Foreground challenges for measurements of spectral distortions

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B-modes from Space, MPA, Munich
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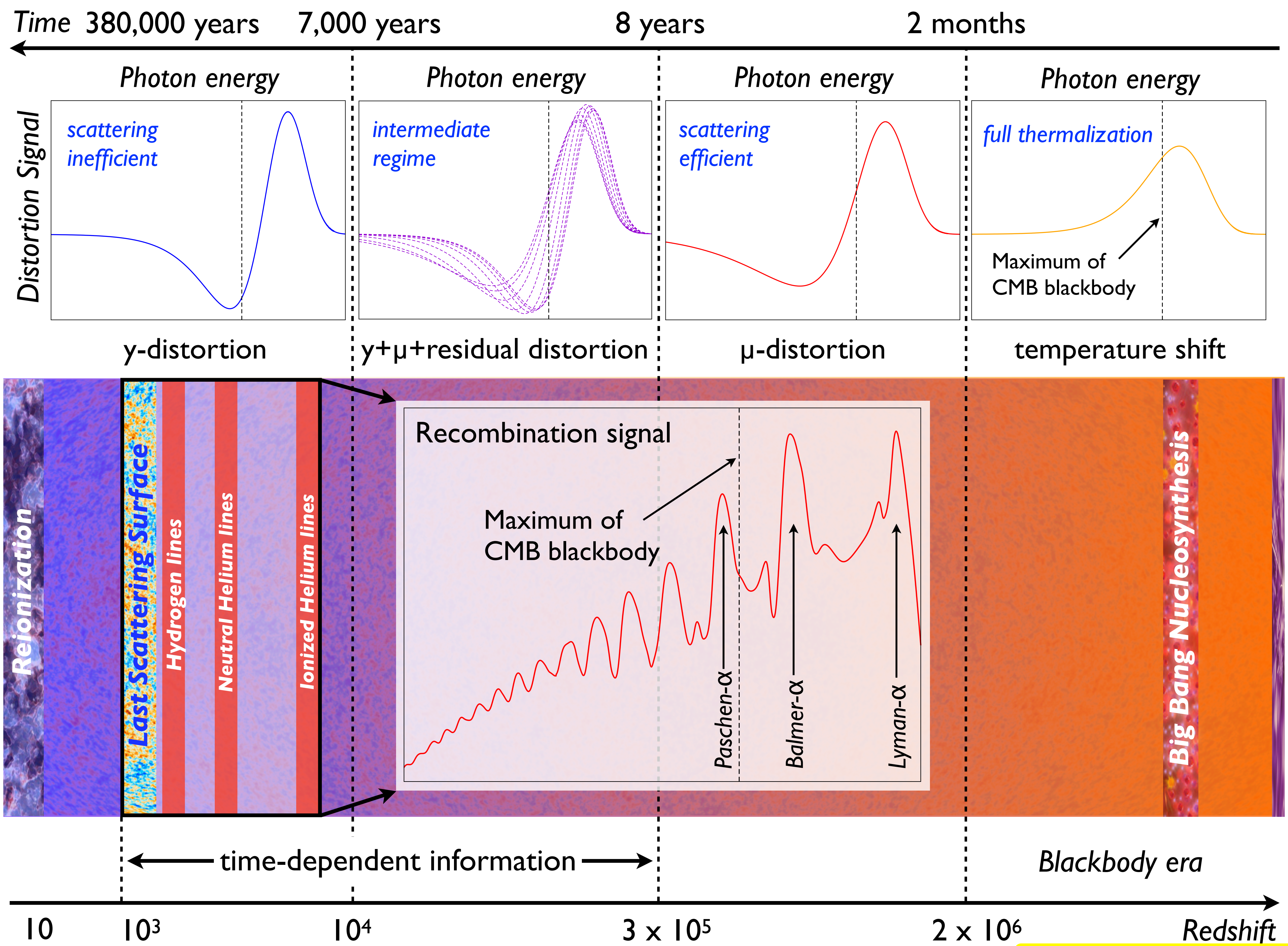
Take away

- A first demonstration of **recovery of average sky signals** using moments and ILC methods
- High precision modeling of foregrounds → ***CRITICAL***
- Partially modeling out foregrounds (semi-blind) is better than being blind to them when performing component separations
- A demonstration study - **NOT A FORECAST for spectral distortion measurements**

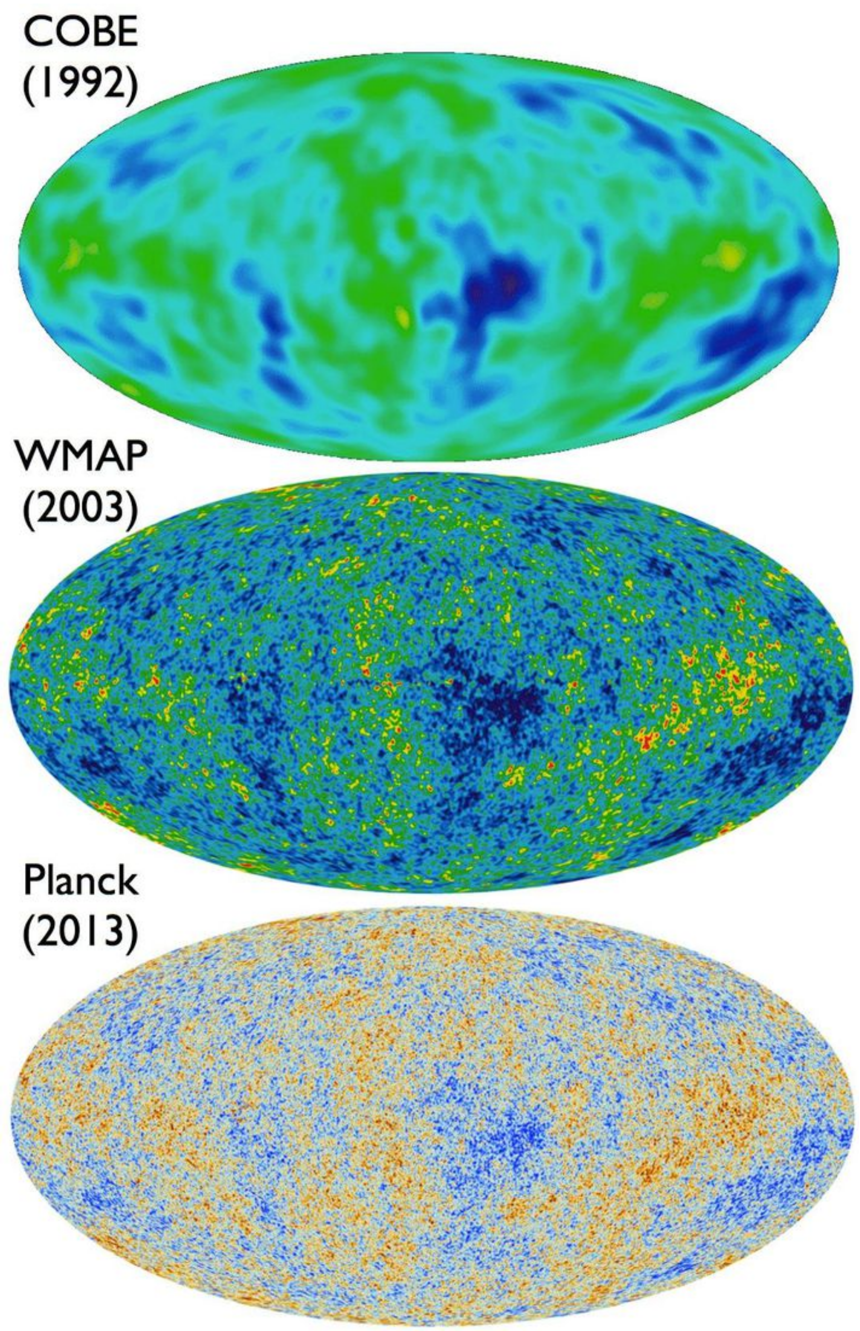
Lightening recap of spectral distortions



Voyage 2050 white paper: arXiv:1909.01593

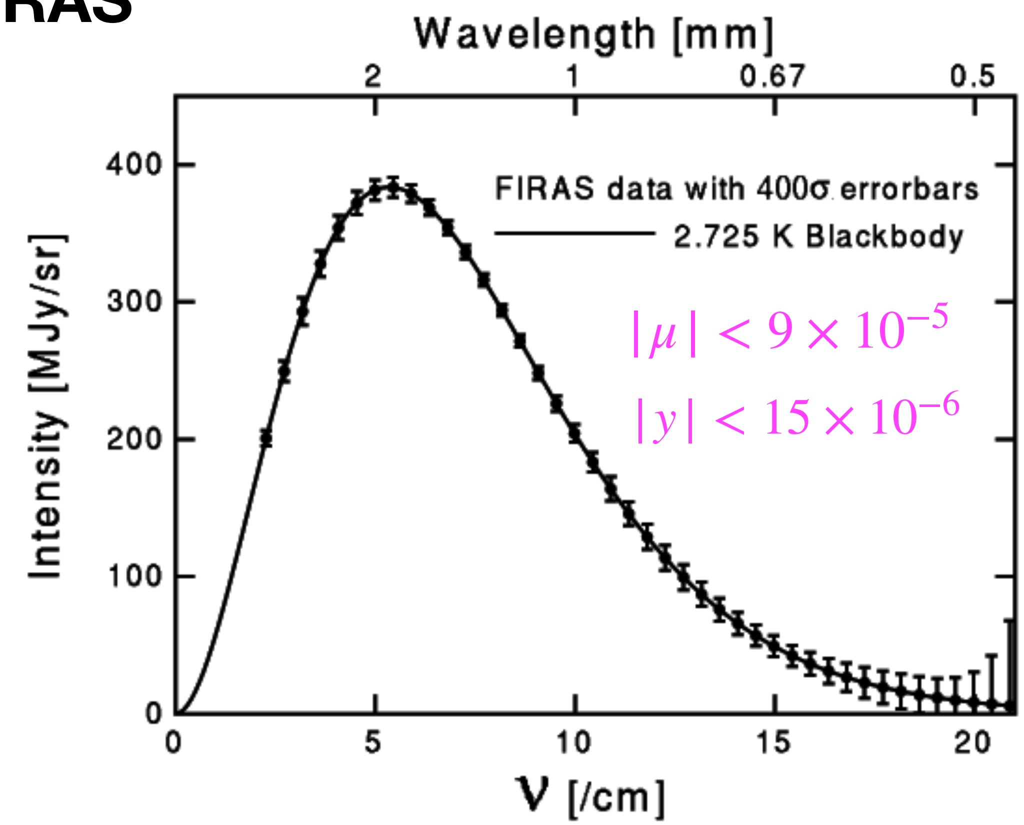
CMB: Spectral distortions vs Spatial anisotropies

PROGRESS



B-modes, lensing, etc…
LiteBird, AdvAct, SPT-3G, SO, etc…….

COBE/FIRAS



Stalled for 25 years….

?

New observations ?
New analysis techniques?

There exist **definite signals**
($T_{\rm CMB}$, $\langle y \rangle$, μ, frgs.)
But a **challenging measurement**
(similar to B-modes)

Requirements for “measuring” spectral distortions?

- **Sensitivity (~ 0.01 Jy)**
- **Many many channels (~20-100s)**
  (think spectroscopy)
- **Good channel cross calibration**
- **Sky coverage**

Voyage 2050 SDWP : arXiv:1909.01593

See talk by Jens Chluba tomorrow!

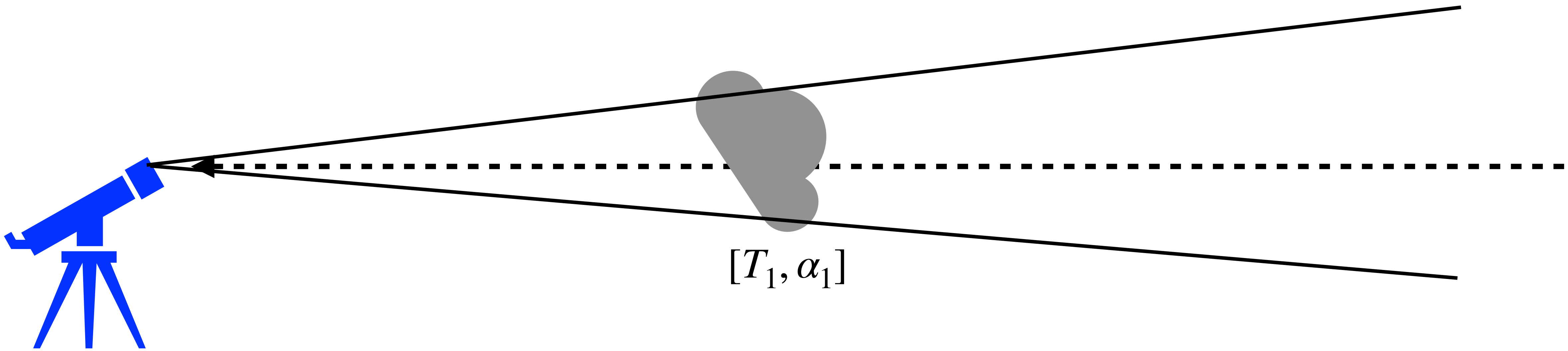
Why?

- **Signals are small!**
- **Many many foregrounds (+ ones we have not seen yet)**
- **Variation in signals are small.**
- **In principle, single pixel measurement is enough. But, sky coverage is expected to help with mitigating the foregrounds challenge.**

Observers assumption (current)

Each cloud emits a modified black body spectrum.

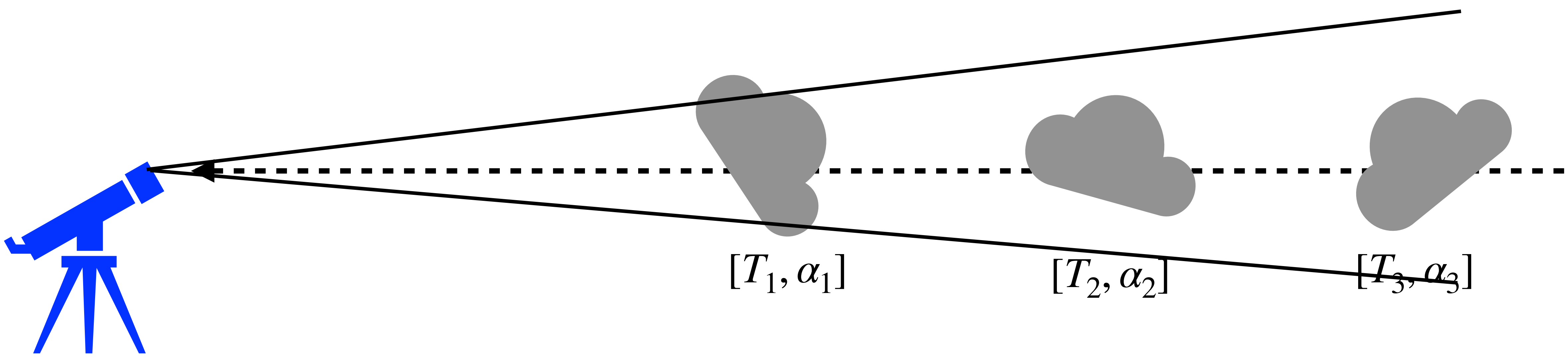
$$B_\nu(\alpha, T) = A\frac{2h\nu^3}{c^2}\left(\frac{\nu}{\nu_0}\right)^\alpha \frac{1}{e^{\frac{h\nu}{kT}} - 1}$$



Reality in nature

Each cloud emits a modified black body spectrum.

$$B_\nu(\alpha, T) = \frac{2h\nu^3}{c^2}\left(\frac{\nu}{\nu_0}\right)^\alpha \frac{1}{e^{\frac{h\nu}{kT}} - 1}$$



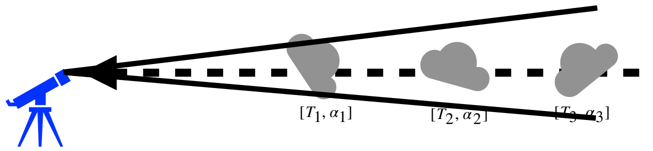
$$S_\nu = \int \frac{dI}{ds} ds \neq B_\nu(\alpha', T')$$

Furthermore…

- We don't observe with a Delta function beam —> inescapable angular averaging, which can't be undone!
  - Maybe combine high res. with low res. obs., sensitivity details!
  - Do we have to worry about frequency dependent beams?

- Analysis choice results in another form of averaging
  - PS level data modeling   Recall talk by Jonathan Aumont yesterday!
  - Harmonic space ILC methods + variants
  - Real space cleaning methods: COMMANDER

What are moments?



Describing SED resulting from sum of modified black bodies:

$$S_\nu = \int \frac{dI}{ds} ds = \int B_\nu(\alpha, T) P(\alpha, T) d\alpha dT$$

Building on top of the simple parametrization:

$$S_\nu = \sum_{m,n} \partial_\alpha^m \partial_T^n B_\nu(\alpha_0, T_0) \int (\alpha - \alpha_0)^m (T - T_0)^n P(\alpha, T) d\alpha dT$$

Moments of the distribution function

$$S_\nu(\alpha_0, T_0, A, p_\alpha, p_T, p_{\alpha\alpha}, p_{\alpha T}, p_{TT}, \cdots) \simeq A B_\nu(\alpha_0, T_0)$$
$$+ p_\alpha \partial_\alpha B_\nu(\alpha_0, T_0) + p_T \partial_T B_\nu(\alpha_0, T_0)$$
$$+ p_{\alpha\alpha} \partial_\alpha^2 B(\alpha_0, T_0) + p_{\alpha T} \partial_\alpha \partial_T B(\alpha_0, T_0) + p_{TT} \partial_T^2 B(\alpha_0, T_0)$$
$$+ \cdots$$

J. Chluba, J. C. Hill & M. H. Abitbol, MNRAS, Vol. 472, Iss. 1, 1195-1213

Measuring moments

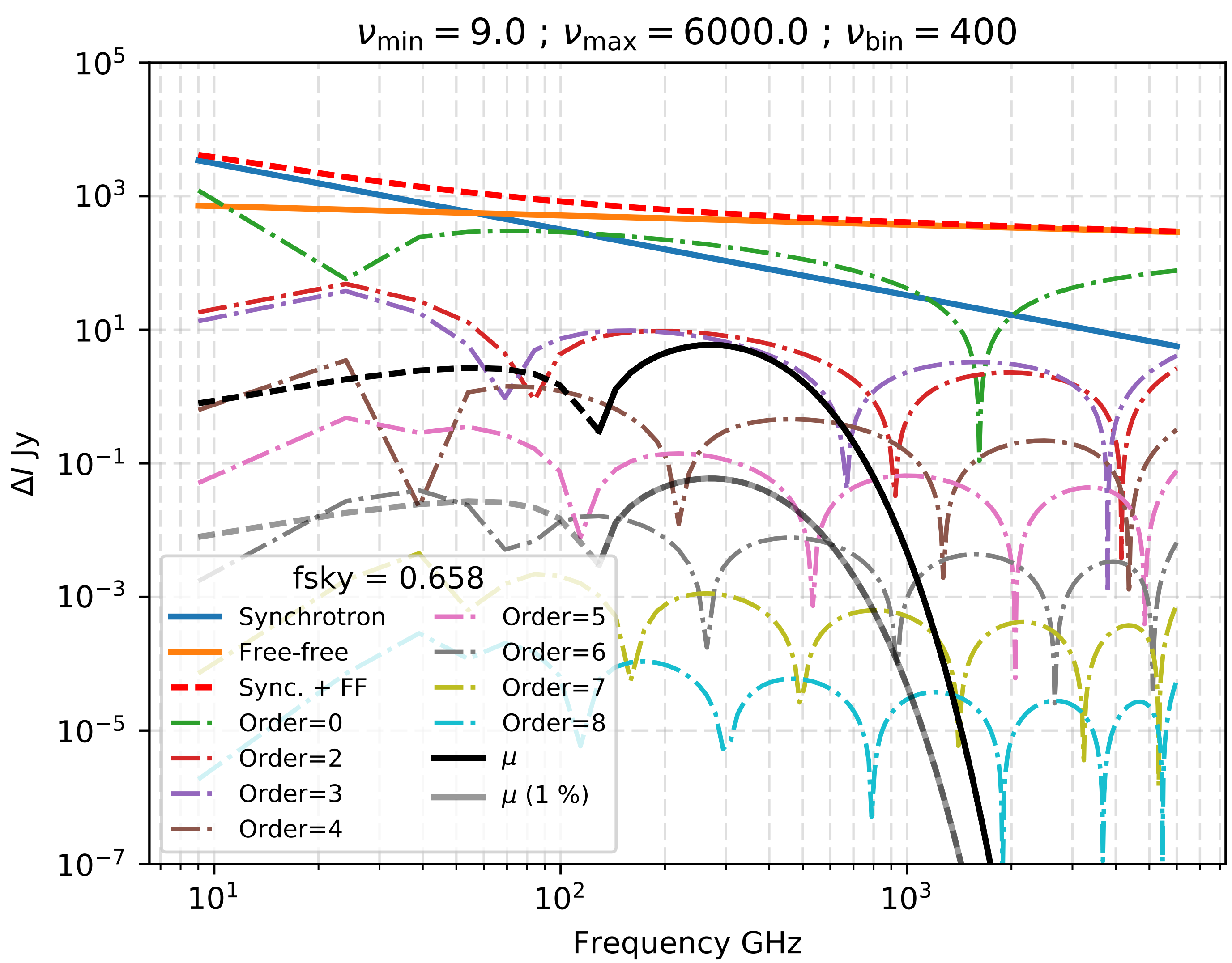
Spectro-Spatial

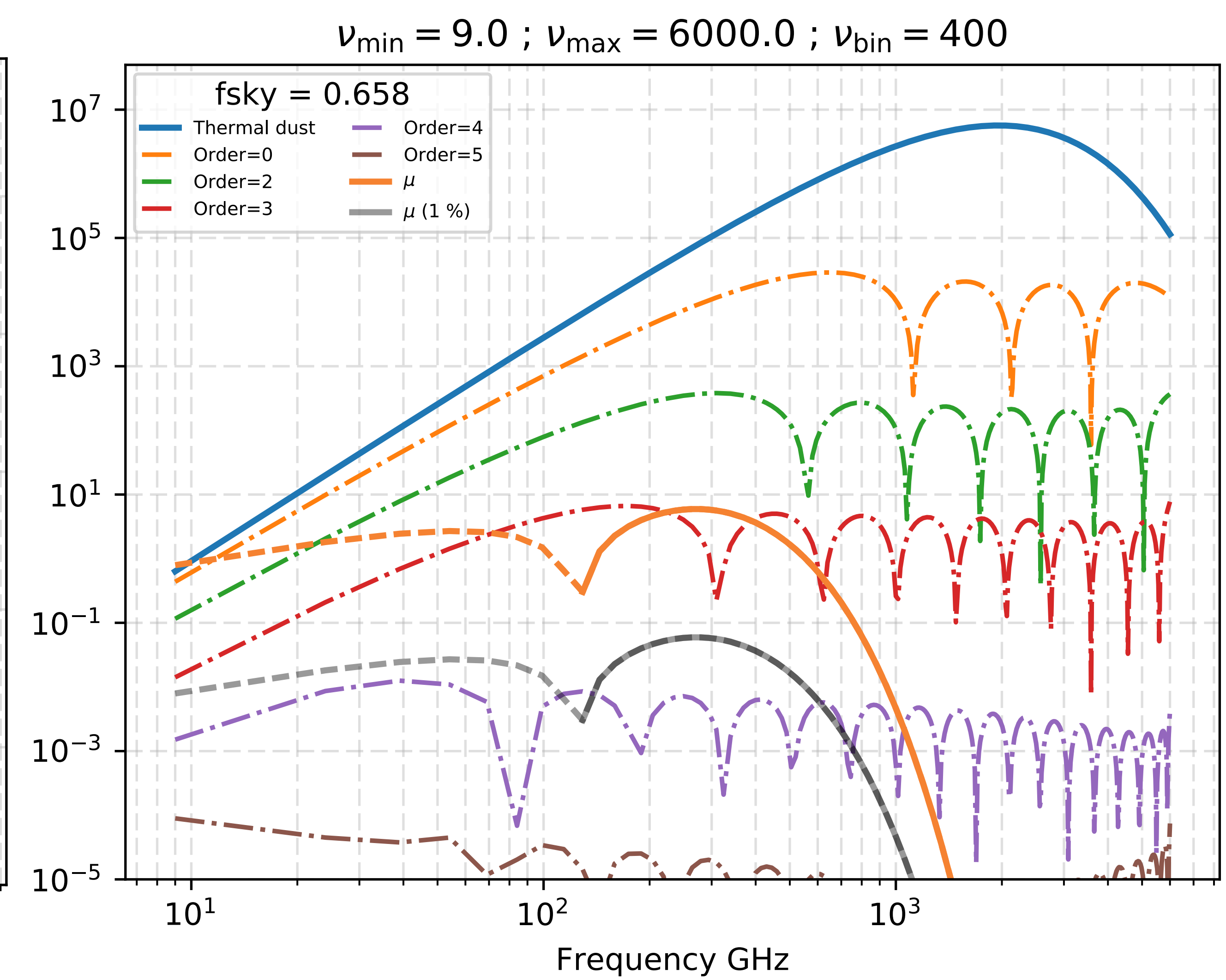
$$S_\nu(\overrightarrow{p}_0, \mathscr{M}_i^{\text{Sig.}}, \mathscr{M}_i^{\text{Frg.}}, \cdots) = \sum_i B_{\nu i}(\overrightarrow{p}_0)\mathscr{M}_i + \epsilon_i$$

- **This is not written in any particular basis - real/harmonic.**
  (which space requires fewer basis vectors to model foregrounds?)
- **Spatial and spectral complexity of foregrounds are correlated!**
  (the moment way of thinking about foregrounds!)

How many moments to model foregrounds to desired accuracy?

SKY AVERAGED – SINGLE PIXEL





- **SED evaluated from sky sims. generated using Python Sky Model (fsky=0.66)**
- **These moments are generated from spatial averaging.**
- **Maybe one expects similar order of magnitude moments arising from line of sight averaging**

ILC RECAP

DATA MODEL

$$d_{\nu i} = \sum_c s_\nu^c \tau_i^c + n_{\nu i}\,,$$

SIMPLE ILC

$$\hat{a}_i^{c_0} = \sum_\nu w_\nu^{c_0} d_{\nu i} = w_{c_0}^T \cdot d\,. \qquad \sum_\nu w_\nu^{c_0} s_\nu^{c_0} = w_{c_0}^T \cdot s_{c_0} = 1.$$

Tegmark et. al. 2003

INJECT **ONLY** SED OF SIGNAL OF INTEREST

CONSTRAINED ILC

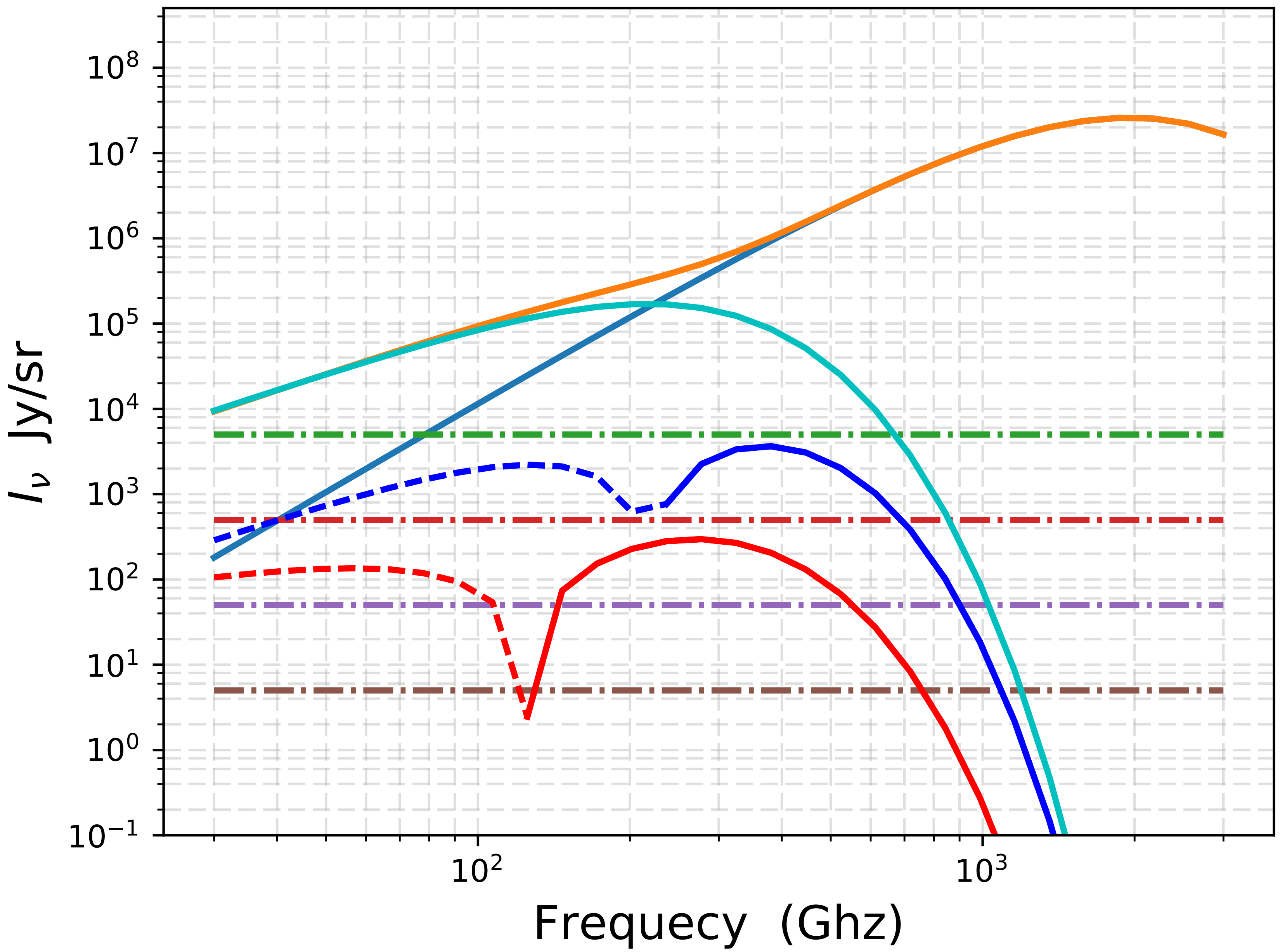
$$w_{c_0}^T \cdot [s^{c_0}, s^{c_1}, s^{c_2} \cdots s^{c_n}] = [1, 0, 0 \cdots 0],$$

Remazeilles et. al. 2011

INJECT **SED OF ALL SIGNALS OF INTEREST** AND SOLVE FOR THEM **SIMULTANEOUSLY**

$$\hat{a}^{c_0} = a^{c_0} + \sum_c^{c \neq c_0} \left(w_c^T \cdot s^c a^c + w_c^T n \right) = a^{c_0} + \mathcal{B}^{c_0} + n^{c_0}.$$

Simulated "absolutely calibrated" data

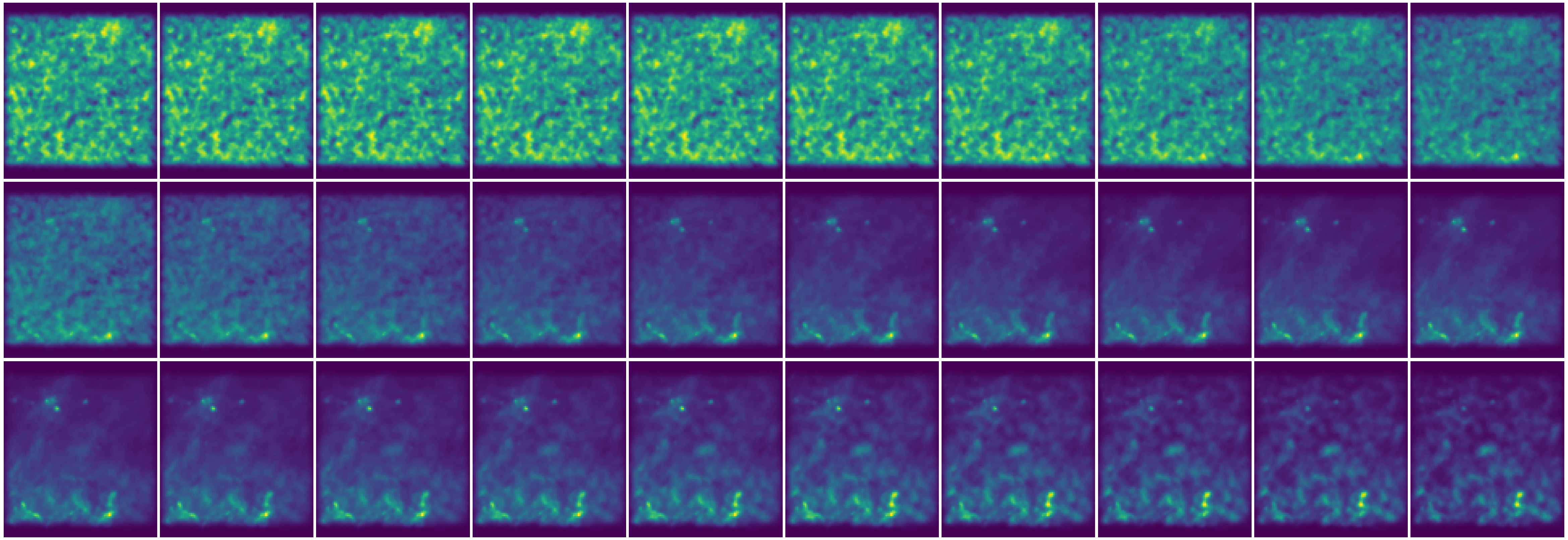


- **30 channels from 30-3000 GHz**
- **30 arc minute Gaussian beam smoothing**
- **Only dust frg. D2 model from PySM**
- **No rSZ corrections to y-distortions** See talk by Mathieu tomorrow!
- **μ distortion amplitude ~100 smaller than FIRAS**

We assume the 2.725 K CMB is subtracted from the data!

Simulated "absolutely calibrated" data

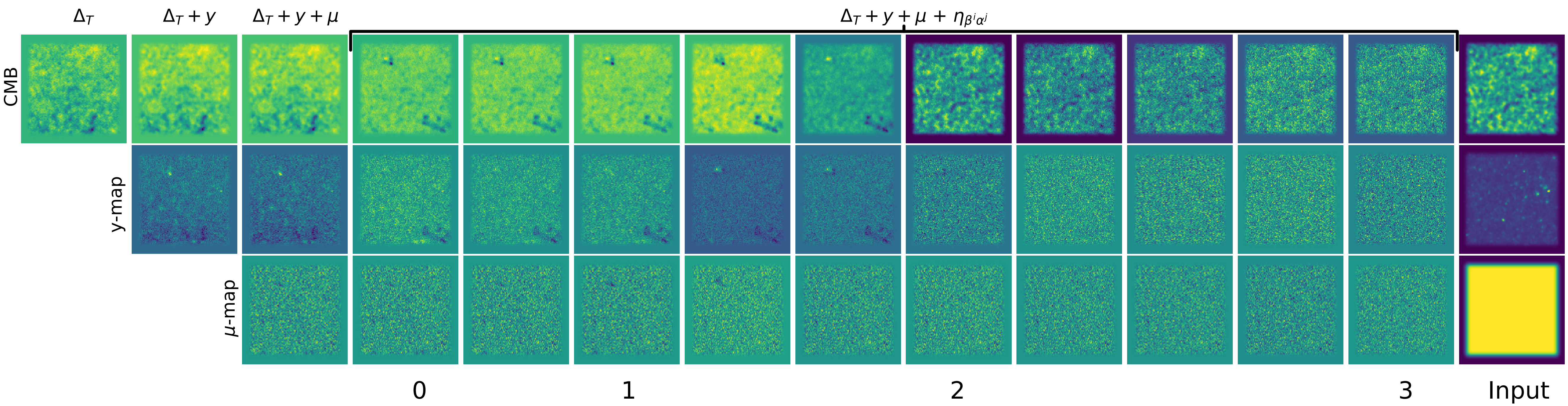
30 GHz



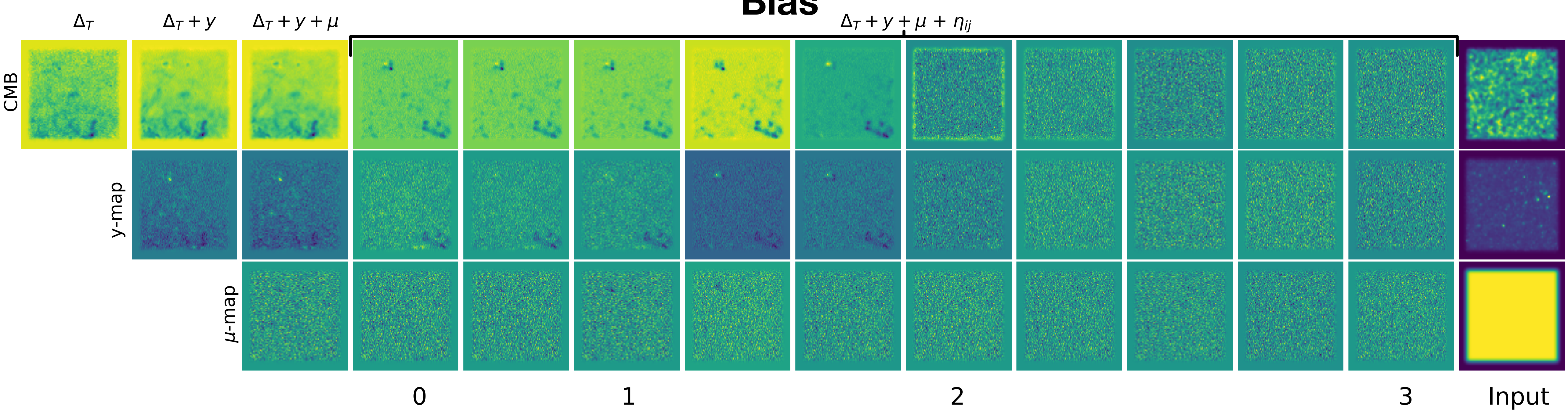
3000 GHz

We assume the 2.725 K CMB is subtracted from the data!

Recovering cosmological observables

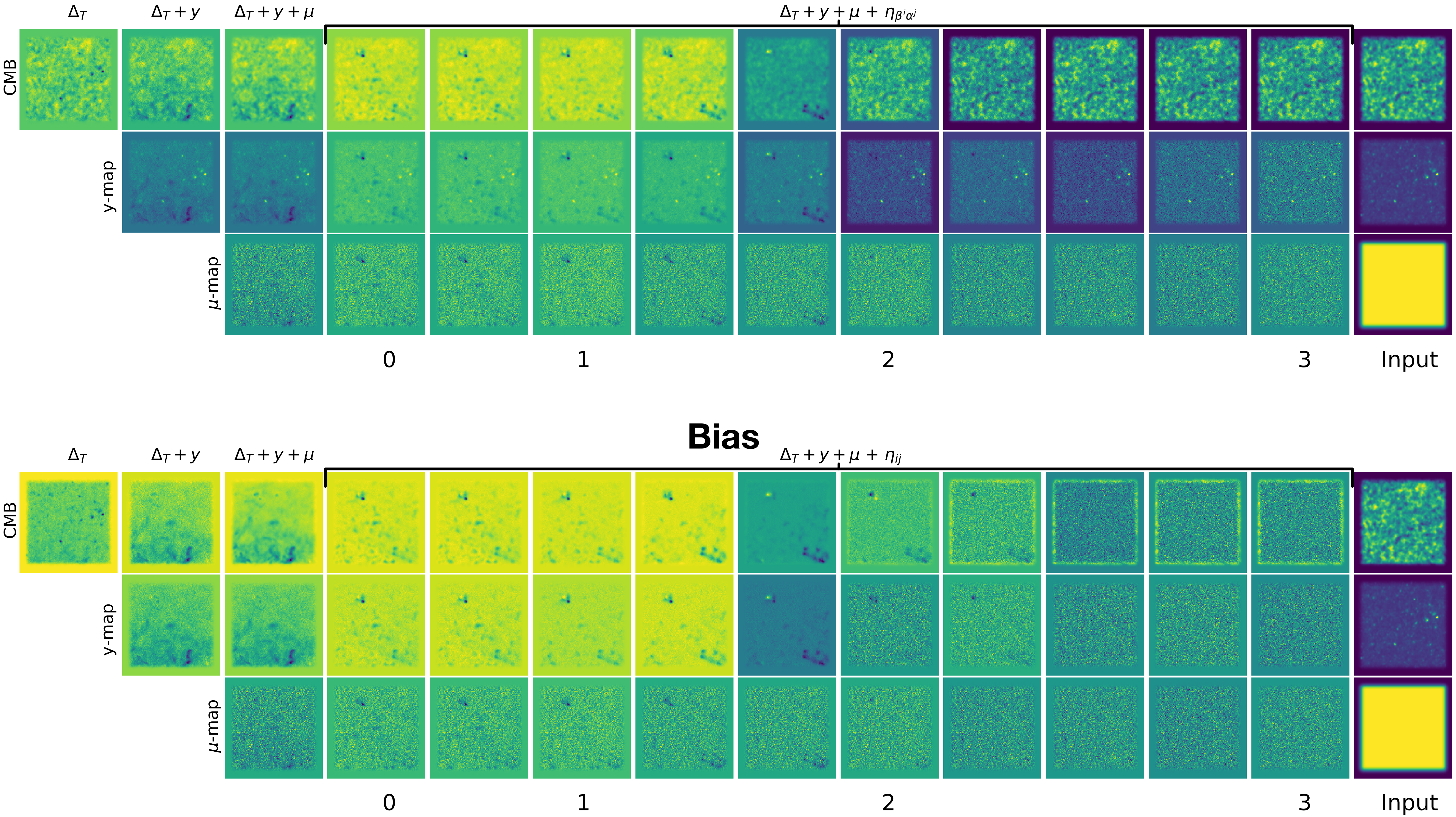


Bias



Noise RMS : 5000 Jy/px

Recovering cosmological observables



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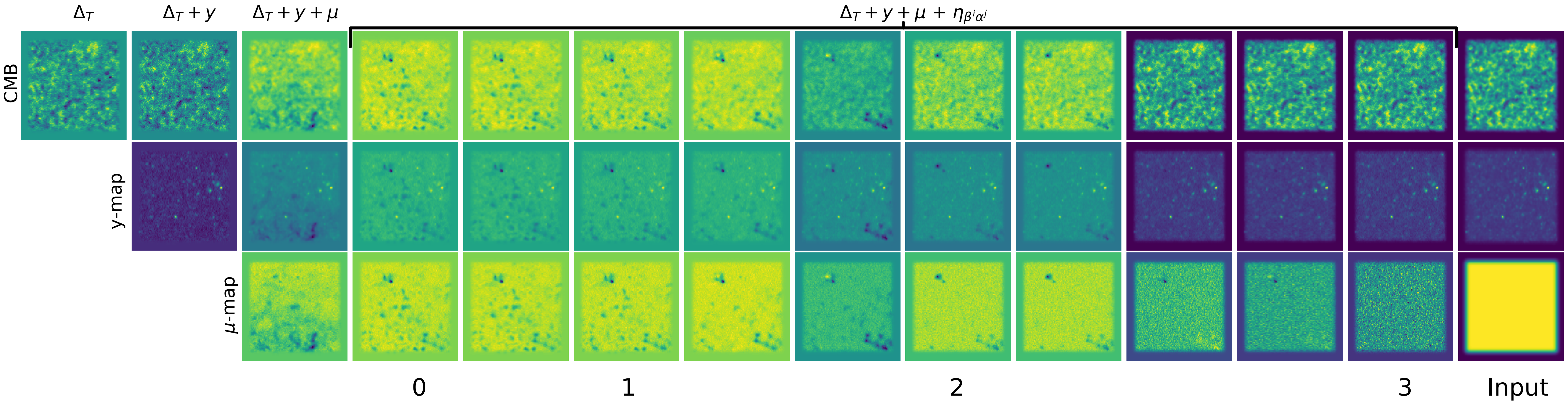
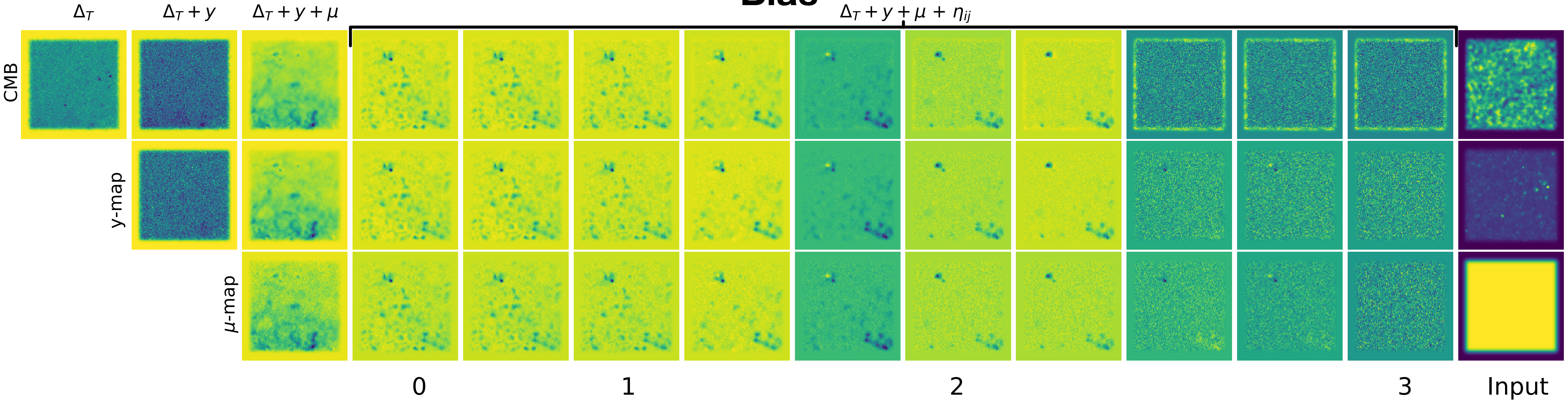


Bias



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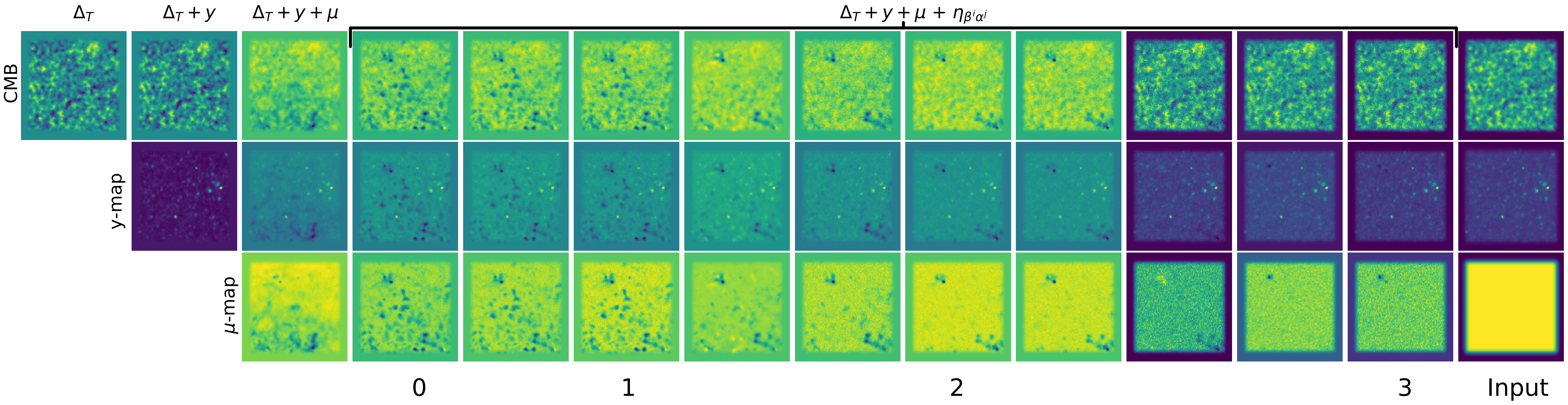
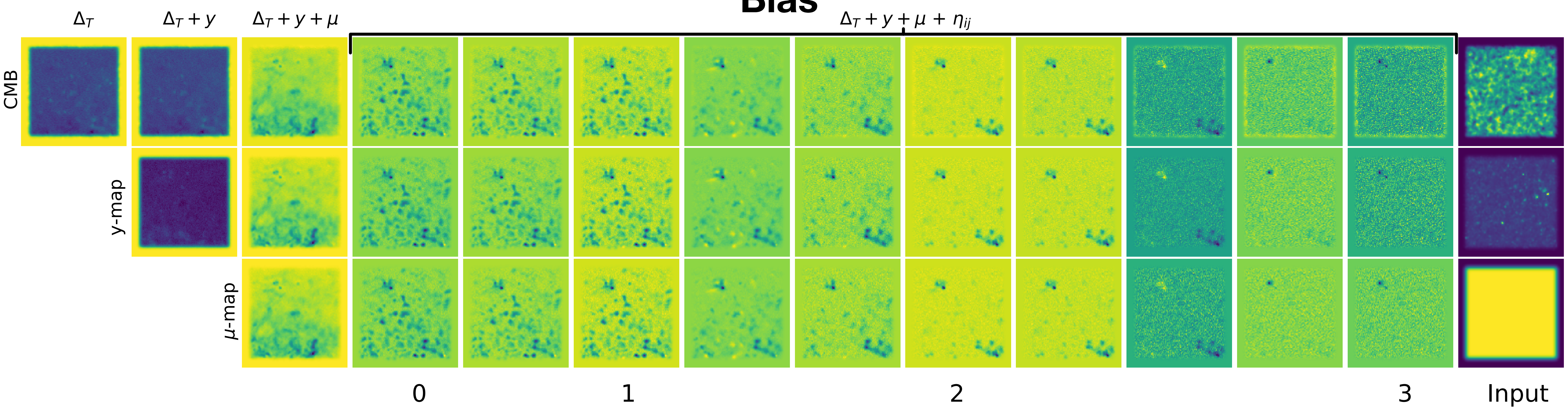
Recovering cosmological observables

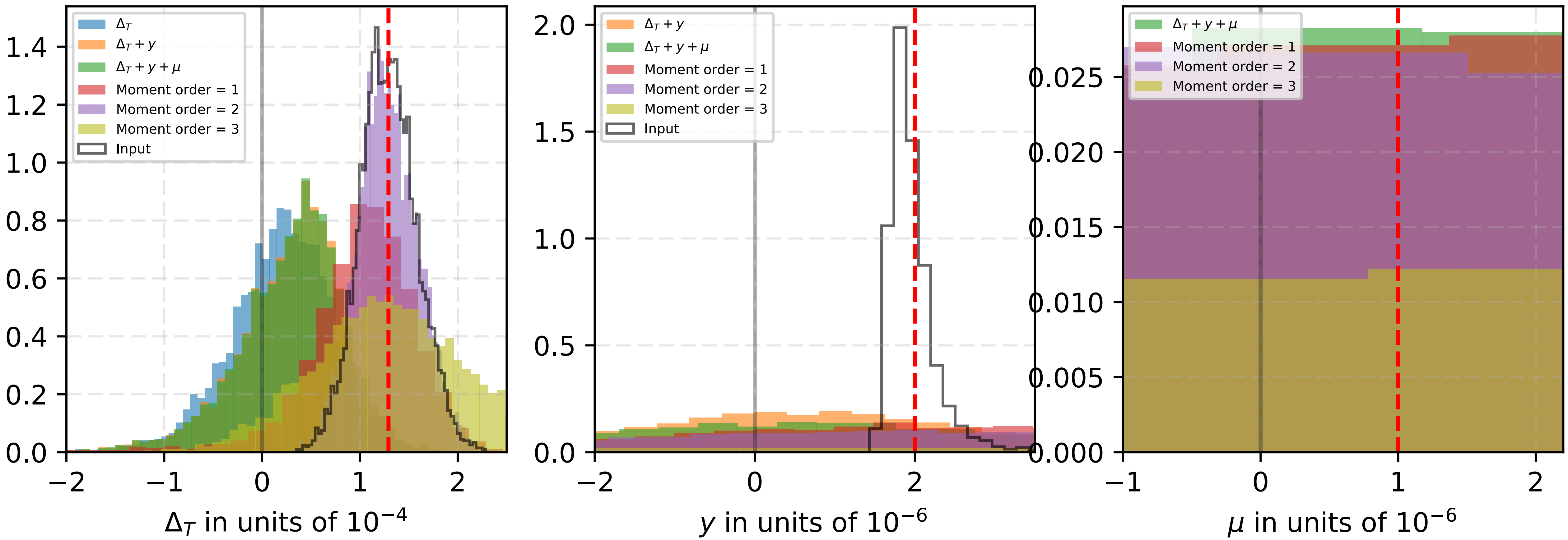


Bias



Noise RMS : 5 Jy/px

1PPDF



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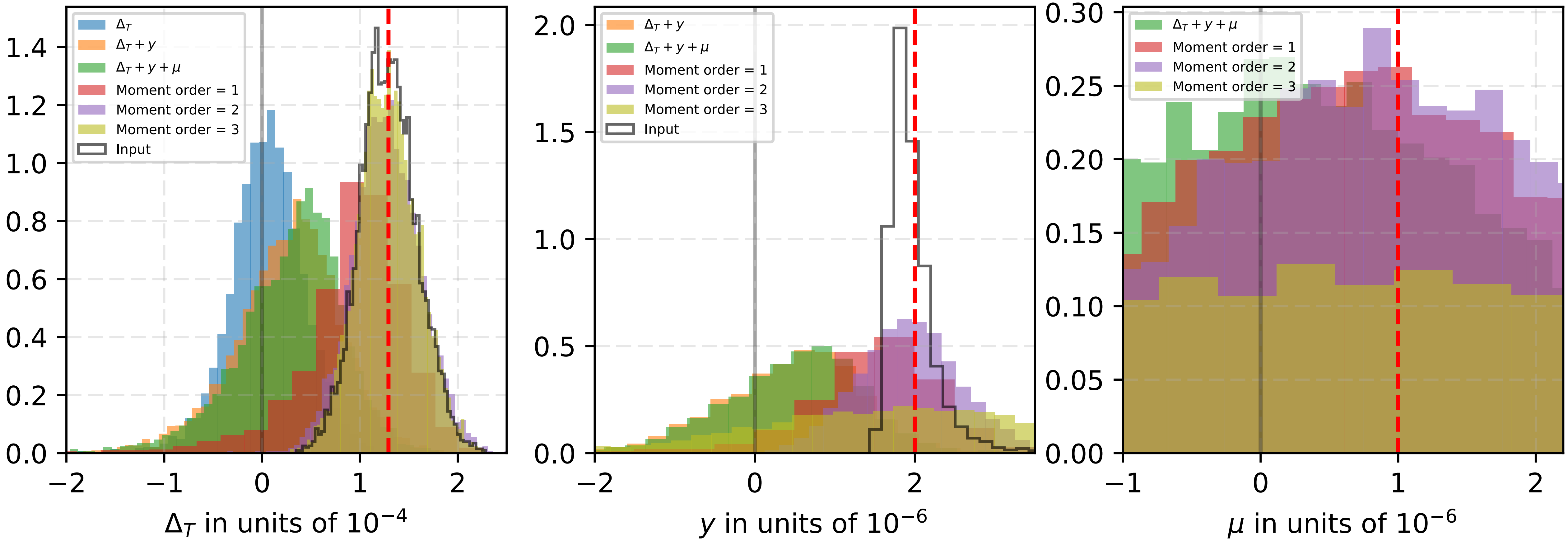

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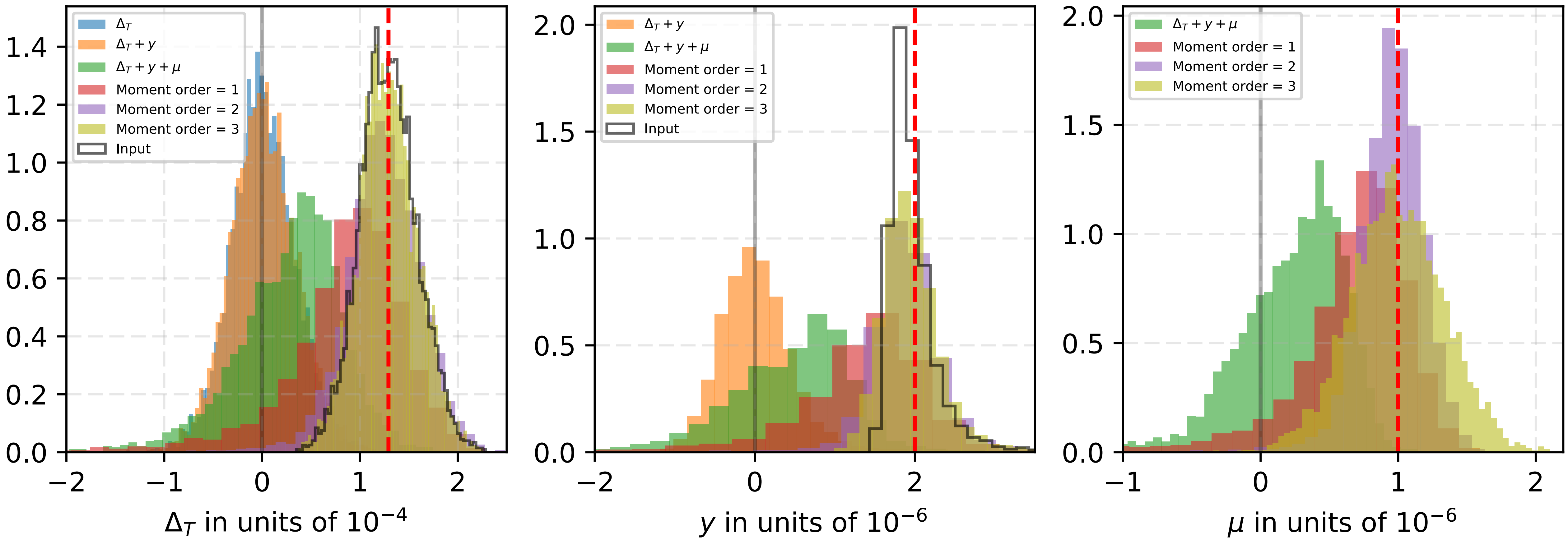

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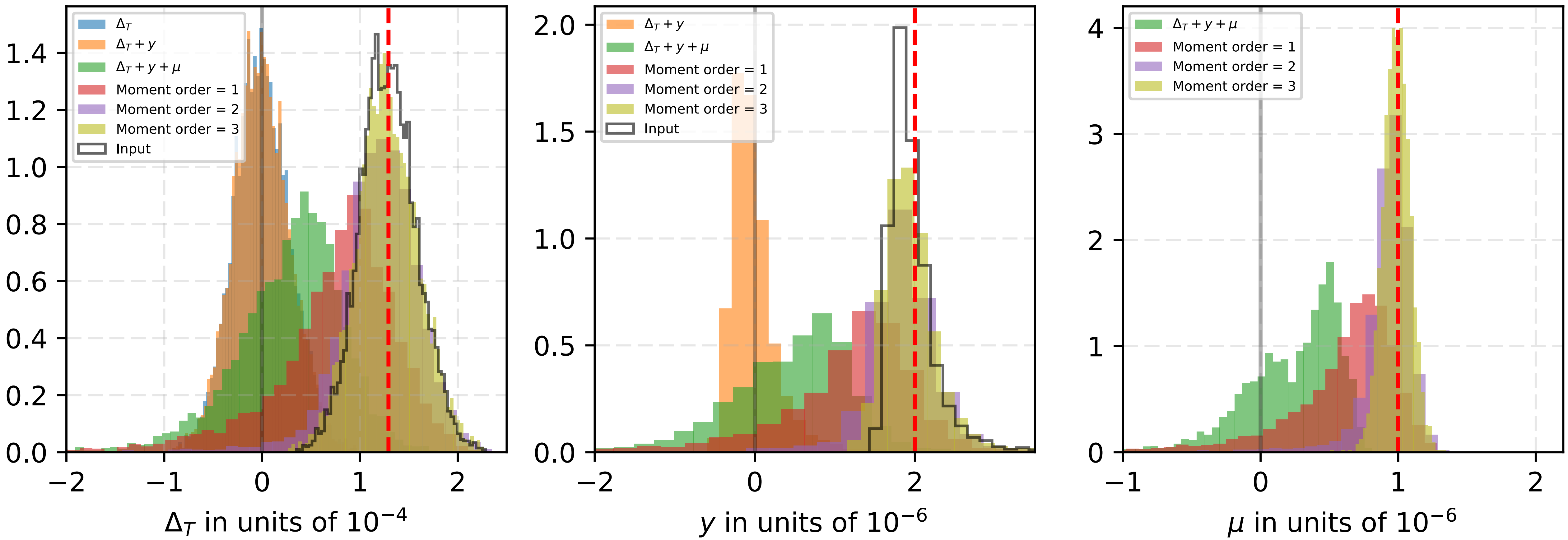
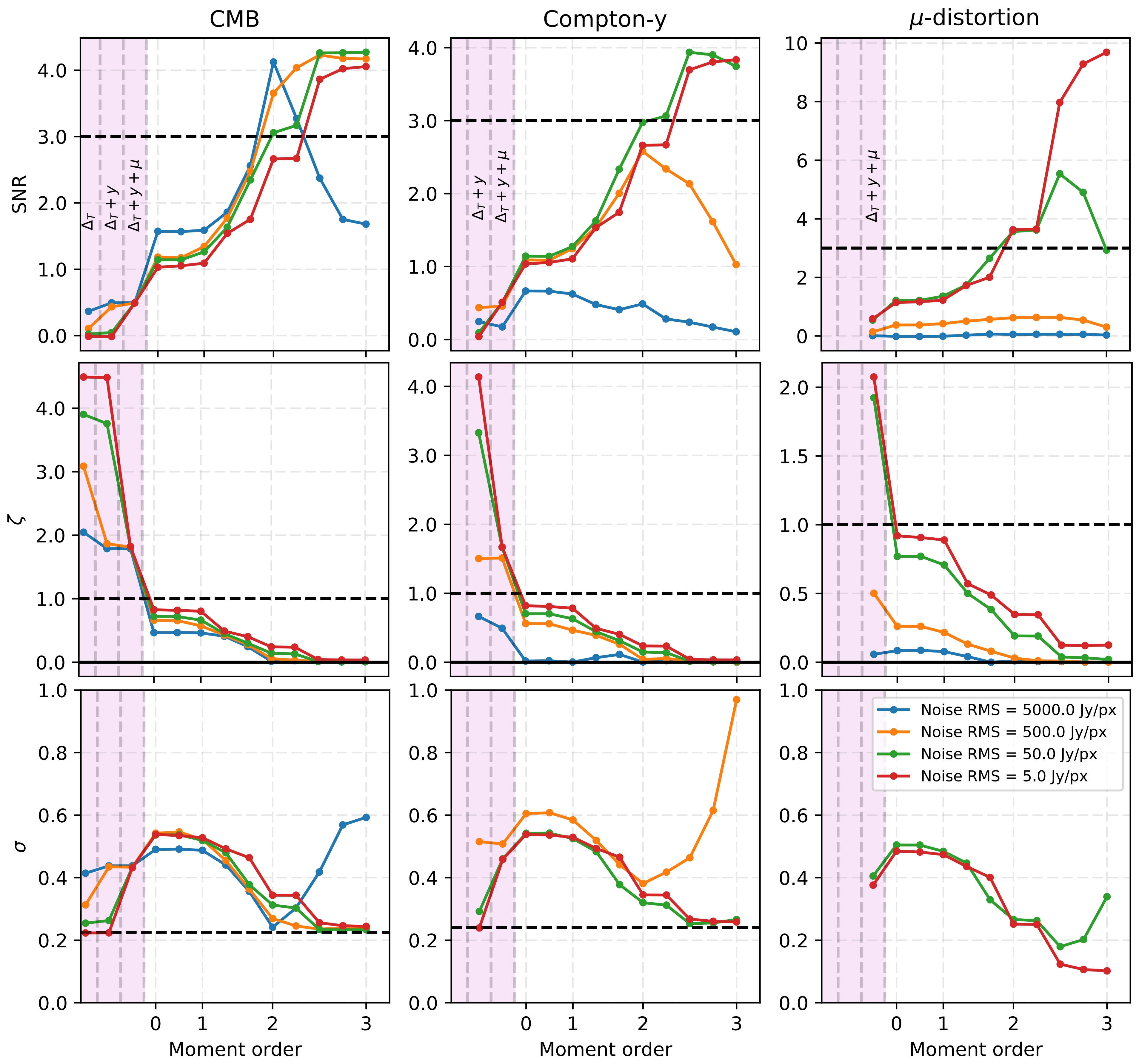


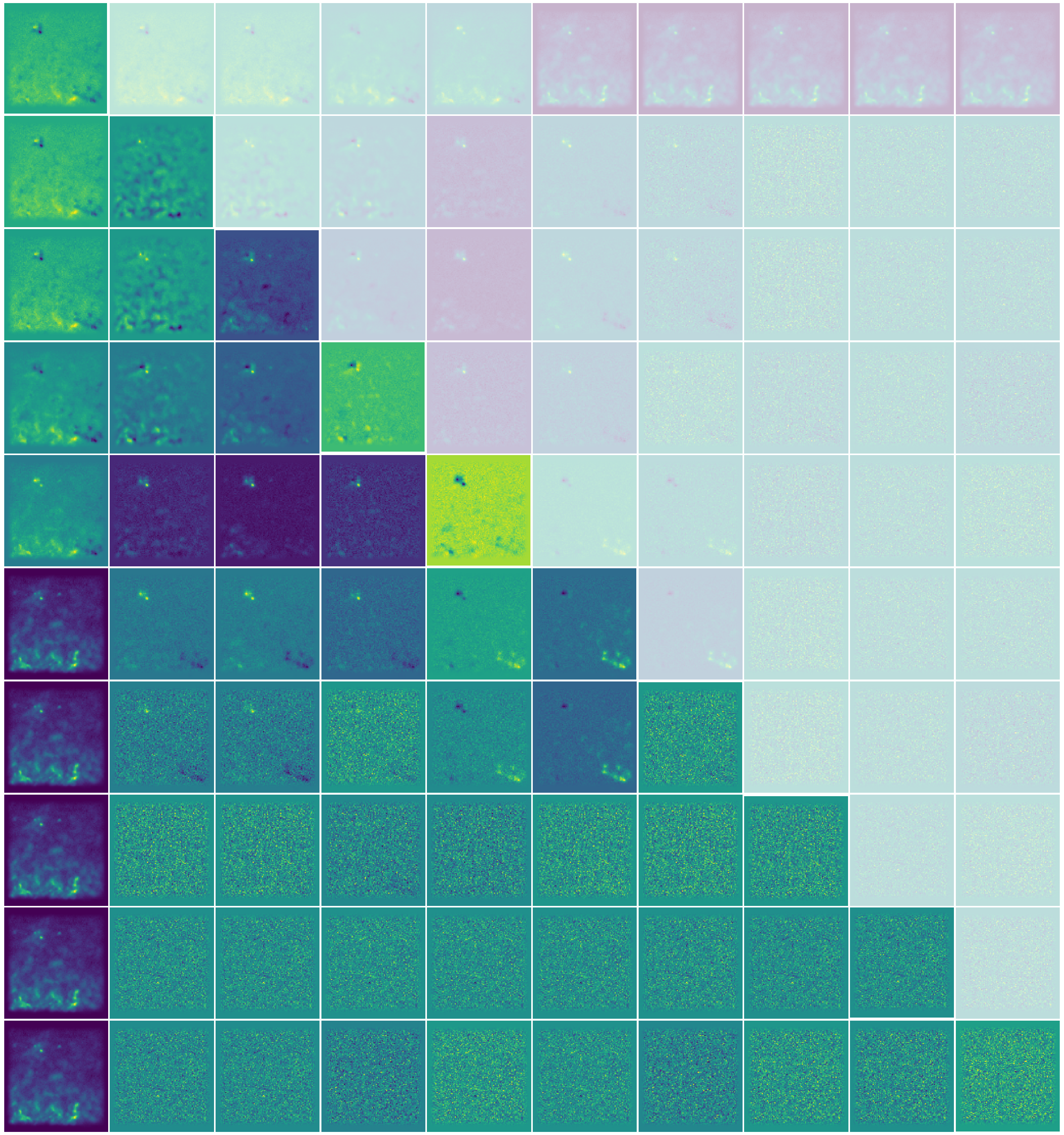
Noise RMS : 5 Jy/px

Summary statistics



Rotti & Chluba, Submitted

Moments the new foreground observables



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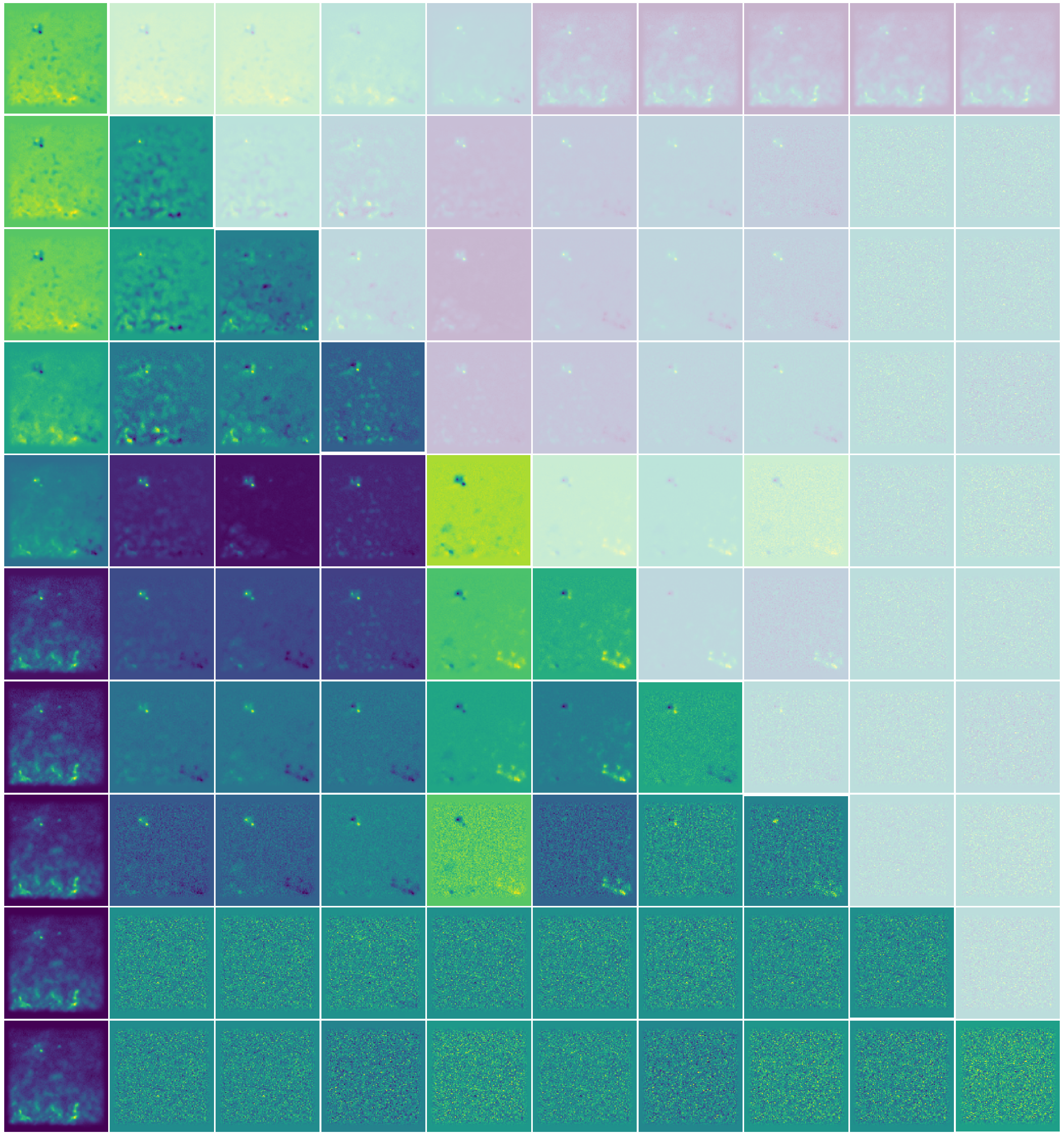

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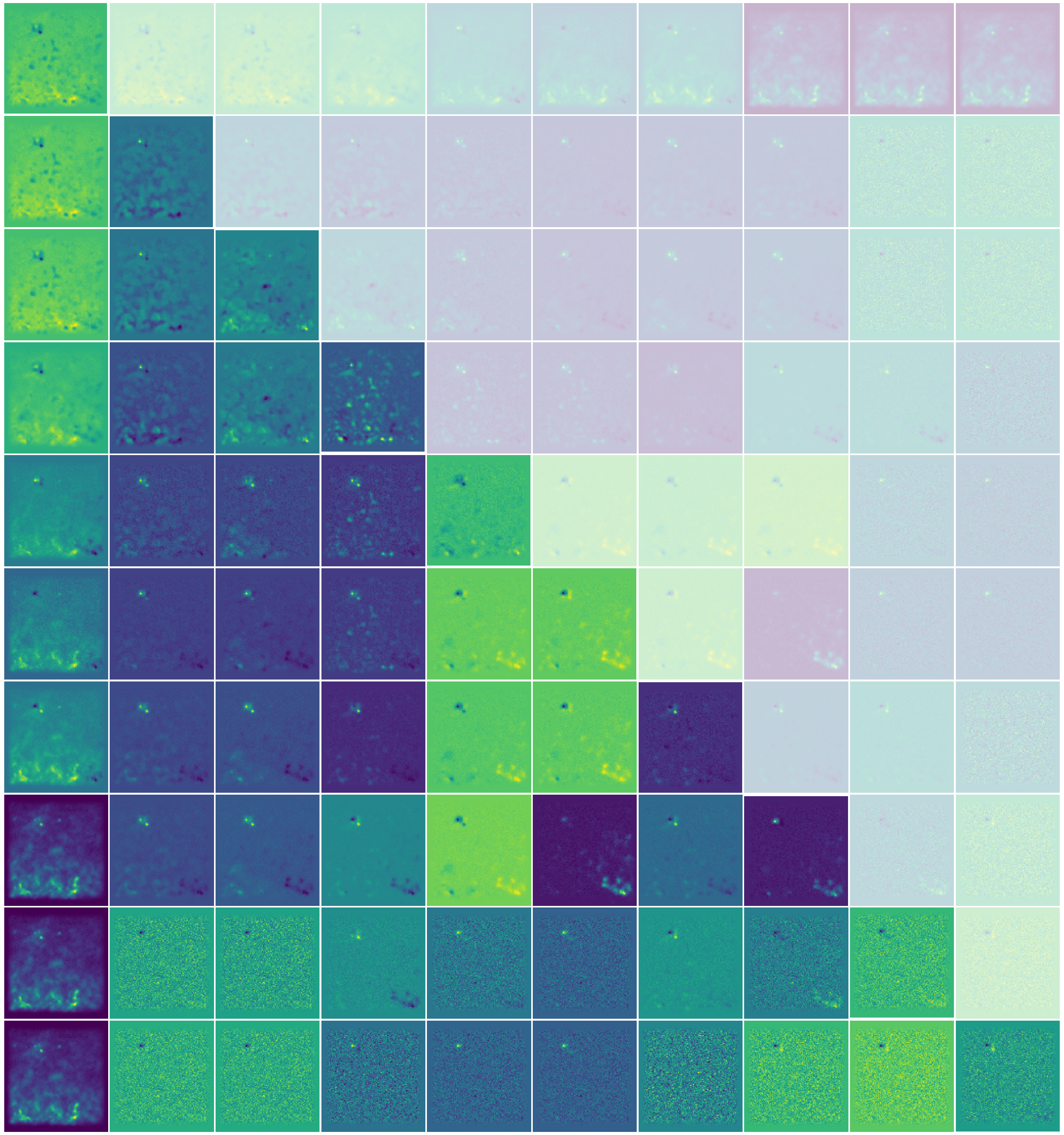

Noise RMS : 50 Jy/px

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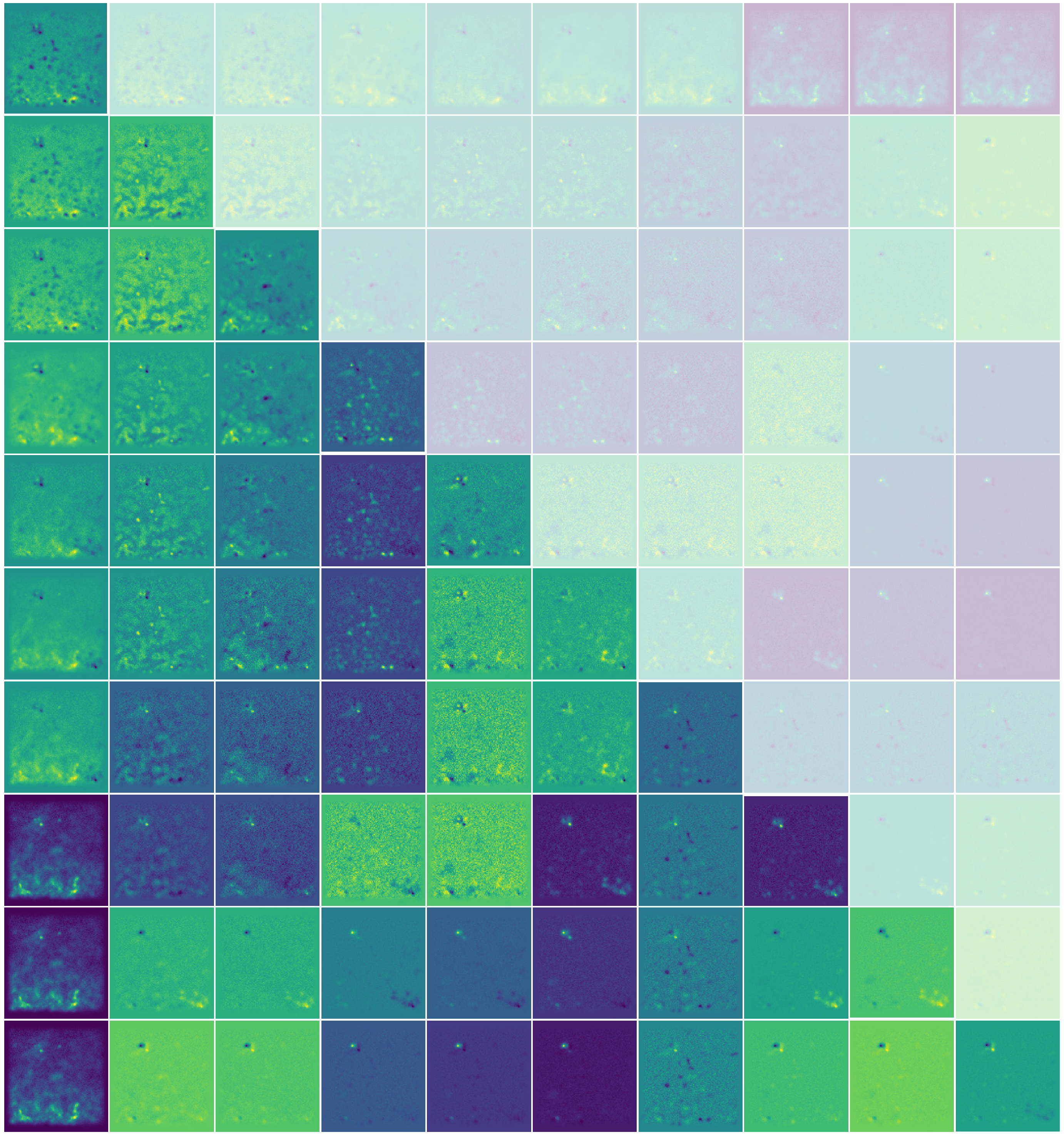

Noise RMS : 5 Jy/px

Summary

- In the moment framework, the **spectral and spatial complexity of foregrounds are tightly correlated.**
- The foreground SED's are not know as precisely as we do for CMB, y, mu. Nonetheless the moment approach allows for this semi-blind modeling.
- Moment-ILC (MILC) can be used to measure monopolar signals.
- The component separated maps have lower noise on projecting out foregrounds.
- Moments maps of foregrounds are a new astrophysical observable. Studying the connection to ISM needs more work.
- Extension of the formalism and methods to B-mode analysis- ongoing work!
- Possible applications to 21cm global signal measurements.

Caveats

- Need to include all foregrounds! **Moment modeling for other foreground models will be essential (CO, AME etc.).**
- Monopole measurement of CMB and y on small patches likely biased by higher multipoles, this is not an issue with μ though!