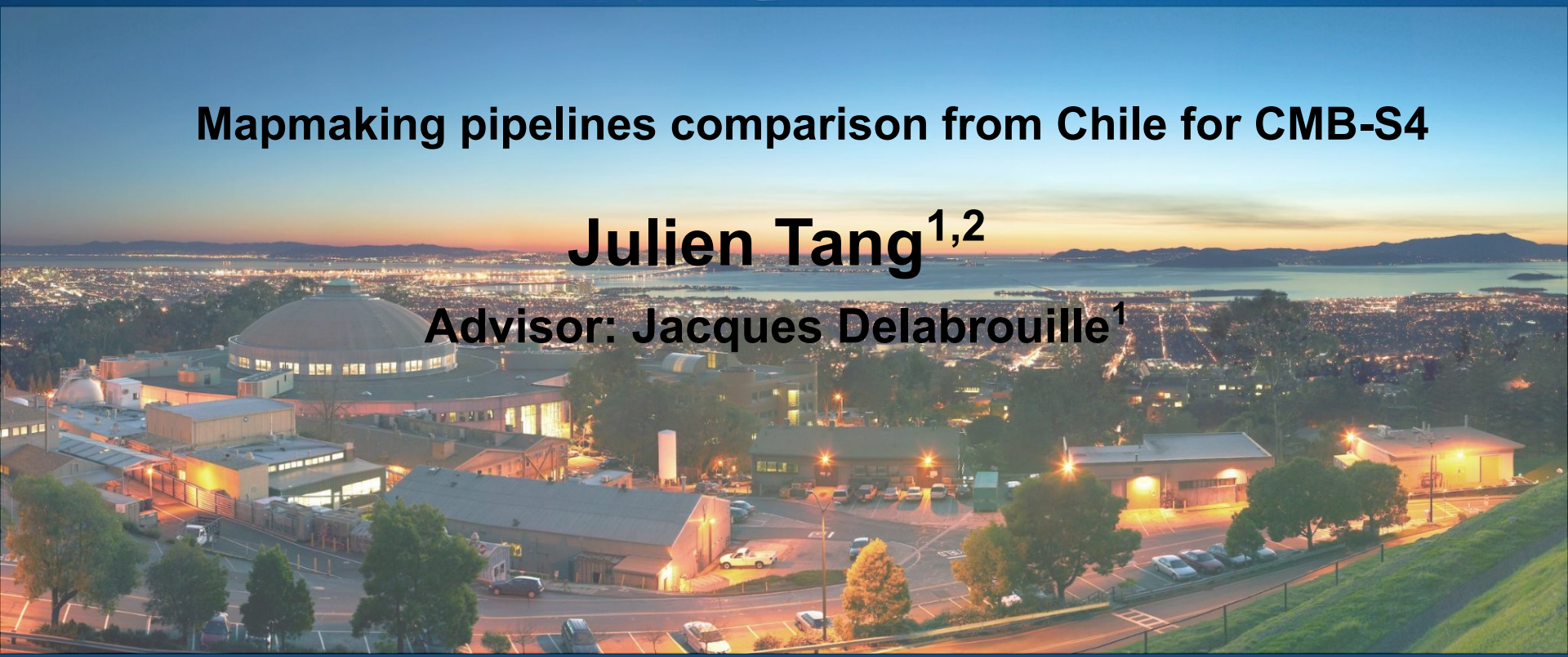
Mapmaking pipelines comparison from Chile for CMB-S4



Julien Tang[1,2]

Advisor: Jacques Delabrouille[1]

BERKELEY LAB

[1]CPB, CNRS/IN2P3 and LBNL, Berkeley
[2]APC

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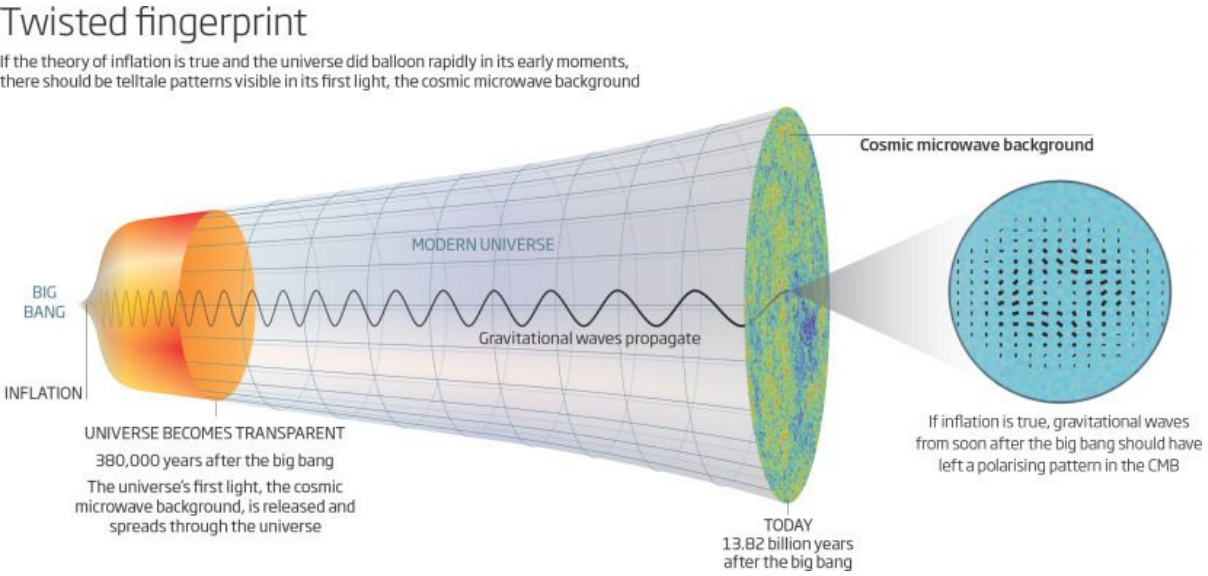
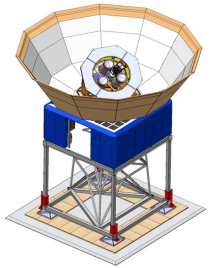
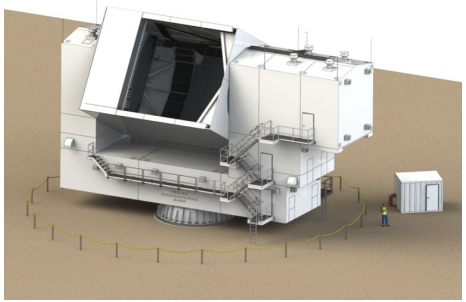
CMB-S4 overview



Inflation, Gravitational Waves & CMB. Credit: New Scientist

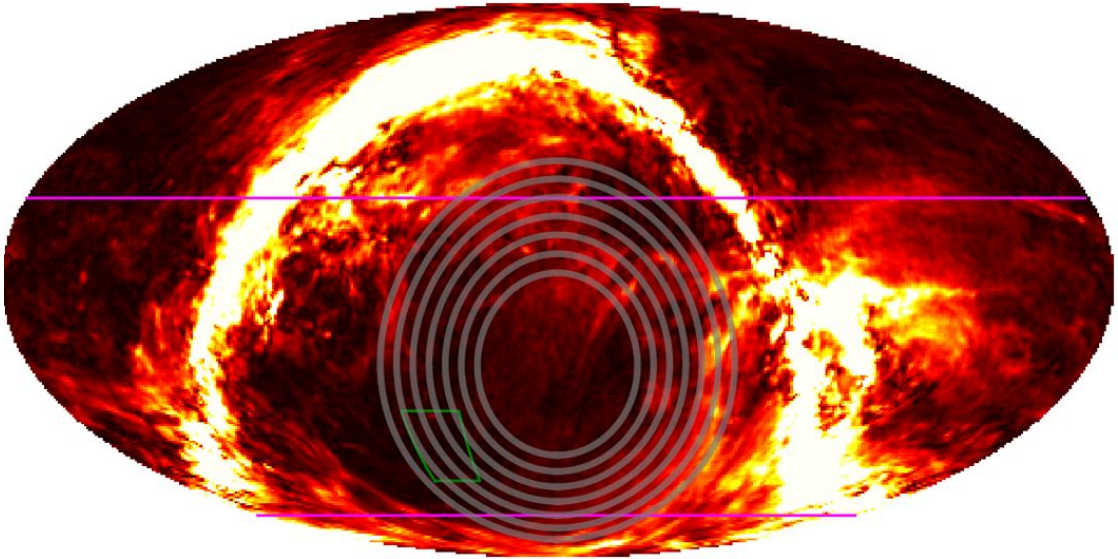


More than 500K detectors!!!



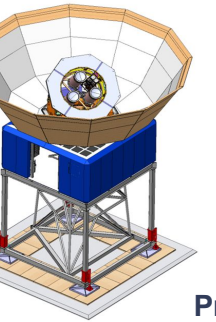
S4 will observe with SATs and LATs.
(Credit: LBNL/SeeQC Inc.)

CMB-S4 : Scanning strategy



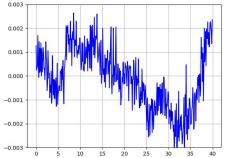
Typical scanning strategy : sets of hour-long observations at constant elevation.
Circles correspond to constant elevation lines from Atacama.

Data reduction pipeline



Detectors

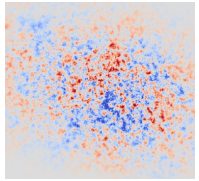
$\mathcal{O}(10^{13-15})$



Pre-processing

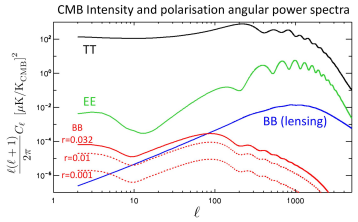
Mapmaking

$\mathcal{O}(10^{7})$



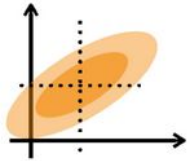
Component separation

$\mathcal{O}(10^{3})$



Estimation of power spectra

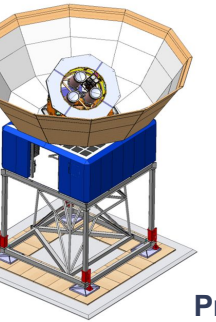
$\mathcal{O}(10)$



Constraints on cosmological parameters

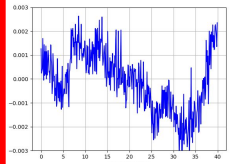
Data reduction pipeline

Focus of this study



Detectors

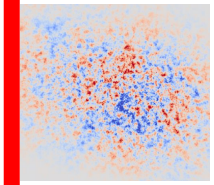
$\mathcal{O}(10^{13-15})$



Pre-processing

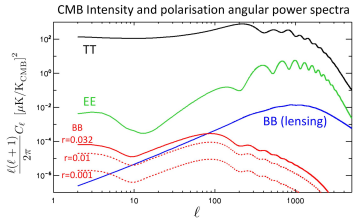
Mapmaking

$\mathcal{O}(10^{7})$



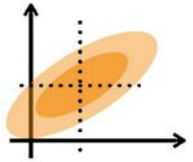
Component separation

$\mathcal{O}(10^{3})$



Estimation of power spectra

$\mathcal{O}(10)$



Constraints on cosmological parameters

The mapmaking problem

TOD ← map

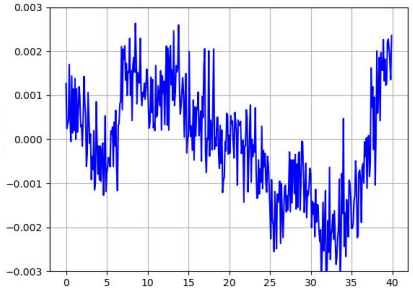
Pointing matrix

$$y_t = \mathbf{P}\mathbf{m} \Leftarrow I_t + \cos(2\psi_t)Q_t + \sin(2\psi_t)Q_t + \mathbf{n}' \Leftarrow$$

White noise

+

Low-frequency drift

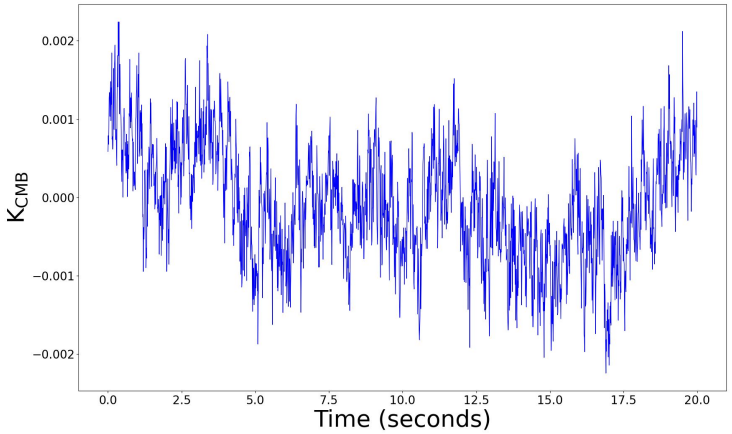


Time (in seconds)

Goal: Develop a mapmaking pipeline which mitigates contamination while minimizing loss of cosmological information!

Striping effect

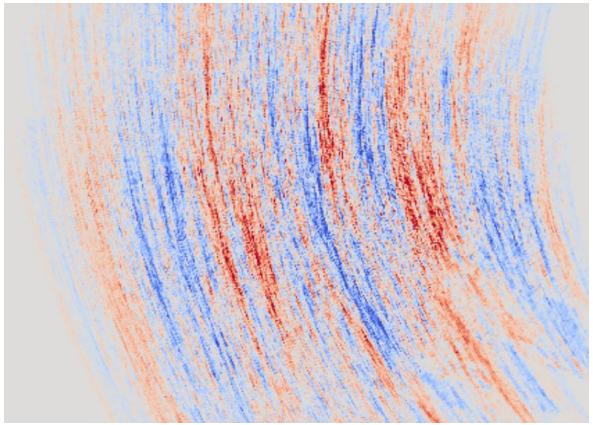
Low-frequency drift



$$\frac{\sum_t y_t}{\#\text{hits}}$$

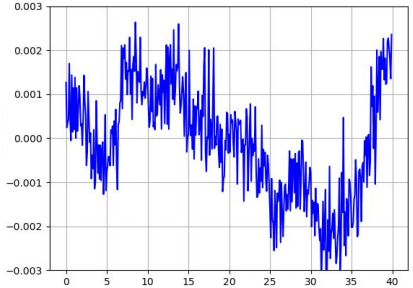
Binning

“Stripes” along the scans

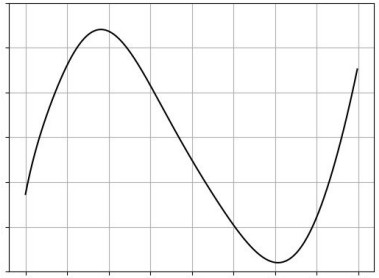


FilterBin (baseline for S4, inherited from BK)

$$y = Pm + Fa + n$$



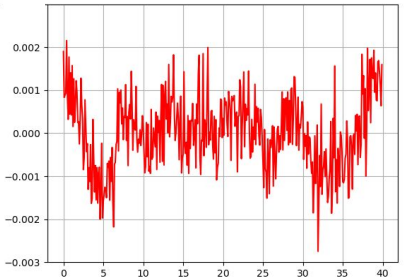
Time (in seconds)



Z_F

Polynomial filtering

$$y' = Z_F Pm + Z_F Fa + Z_F n$$



Time (in seconds)

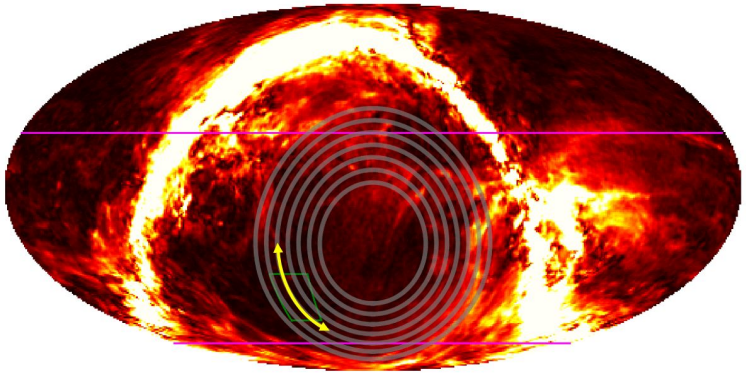
Filtered TOD

Binning

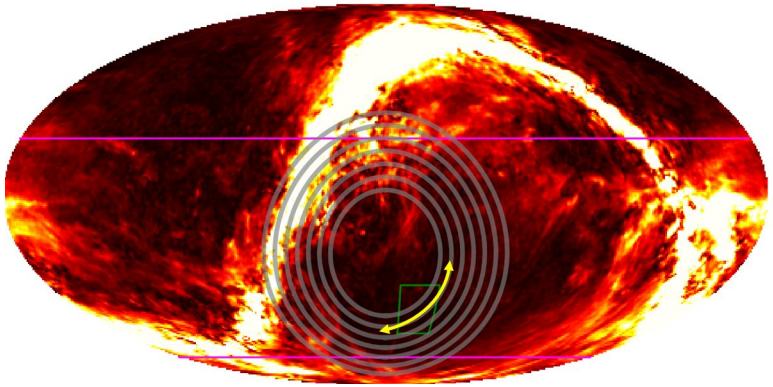
Map

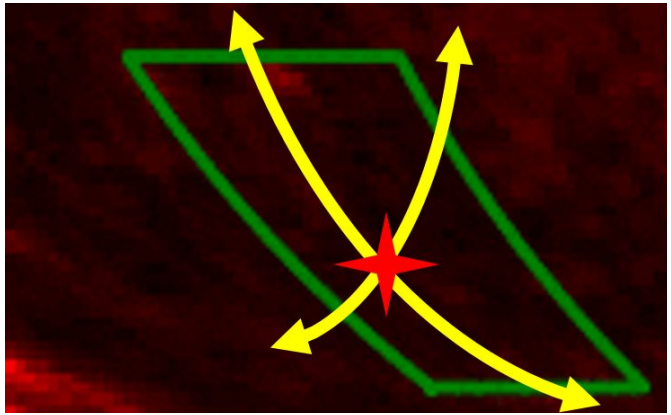
Destriping (“déstriage”)

At t1



At t2





$$p_{t_1} = p_{t_2} = p$$

$$\begin{cases} s(t_1) = m(p) + n_{t_1} \\ s(t_2) = m(p) + n_{t_2} \end{cases}$$

Sky-synchronous

Focus of the study

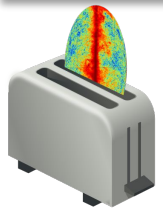
MapMaker	Pros	Cons
FilterBin	Efficient removal of low-frequency drift.	Biased : large scale modes are also removed
Destriping	Unbiased and accurateness improves with good cross-linking : interesting from Chile!	Need fine tuning to efficiently remove contamination; also expensive computationally.

Both methods are linear→ we can study them on simulations of :

- Astrophysical signal only
- Detector noise only

Trade-off between mitigating contamination and preserving information

Simulation Framework : TOAST



TOAST

Time-ordered Astrophysics Scalable Tools (TOAST)

Experiment simulation

- Instrument :
  - Focalplane
  - Modulation with HWP
- Site : Atacama, South Pole,...
- Schedule→Observed Patch
- Weather conditions

“Flavor” of the timestreams

- **Sky-synchronous signal : astrophysical signal**
- **Detector noise**
- Atmosphere
- …

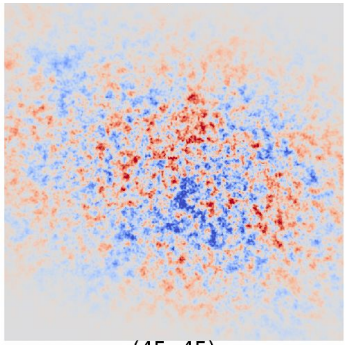
MapMaker

- FilterBin
- Destriper
- …

Effect of pipeline on pure signal simulation → mode loss

Showing in Intensity; effect in polarization is similar.

Input

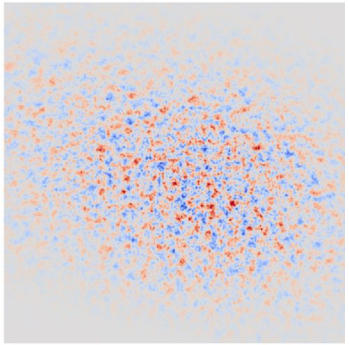


-200 200

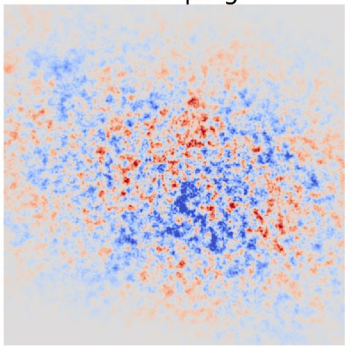
μK_{CMB}

Outputs

FilterBin

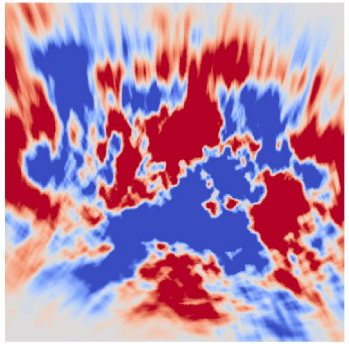


Destriping



Differences: Input-Output

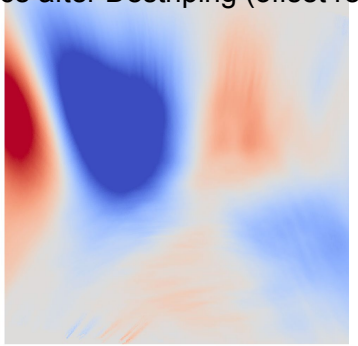
Difference after FilterBin



-20 20

μK_{CMB}

Difference after Destriping (offset removed)

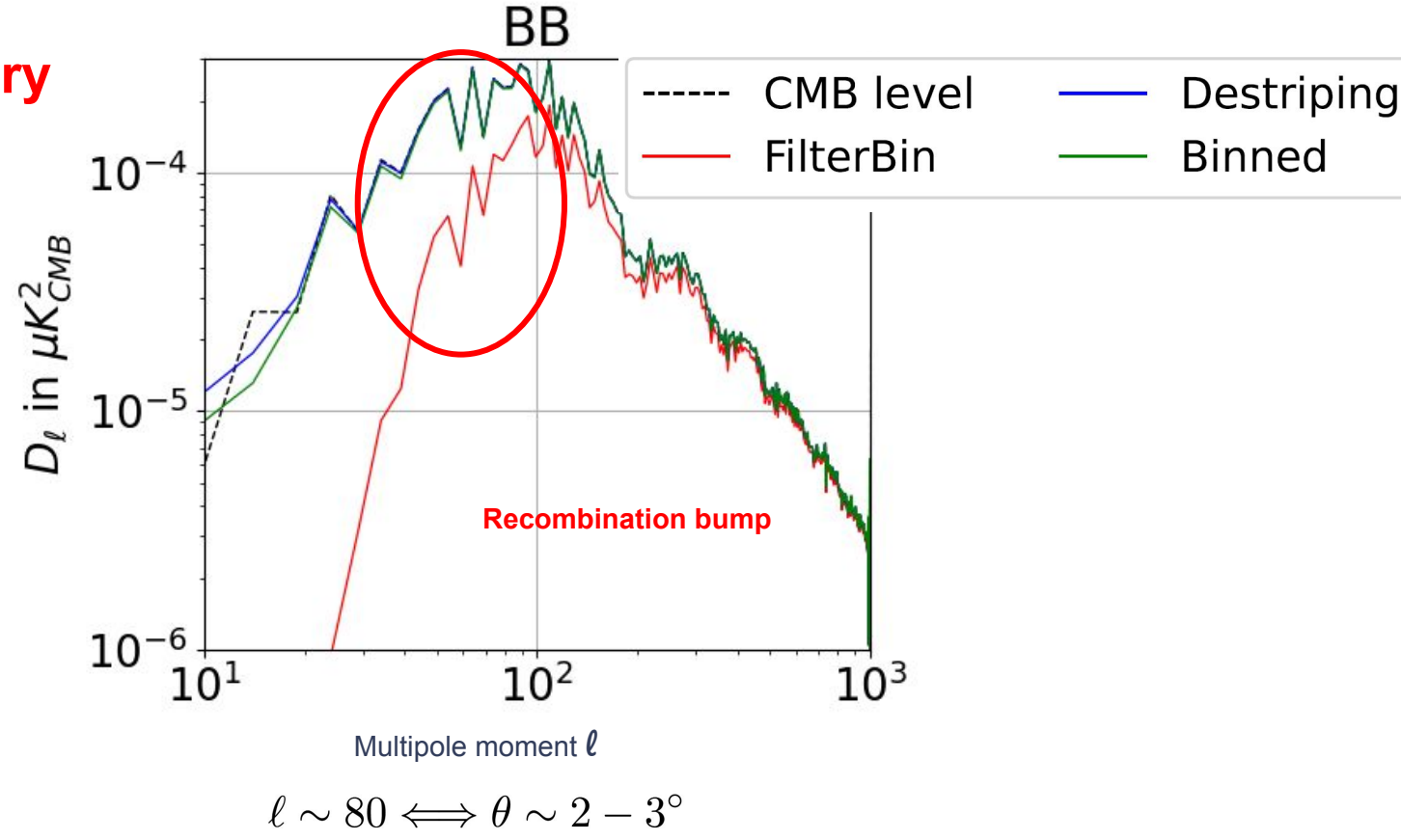


-0.2 0.2

Power spectrum of recovered maps

Preliminary

Input : Primordial B-modes only, with r 10^-3.

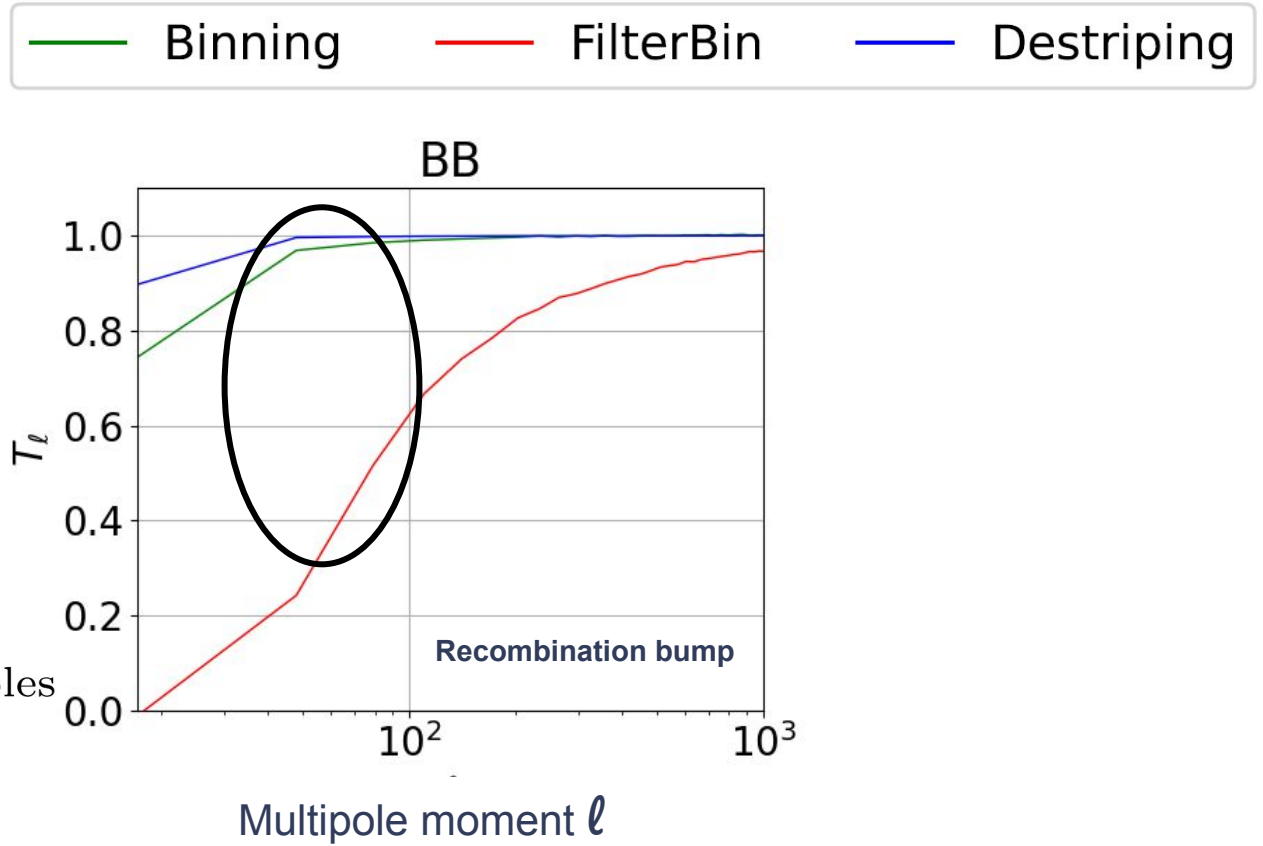


$$\ell \sim 80 \Longleftrightarrow \theta \sim 2 - 3^\circ$$

Transfer Function

Preliminary

$$T_\ell^{XY} = \left\langle \frac{C_\ell^{XY,\mathrm{out}}}{C_\ell^{XY,\mathrm{in}}} \right\rangle_{\mathrm{samples}}$$

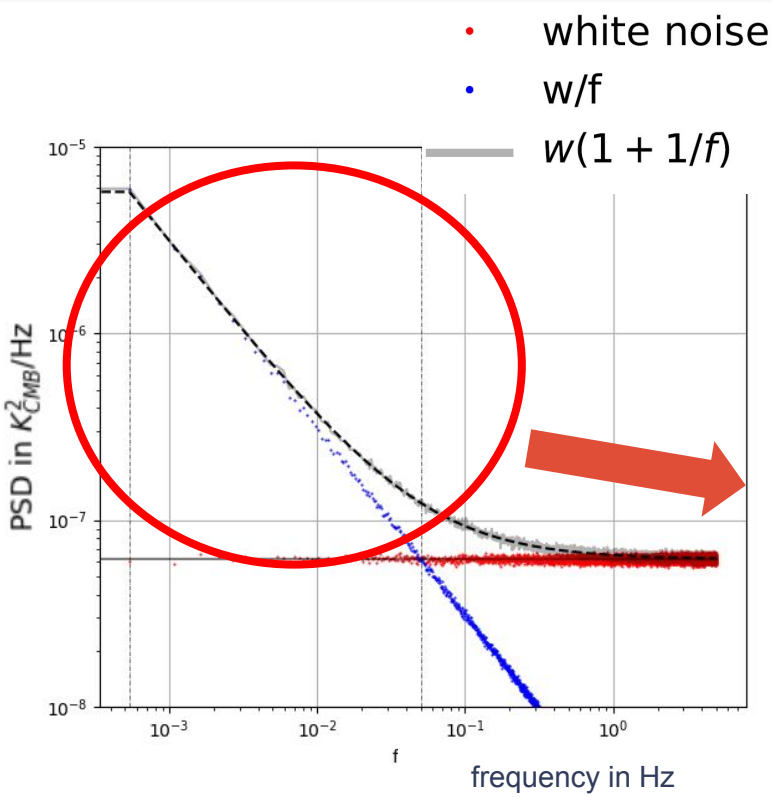


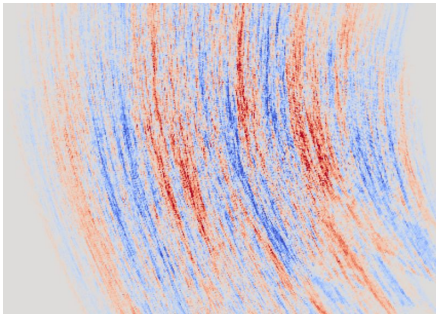
Noise simulation : properties

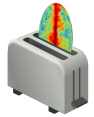
Combination of:

- **white noise**
- **correlated noise characterized by knee frequency and slope**

$$P_f = \frac{w}{f_s} \frac{f^\alpha + f_{\text{knee}}^\alpha}{f^\alpha + f_{\text{min}}^\alpha}$$



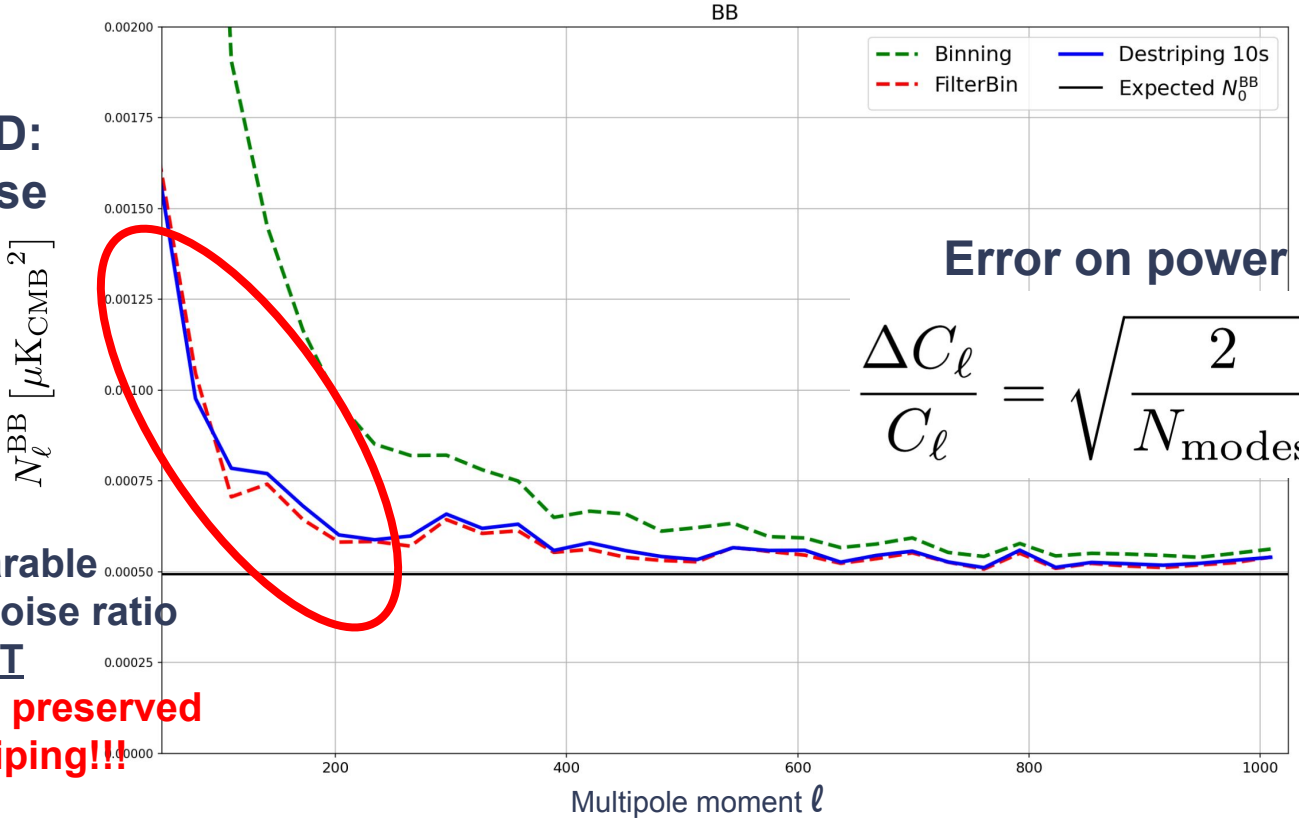




TOAST

Transfer function corrected noise spectra

Input TOD: Total Noise



Comparable Signal-to-Noise ratio

<u>BUT</u>

more modes preserved by destriping!!!

Error on power spectra([3])

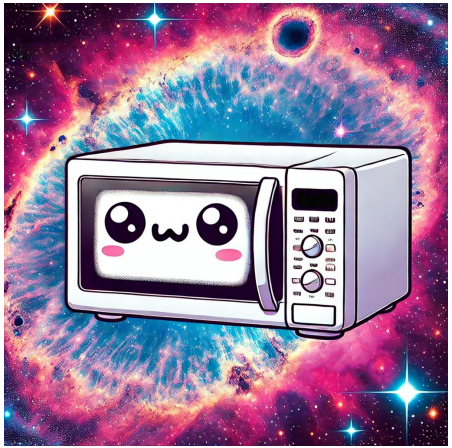
$$\frac{\Delta C_\ell}{C_\ell} = \sqrt{\frac{2}{N_{\rm modes}}}(1+{\rm SNR})$$

Conclusion

- **CMB science is exciting, and so is CMB-S4!**
- Comparison of two mapmaking methods on simulations from Chile for CMB-S4:
  - On pure sky-synchronous signal:
    - Transfer functions:
      - 50% mode loss for FilterBin at degree-angular scales
      - Better mode preservation by Destriping
  - On noise:
    - Destriping performance similar to FilterBin in signal-to-noise ratio

Bottom Line : destriping is an interesting alternative pipeline to FilterBin for a Chile configuration!

Thank you!



CMB-S4 2024 Summer Meeting, University of Illinois at Urbana-Champaign

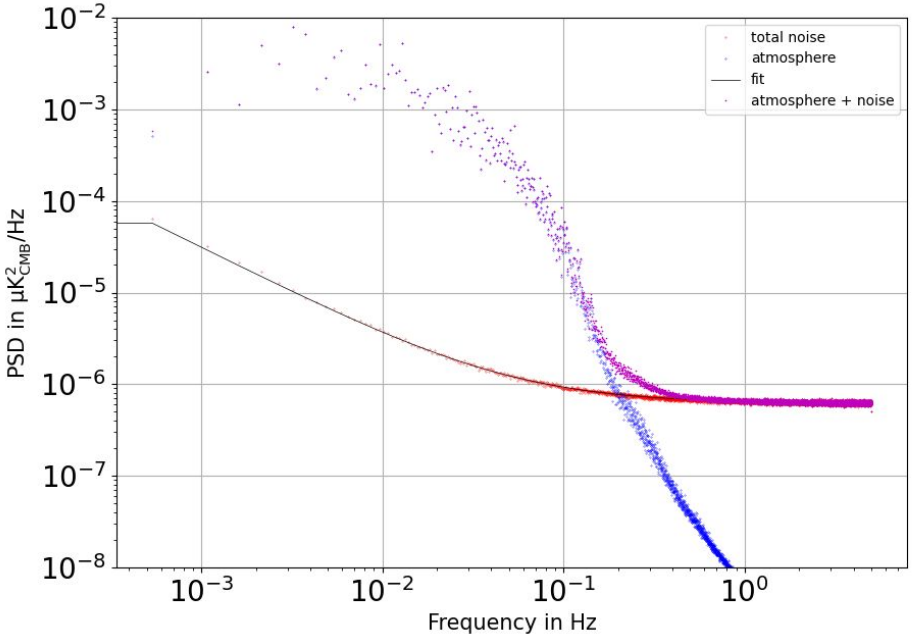
References

1. *CMB-S4 Science Case, Reference Design, and Project Plan*, CMB-S4 Collaboration. https://doi.org/10.48550/arXiv.1907.04473
2. *Making cosmic microwave background temperature and polarization maps with MADAM*,E. Keihänen, R. Keskitalo, H. Kurki-Suonio, T. Poutanen, A.-S. Sirviö, A&A 510 A57 (2010) –DOI: 10.1051/0004-6361/200912813
3. *Determination of inflationary observables by cosmic microwave background anisotropy experiments*, Lloyd Knox. https://doi.org/10.1103/PhysRevD.52.4307
4. *MASTER of the CMB Anisotropy Power Spectrum: A Fast Method for Statistical Analysis of Large and Complex CMB Data Sets,* E. Hivon,K.M. Gorski et al.https://doi.org/10.48550/arXiv.astro-ph/0105302

Backup slides

In progress

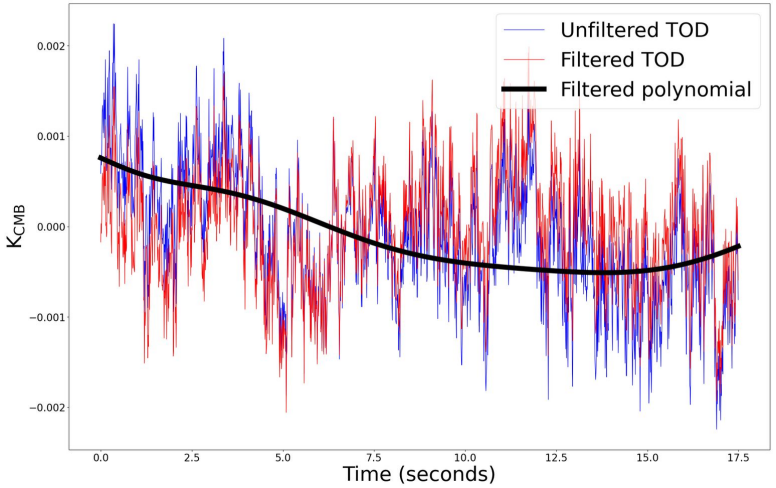
- Same study with rotating HWP.
- Explore including atmospheric emission
  - Increases thermal load and white noise level + knee frequency



Atmosphere (purple) and noise (red) Power Spectral Density

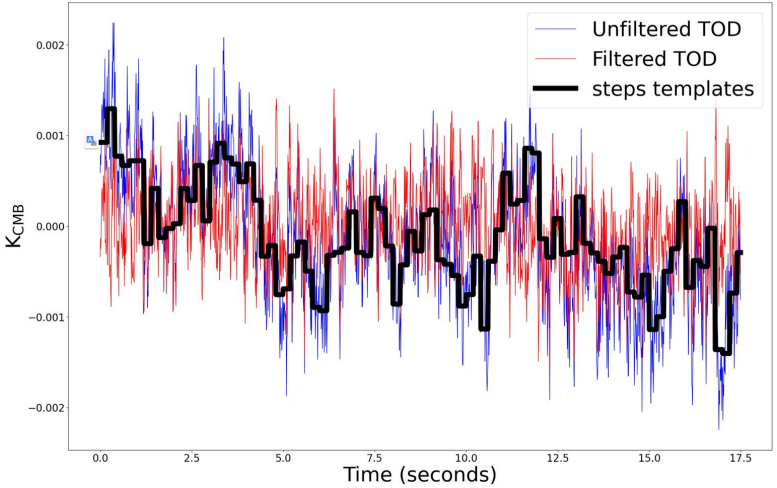
Noise mitigation

FilterBin



VS

Destriping



Polynomial filtering of TOD

Estimation and subtraction of noise