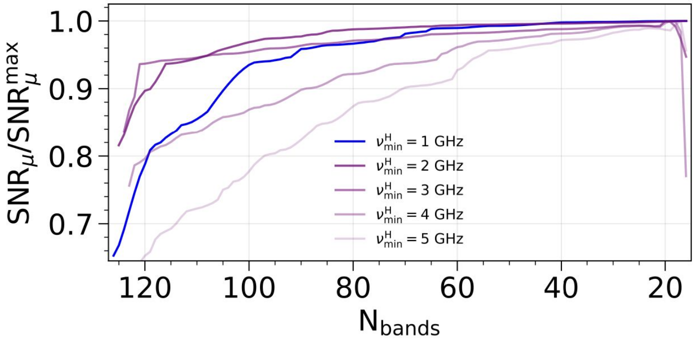


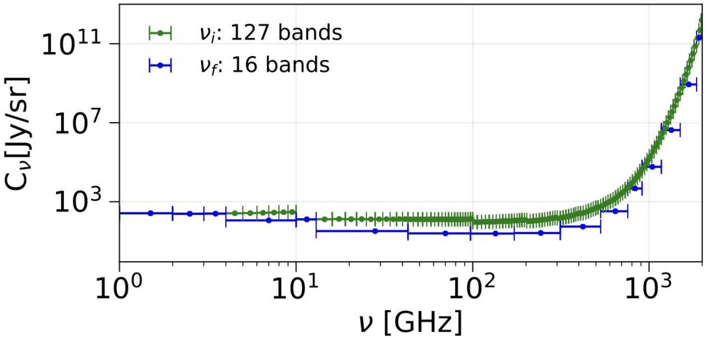


➔ Start with **narrow frequency bands**.

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

(1) Find optimal frequency bands



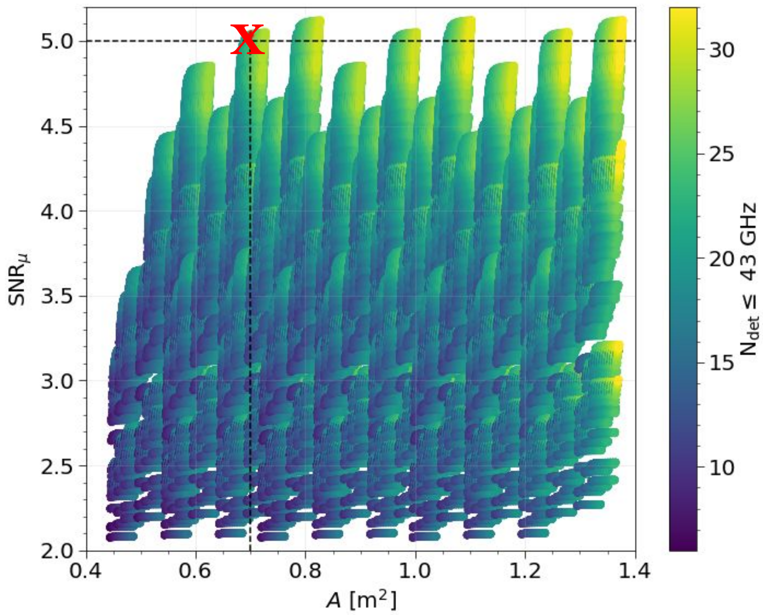


➔ Start with **narrow frequency bands**.

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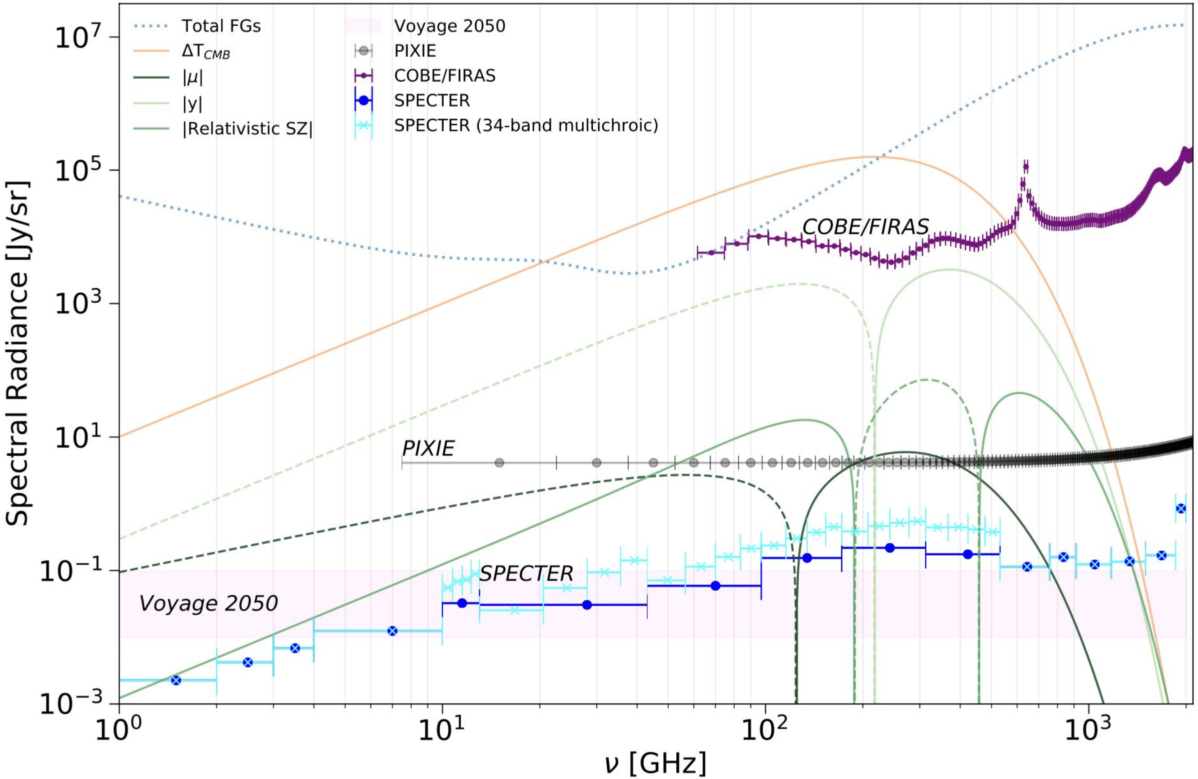
parameter & fiducial value	16-band optimized		34-band multichroic	
	SNR	σ	SNR	σ
$\Delta_T = 1.2 \times 10^{-4}$	37157	3.2×10^{-9}	30378	4.0×10^{-9}
$\mu = 2 \times 10^{-8}$	5	4.0×10^{-9}	4.5	4.4×10^{-9}
$y = 1.77 \times 10^{-6}$	955	1.9×10^{-9}	807	2.2×10^{-9}
$k_B T_{eSZ} = 1.245$ keV	33	0.037	42	0.029

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.



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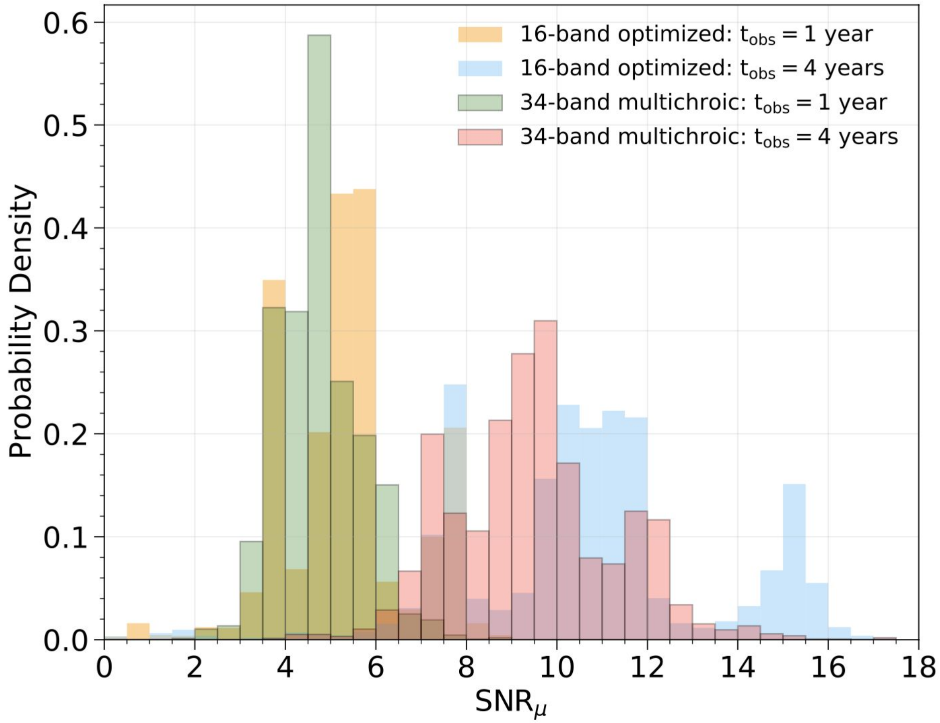
34-band multichroic: more frequency **resolution** at **no additional cost**!

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



- ➔ **Vary foreground** spectral parameters (e.g., ~16000 combinations)
- ➔ Can obtain **higher** SNR!
- ➔ Higher **frequency resolution + longer observation time** → more **robust** to sky modeling assumptions.

e.g., 34-band multichroic + t_{obs}=4 years:
< 1% chance of < 5σ detection!

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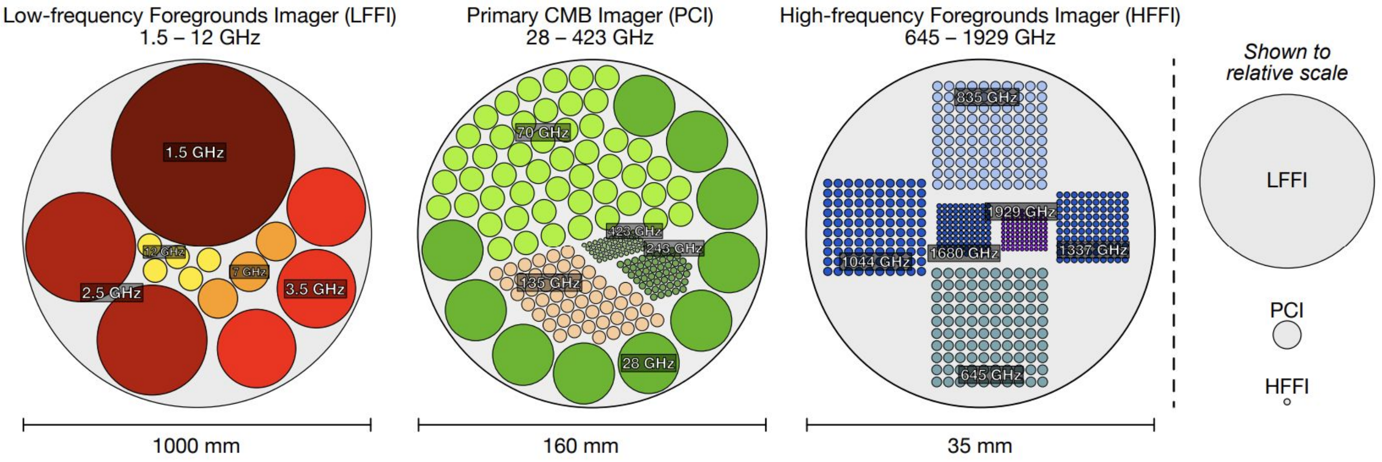
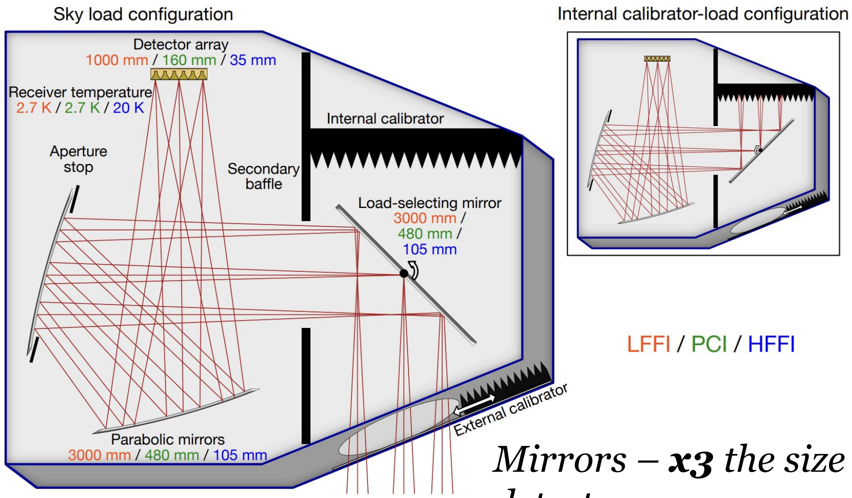
SPECTER:

Split into 3 instruments.

➔ *Total focal plane area ~0.8 m²*





*Mirrors – **x3** the size of the detector array.*

Calibration requirements:

➔ **2-3 calibrators** are required at most.

➔ **$\sim 10^{-3}$ μK_{RJ}** calibration + can **lower the requirements for LFFI** to $\sim 10^{-2}$ 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*)

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

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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*)

Ingredients:

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

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

3. *FIRAS* sky maps:

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

~3.5° resolution

Frequency monopole – fitting sky-averaged spectrum.
Pixel-by-pixel – fitting spectra in each pixel.

Data:

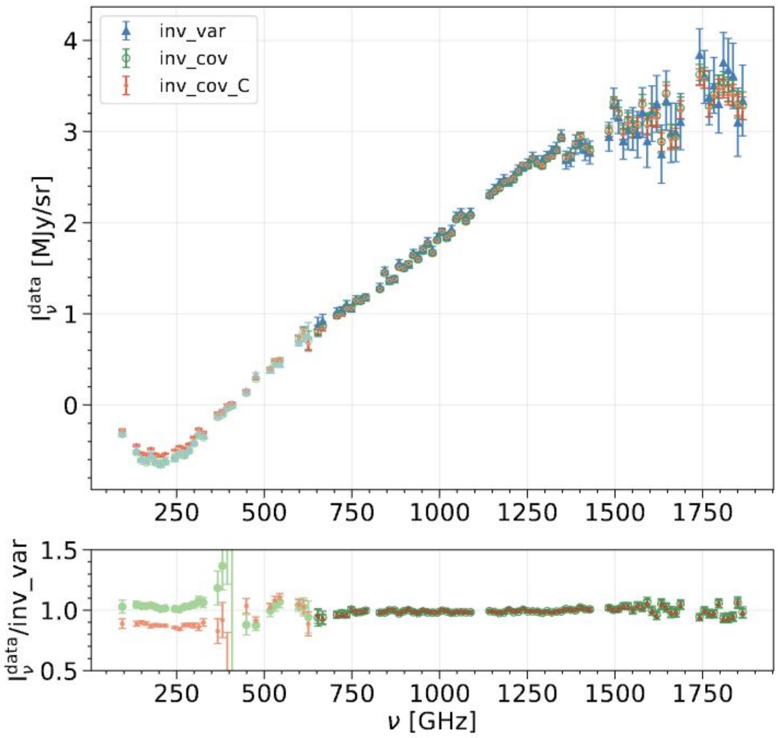
Frequency ranges:

- **ν_{600}**: 27 channels, 95-626 GHz
- **ν_{800}**: 36 channels, 95-626 GHz and 653-789 GHz

Three averaging methods for the *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

preliminary

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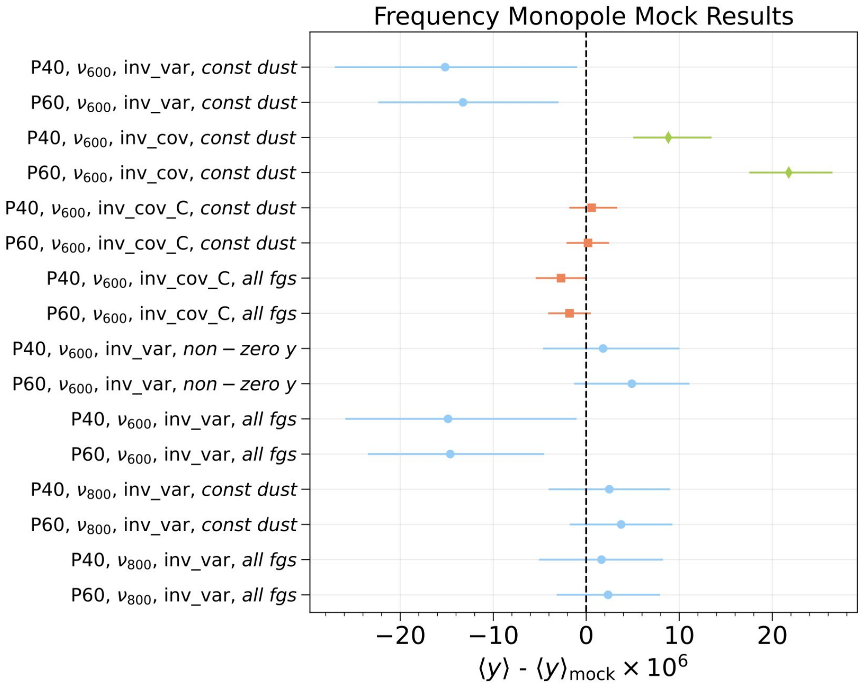
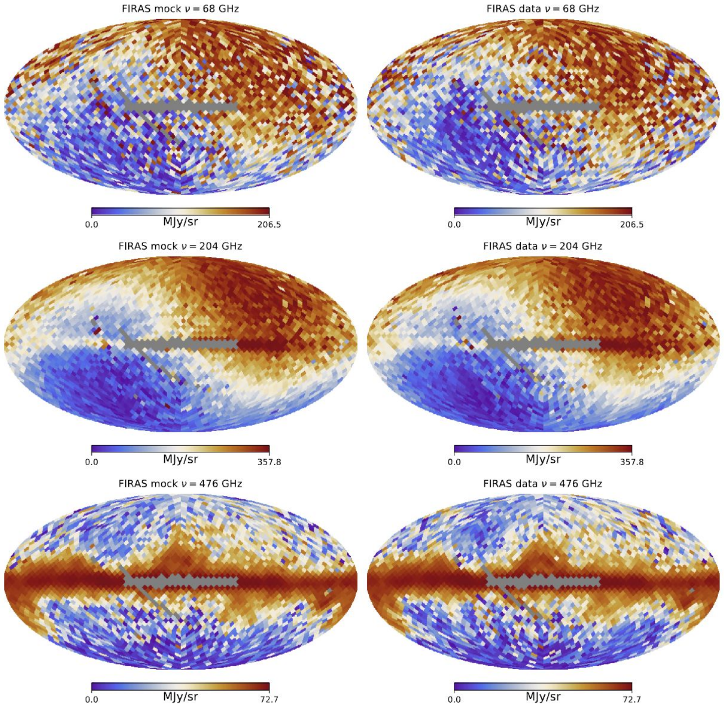
Results from Mocks

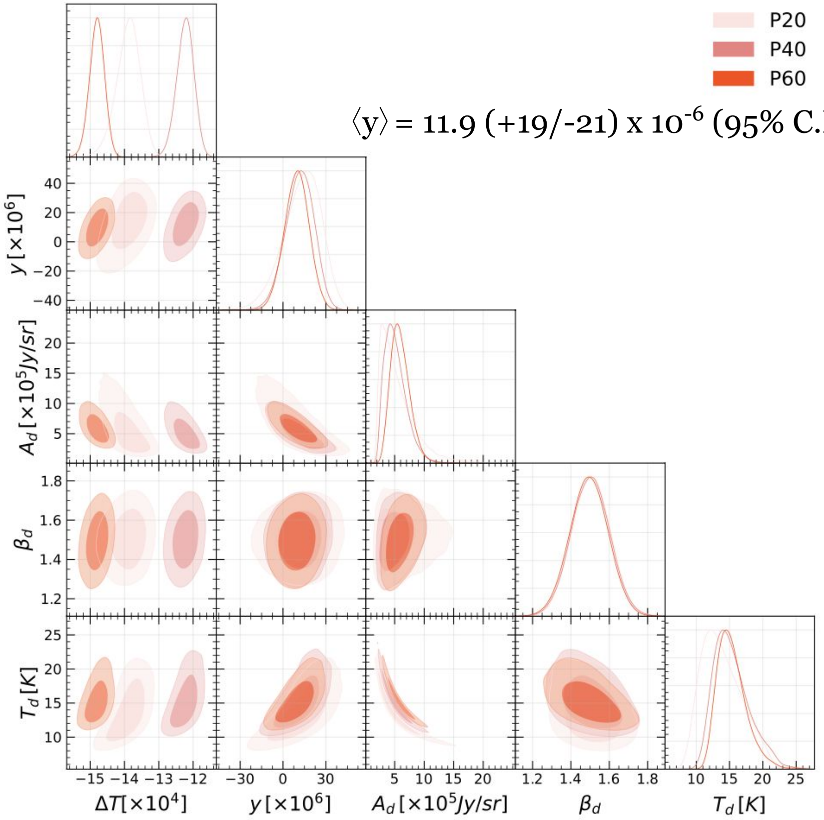




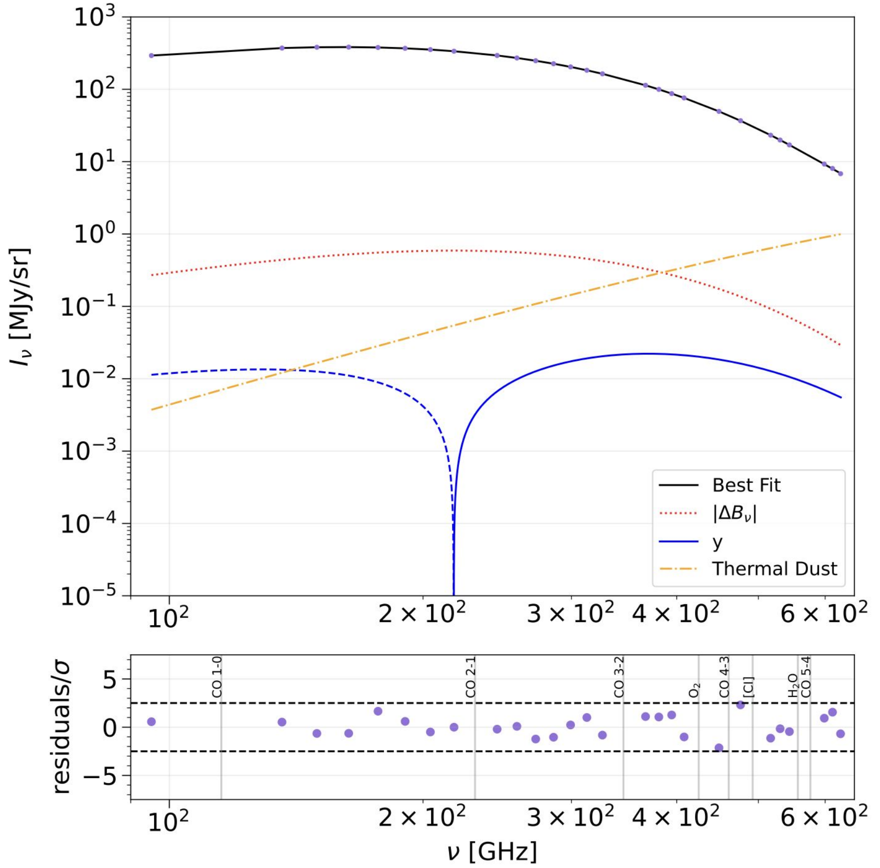
- ➔ Adopt **inv_var** method for the *frequency monopole*.
- ➔ Adopt flat priors for the dust in the *pixel-by-pixel* method.

preliminary

Results from data: *frequency monopole*



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



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

preliminary

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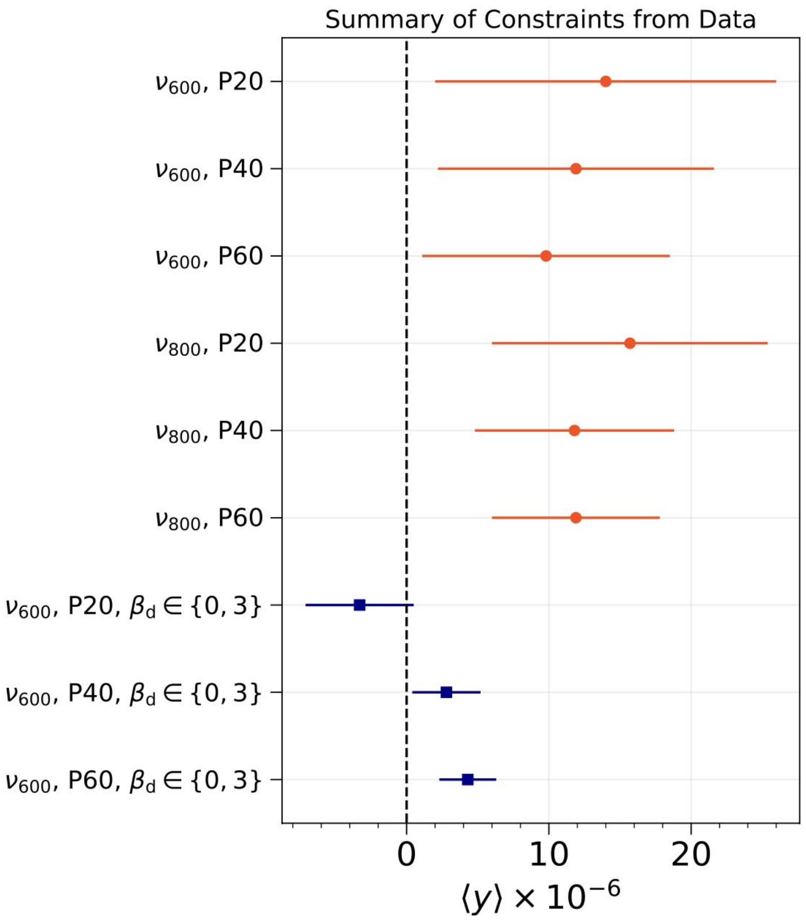
Method comparison:

***pixel-by-pixel* –**

~3-4x tighter constraints than from the *frequency monopole*

Fisher forecast validation:

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

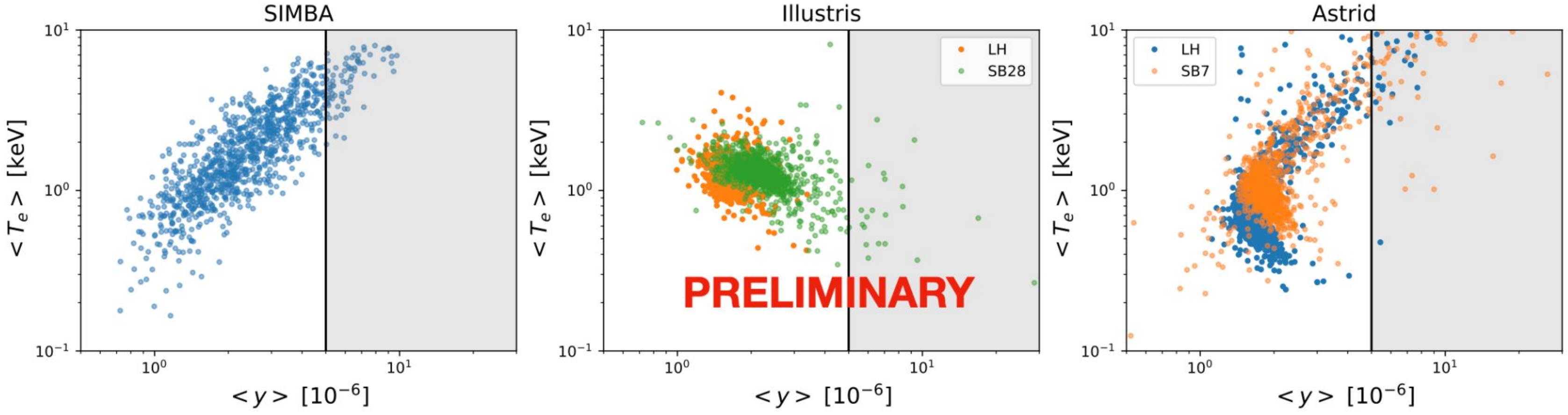


preliminary

Interpretation:

Fabbian+in prep. 2024

Stay tuned!



preliminary

Summary:

- *SPECTER* can detect **μ-distortion** → probe early Universe/fundamental physics!
- Fisher forecast approach **validated with *FIRAS*** data.
- **Better constraints** can be achieved using spatial information → forecasts are conservative.

What is 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 **instrumentation** & **forecast set-up**.
- **Prototype** y-distortion mission.

Future cosmology with CMB spectral distortions and secondaries

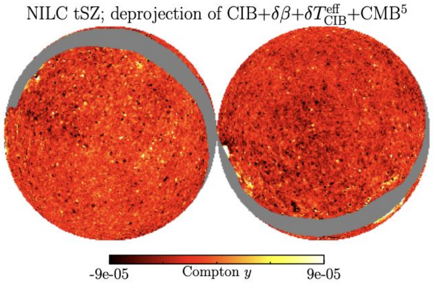
Alina Sabyr, Columbia University

Constraining cosmology with the thermal Sunyaev-Zel'dovich maps: Minkowski functionals, peaks, minima, and moments

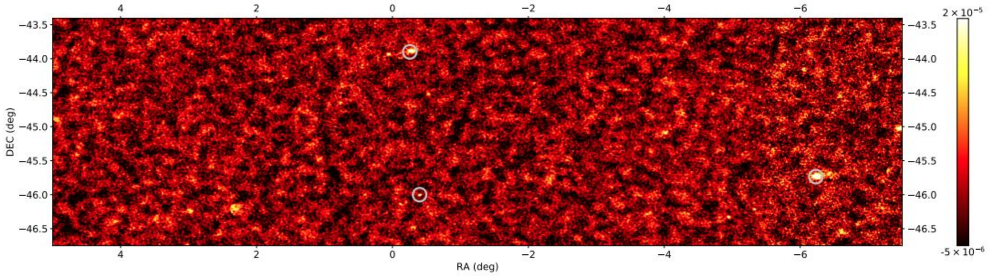
with Colin Hill, Zoltan Haiman (**arXiv:2409.12188**)

- **Thermal Sunyaev-Zel'dovich (tSZ) effect** – inverse-Compton scattering of CMB photons off of free, energetic electrons.
- Sourced by **galaxy groups & clusters**:
  - Powerful cosmological & astrophysical probe σ_8, M_ν, w (e.g., see Komatsu & Seljak 2002, Hill & Pajer 2013, Bolliet+2018)
  - Highly **non-Gaussian.**
  - Can be used via **cluster counts** & **statistically**.

McCarthy & Hill 2024

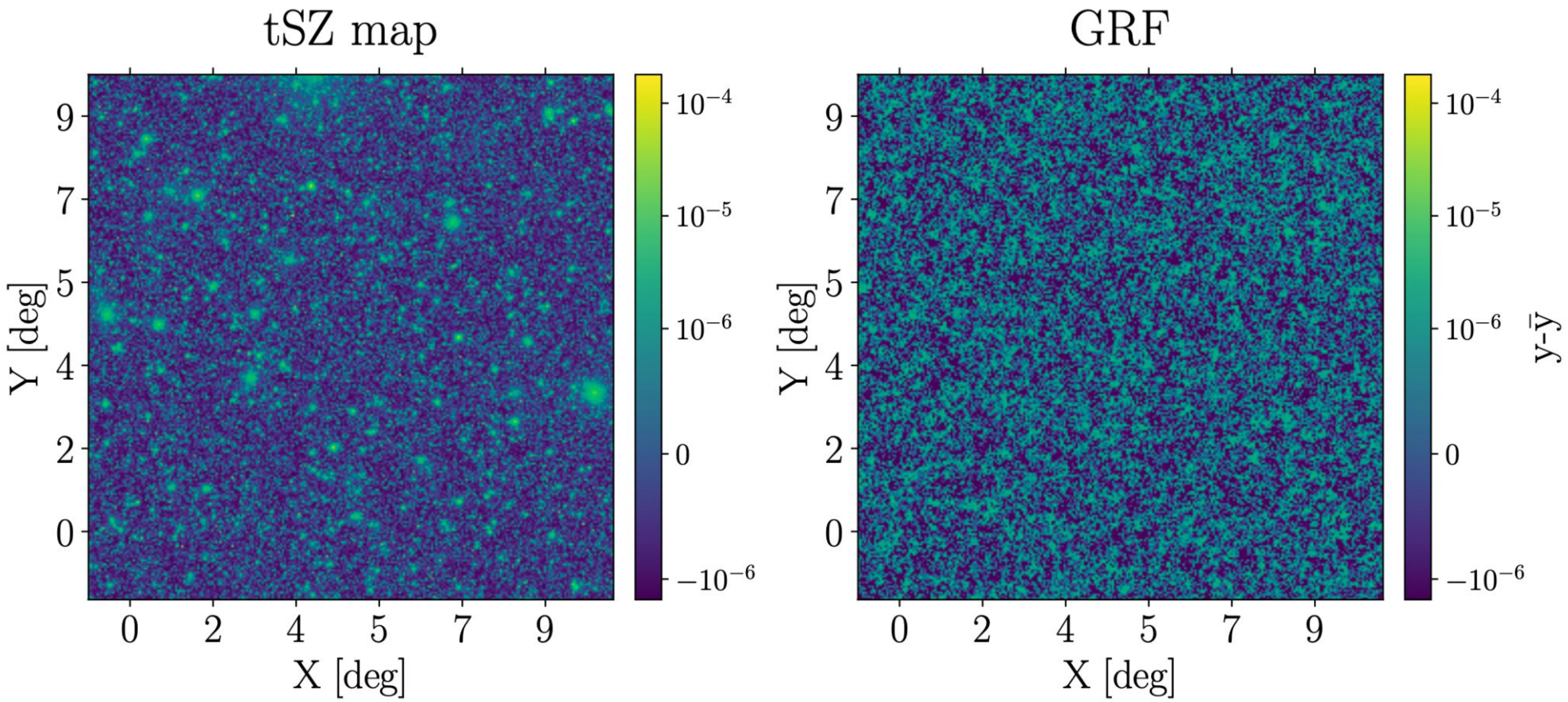


Coulton+2024



(c) Compton-y map.

unique spectral signature → component-separated maps!

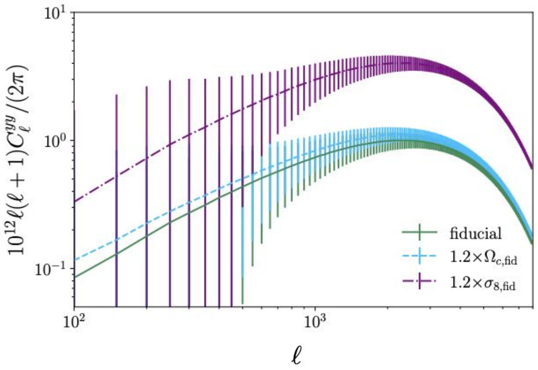


What is the optimal tSZ summary statistic?

Summary statistics:

➔ **power spectrum**

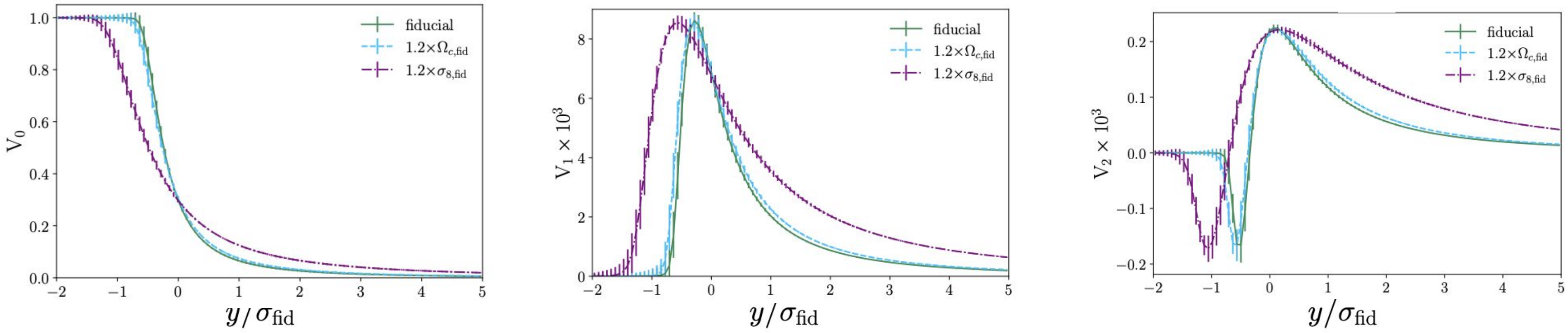
$\ell \in \{25, 7925\}$



Computed via **LensTools** (Petri 2016) https://github.com/apetri/LensTools

Summary statistics:

- ➔ **power spectrum**
- ➔ **Minkowski functionals (MFs)** – V_0 ~ area, V_1 ~ contour length, V_2 ~ genus



$$V_0(\nu) = \frac{1}{A}\int_A \Theta(y(\mathbf{p}) - \nu)didj$$

$$V_1(\nu) = \frac{1}{4A}\int_A \delta(y(\mathbf{p}) - \nu)\sqrt{y_i^2 + y_j^2}didj$$

$$V_2(\nu) = \frac{1}{2\pi A}\int_A \delta(y(\mathbf{p}) - \nu) \times \frac{2y_i y_j y_{ij} - y_i^2 y_{jj} - y_j^2 y_{ii}}{y_i^2 + y_j^2}didj$$

Hadwiger's theorem: D+1 MFs fully characterize morphological properties.

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Summary statistics:

- ➔ **power spectrum**
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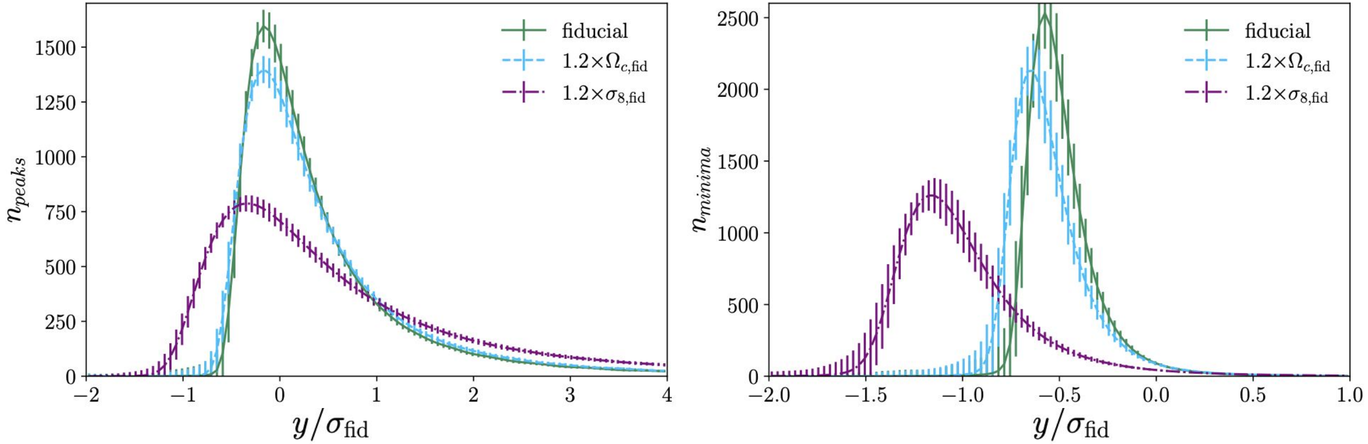
- ➔ **peaks** – local maxima points
- ➔ **minima** – local minima points



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- ➔ **peaks** – local maxima points
- ➔ **minima** – local minima points
- ➔ **moments** – 2 quadratic, 1 cubic, 1 quartic

$$\sigma_0 = \sqrt{\langle y^2 \rangle}, \quad \sigma_1 = \sqrt{\langle |\nabla y|^2 \rangle}$$

$$S_1 = \langle y^2 \nabla^2 y \rangle \quad K_1 = \langle y^3 \nabla^2 y \rangle$$

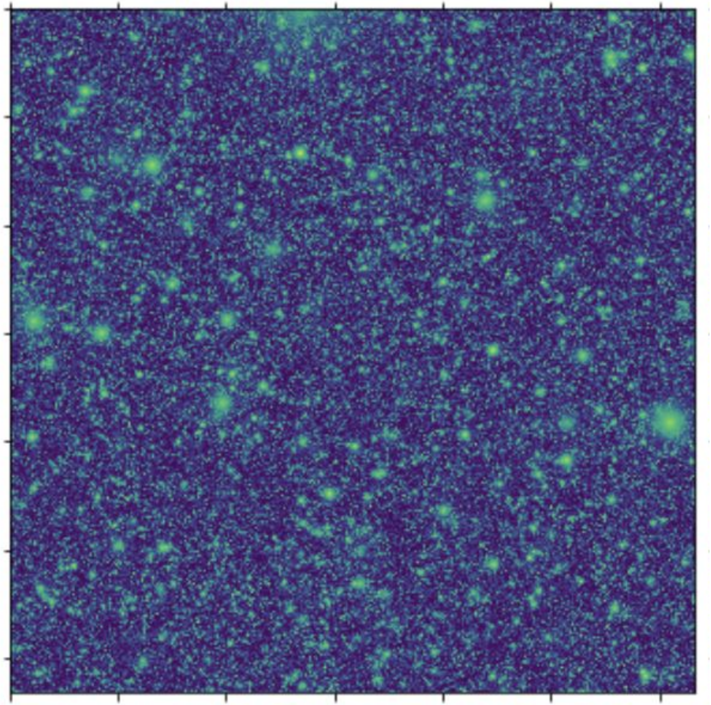
From perturbative expansion of MFs up to 2nd order in variance

(see *Tomita 1986, Matsubara 2000, Matsubara 2010*).

limit to four moments due to challenges wrt to convergence

Computed via **LensTools** (Petri 2016) https://github.com/apetri/LensTools

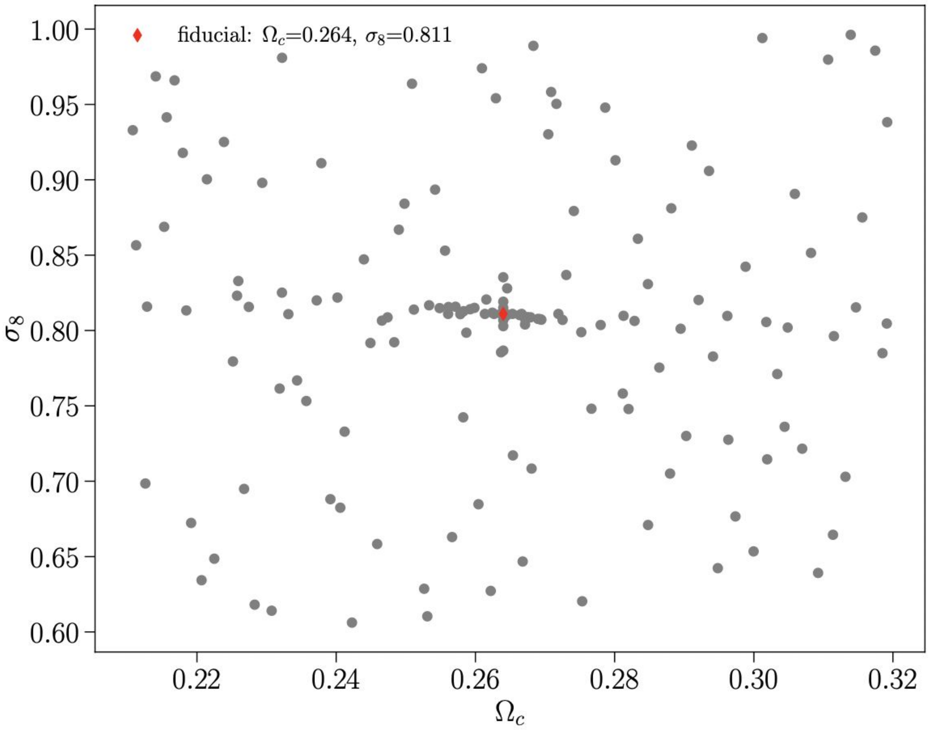
Simulation suite:



- ➔ Simplified tSZ maps generated using **hmpdf** [1]
  - ◆ Poisson sample halos from *Tinker+2010*.
  - ◆ Pressure profile from *Battaglia+2012*
- ➔ 10.5 x 10.5 deg^2 (6321 x 6321 pixels)
- ➔ 0.1 arcmin resolution

[1] https://github.com/leanderthiele/hmpdf (*Thiele+2019*)

Simulation suite:



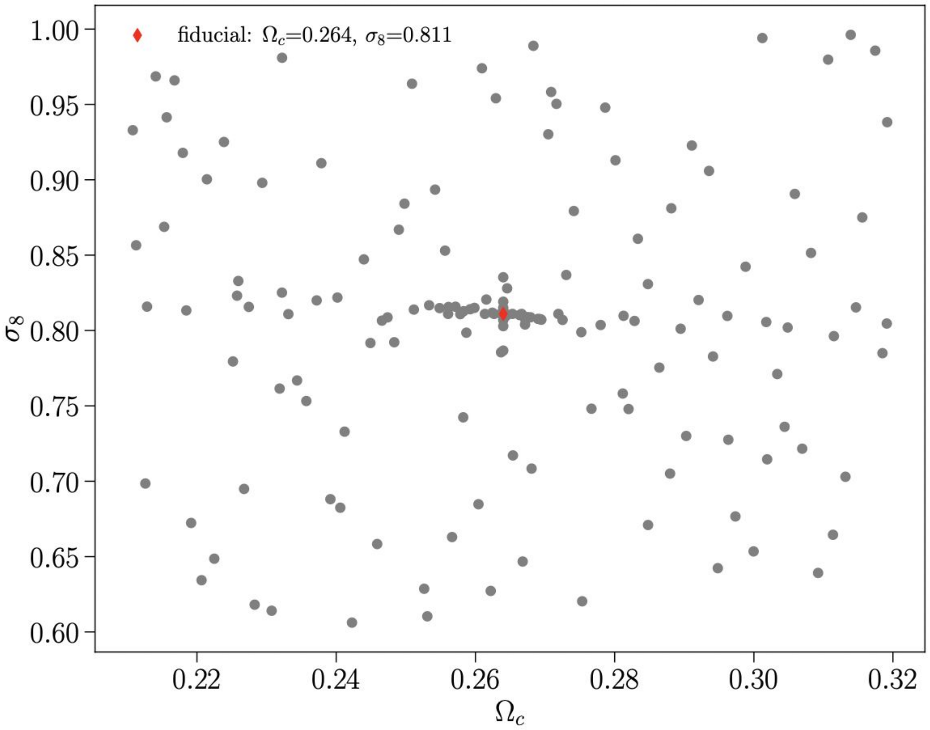
- ➔ fiducial: Ω_c=0.264, σ_8=0.811
- ➔ **154 cosmologies**

  ~**34,560** realizations for the fiducial

  ~**5,112** per each other cosmology

  >800,000 maps in total!

Simulation suite:



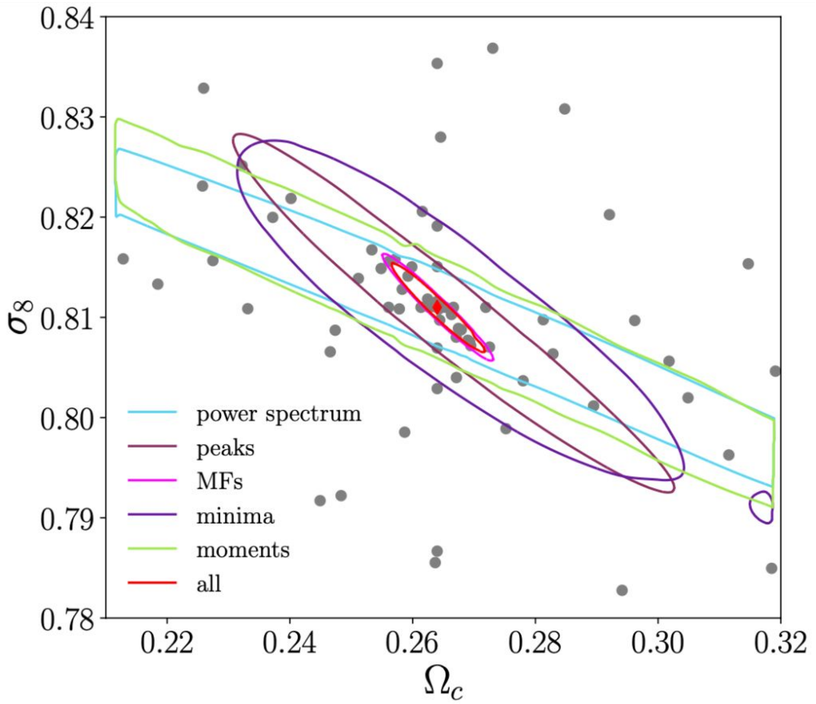
Simulation suite → constraints

1. Compute the statistic(s) across all maps.
2. Interpolate each statistic on a Ω_c x σ_8 grid (10^6 points)
3. Compute the likelihood at each point.

**Gaussian* likelihood + *cosmology-independent* covariance computed at the fiducial cosmology (*Carron 2013, Darsh+2019*)*

Constraints:

Noiseless 10.5 x 10.5 deg² maps (smoothed with θ_{FWHM}=1.4 arcmin)



Constraints tighter than from the power spectrum alone by

+MFs: x23

+peaks: x3.4

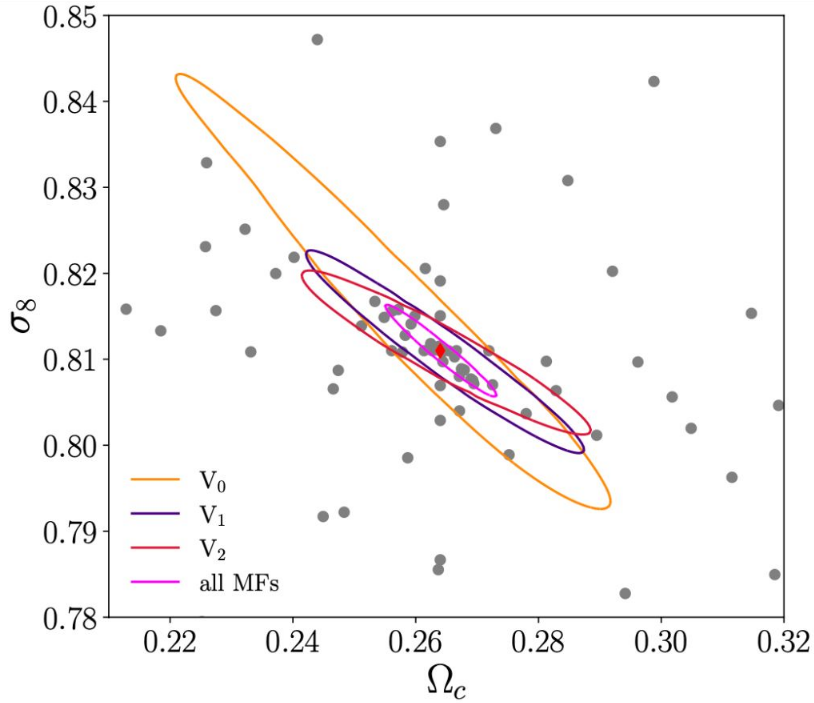
+minima: x1.9

+moments: x1.2

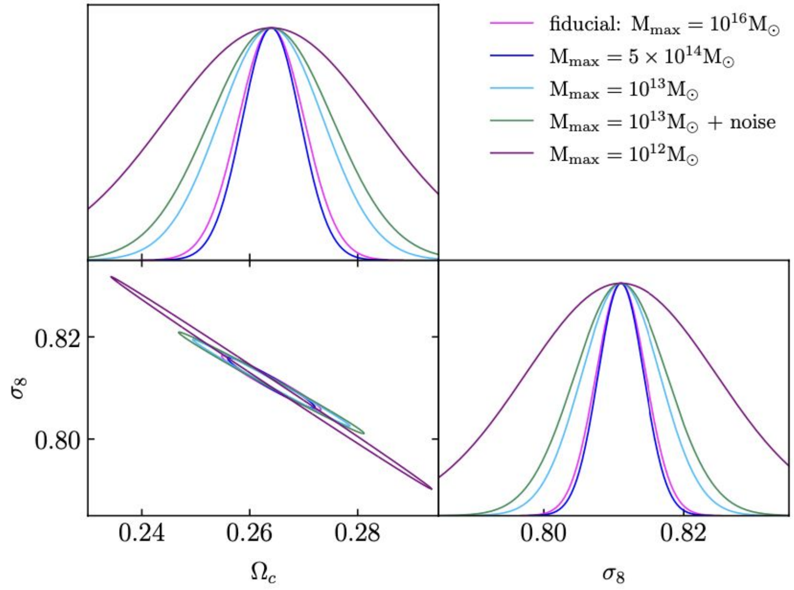
all descriptors: x29

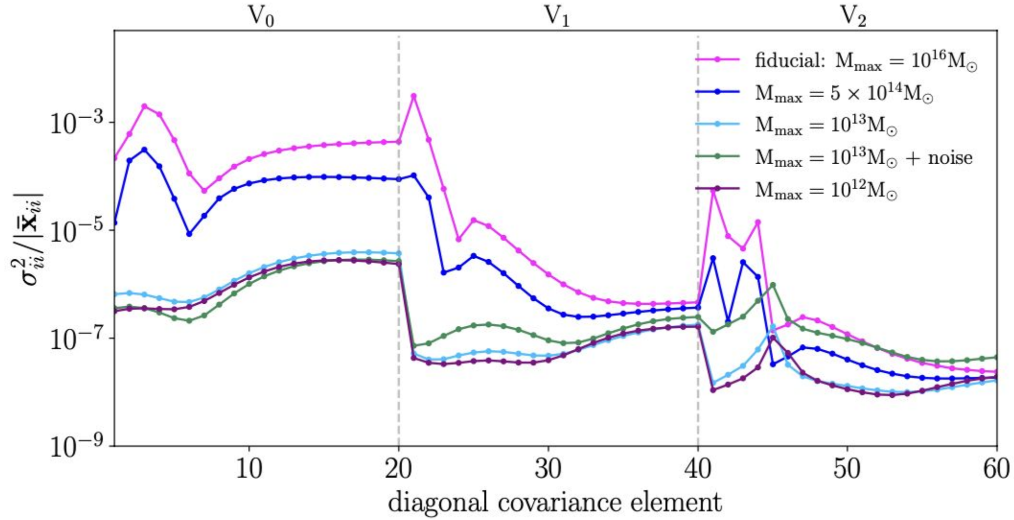
Constraints:

Noiseless 10.5 x 10.5 deg² maps (smoothed with θ_{FWHM}=1.4 arcmin)



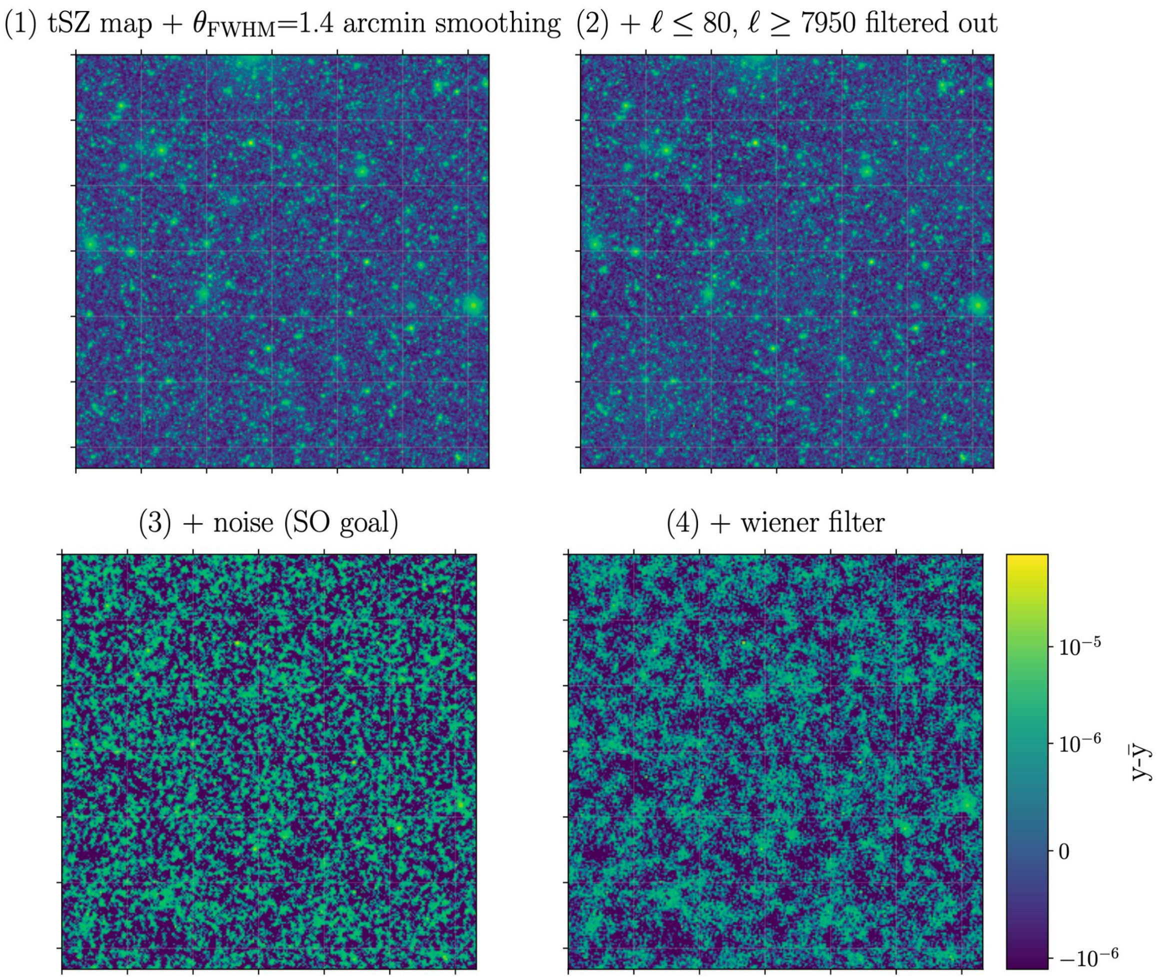
Constraints are driven by the combination of MFs and in particular, V_1 and V_2.





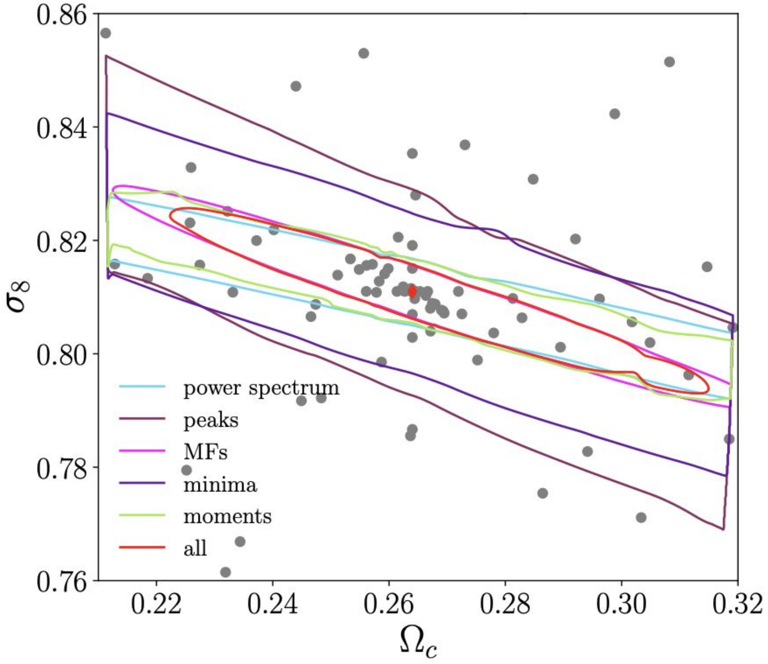
- ➔ Most massive halos – contribute more to the variance.
- ➔ Masking the most massive halos → can improve the constraints (e.g. 20% better if >5 x $10^{14} M_\odot$ halos are not included).
- ➔ Suggests promising synergies with cluster count analyses!

Adding noise:



Constraints:

+ Noise (Simons Observatory post-component separation tSZ noise power spectra)



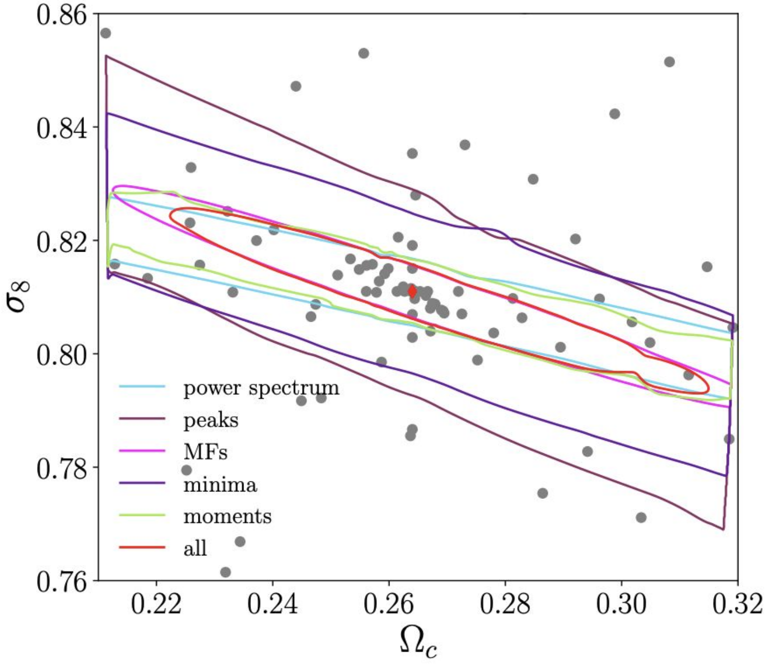
Constraints tighter than from the power spectrum alone by

+MFs: x1.7

all descriptors: x1.8

Constraints:

+ Noise (Simons Observatory post-component separation tSZ noise power spectra)



f_{sky}=0.4:

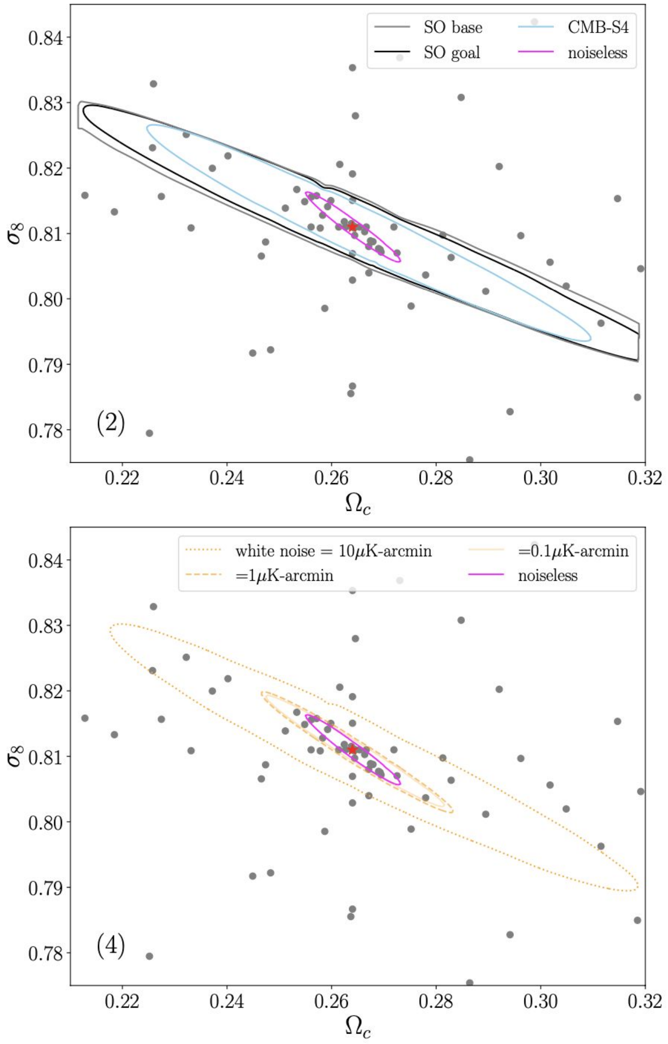
Error on the best constrained parameter combination:

$$S_8 = \sigma_8(\Omega_c/0.264)^{\alpha} \quad \text{where} \quad \alpha = 0.07 - 0.1$$

power spectrum: ~0.06%
MFs: ~0.04%

➔ Degeneracy broken with CMB-S4 noise.

➔ White noise 0.1-1 μK-arcmin – close to noiseless constraints!



Summary:

- ➔ Significant non-Gaussian information in the tSZ maps

  (~**30x/2x** improvement in the **noiseless/noisy** cases)!

- ➔ **MFs** substantially **outperform** other summary statistics.
- ➔ **Ideal time** for applying these statistics (relevant to white noise levels of 0.1-1μK-arcmin).

- ➔ ***Follow-up work:***
  - ◆ Exploring sensitivity to the ***pressure profile*** parameters.
  - ◆ Characterizing the **full information content** of the tSZ field via convolutional neural networks (CNNs).

Fisher & fiducial simulations + summary statistics are publicly available at https://columbialensing.github.io/!
Pipeline available at: https://github.com/asabyr/tSZ_NG

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