CO Mapping Array Project
COMAP

HI Intensity Mapping Workshop, Trieste 2022

Stuart Harper, University of Manchester, 25 May 2022

COMAP Collaboration

37 Members across 11 Universities

Caltech

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Tzu-Ching Chang
Todd Gaier
Joseph Lazio
Liju Philip

Princeton University

Brandon Hensley

Université de Genève

Hamsa Padmanabhan

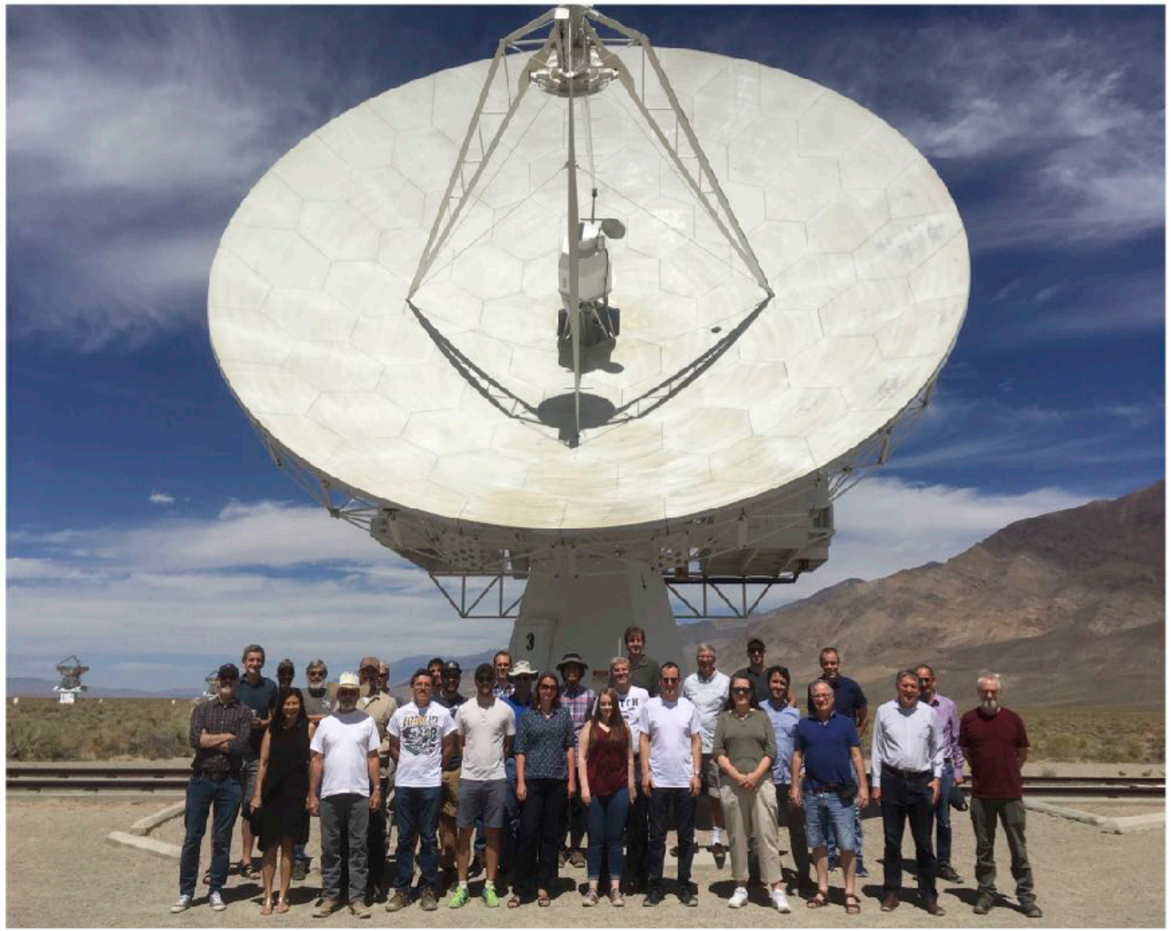
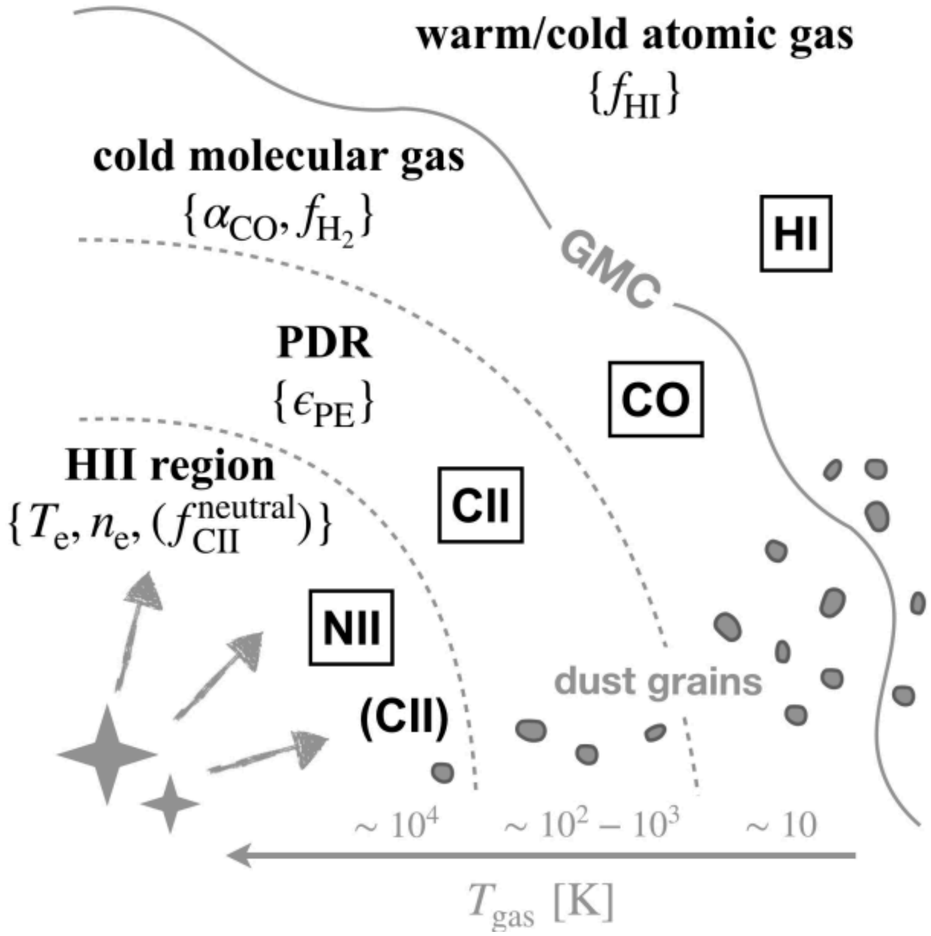
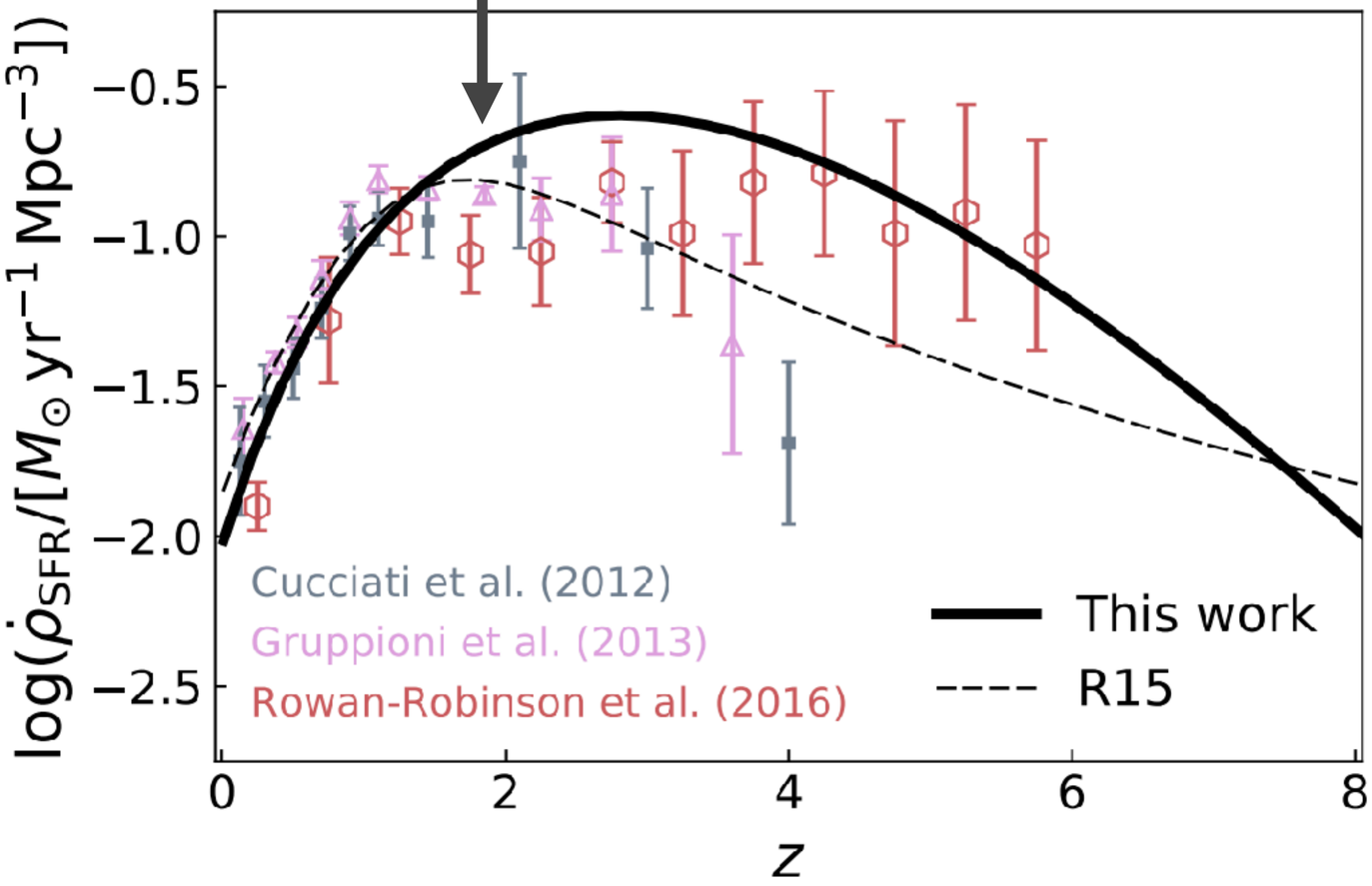


Image sourced from comap.caltech.edu

COMAP
Some Motivation



Why is this happening?



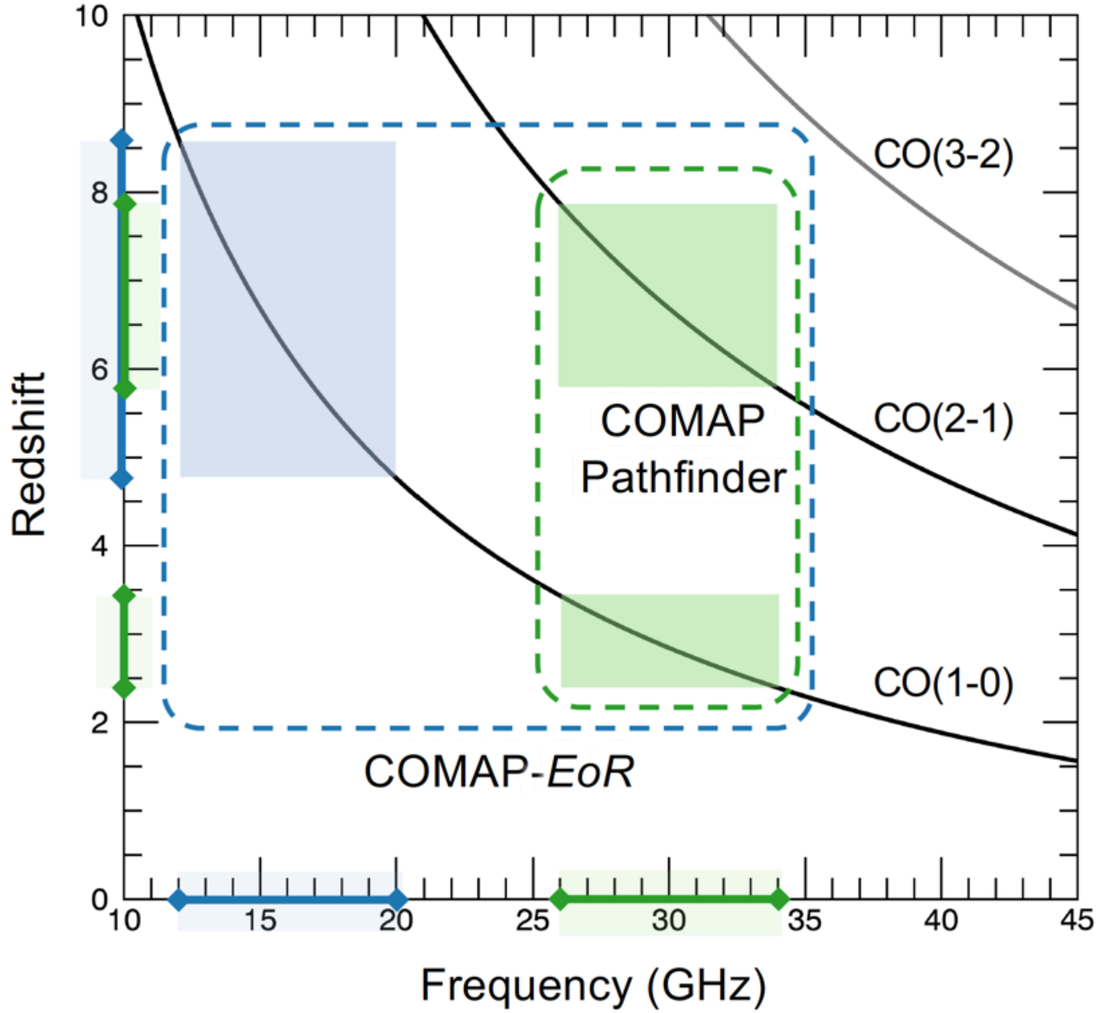
Sun et al. 2019 arXiv: 1907.02999

COMAP Pathfinder
Instrument

- $26 - 34$ GHz frequency coverage
- 4096 channels with ~ 2 MHz channel bandwidth
- $4.5'$ beam FWHM at 30 GHz
- 19 forward-facing feeds (pixels) in a hexagonal lattice arrangement
- Intensity only, no polarisation information

COMAP Pathfinder
Science Goals

- Already ruling out several CO models after 1 year of observing (arxiv:2111.05927)
- S/N of 9 to 17 in CO auto-power spectrum after 5 years.
- HETDEX cross-spectrum S/N~7 after 3 years; S/N~19 in 5 years



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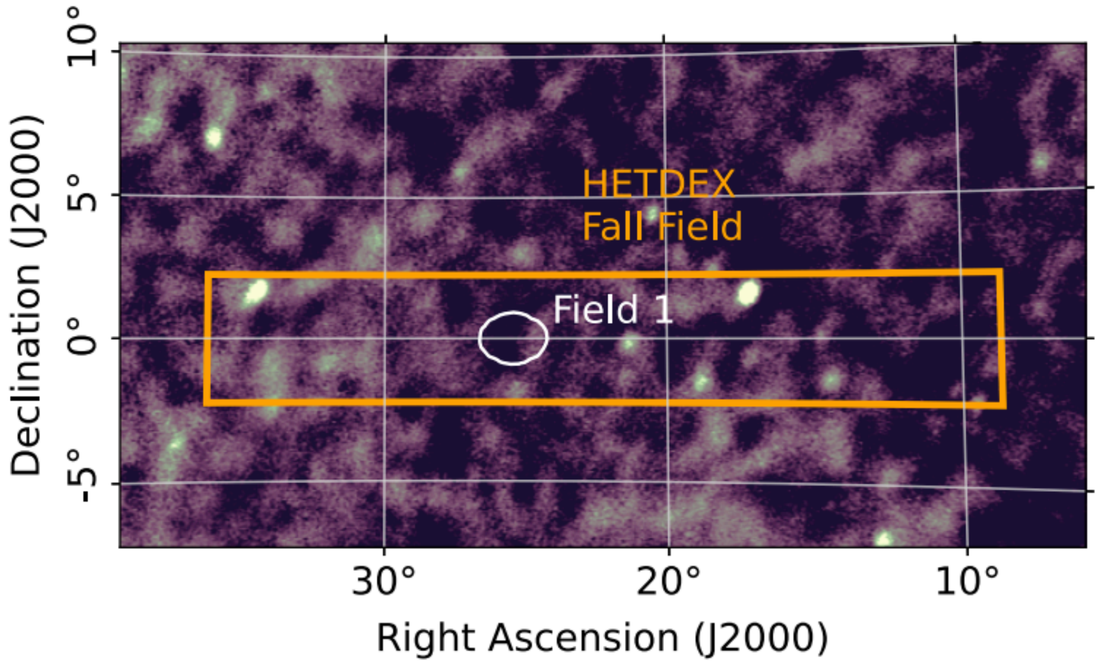
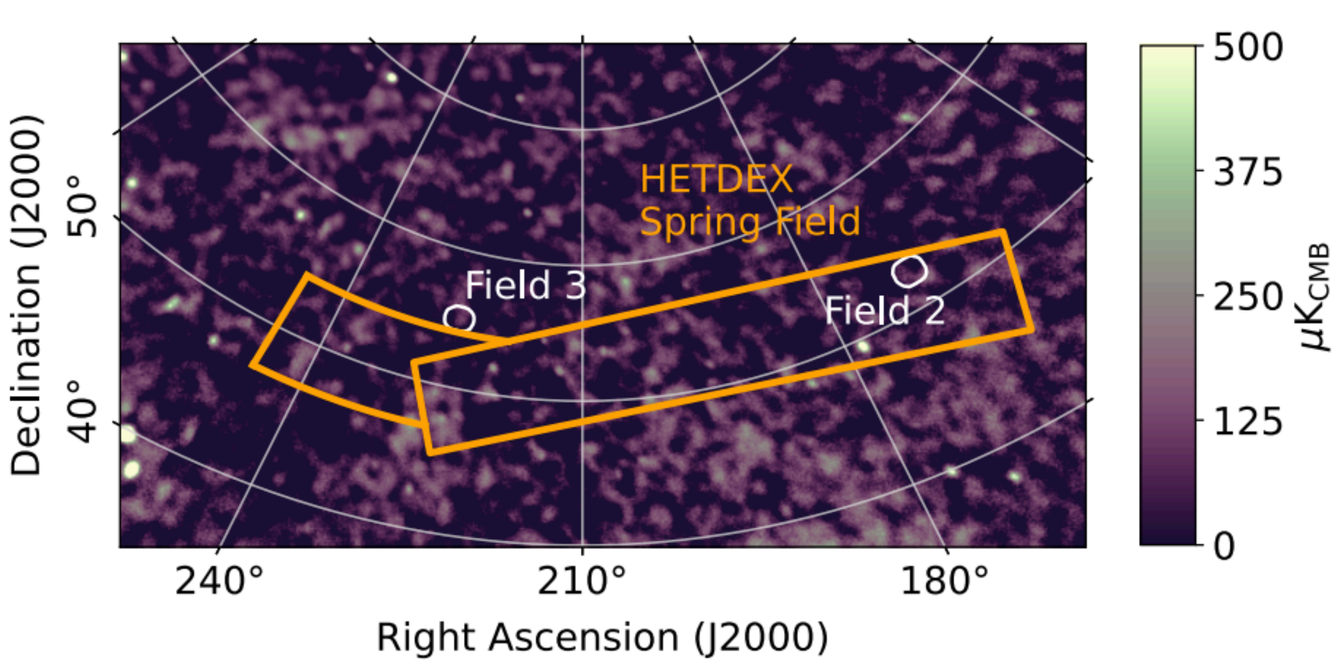
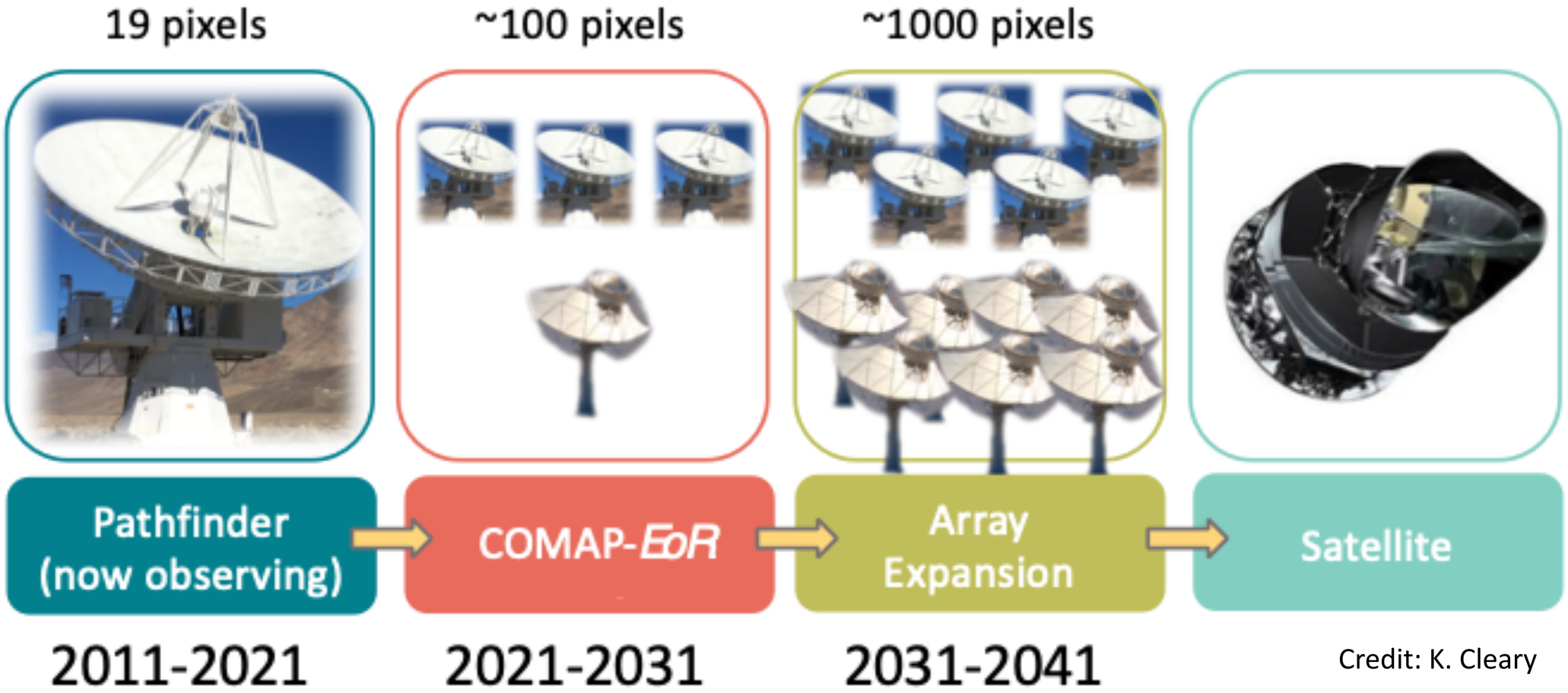
Cross-Correlation with HETDEX





COMAP Pathfinder

The Future



Credit: K. Cleary

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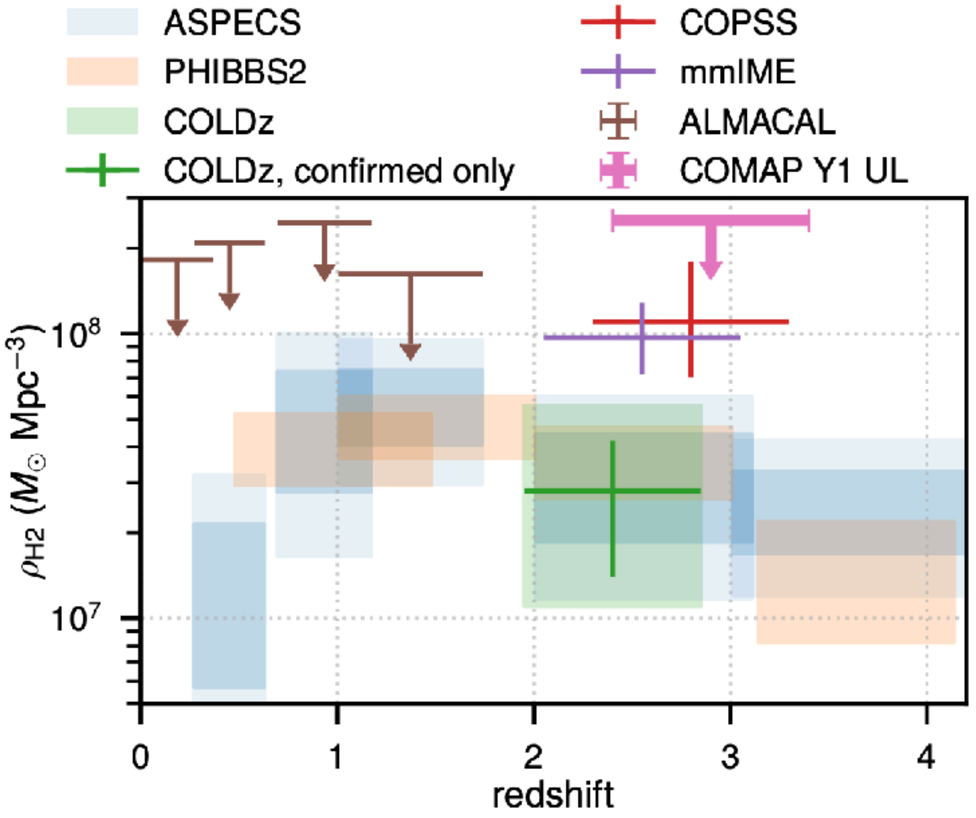
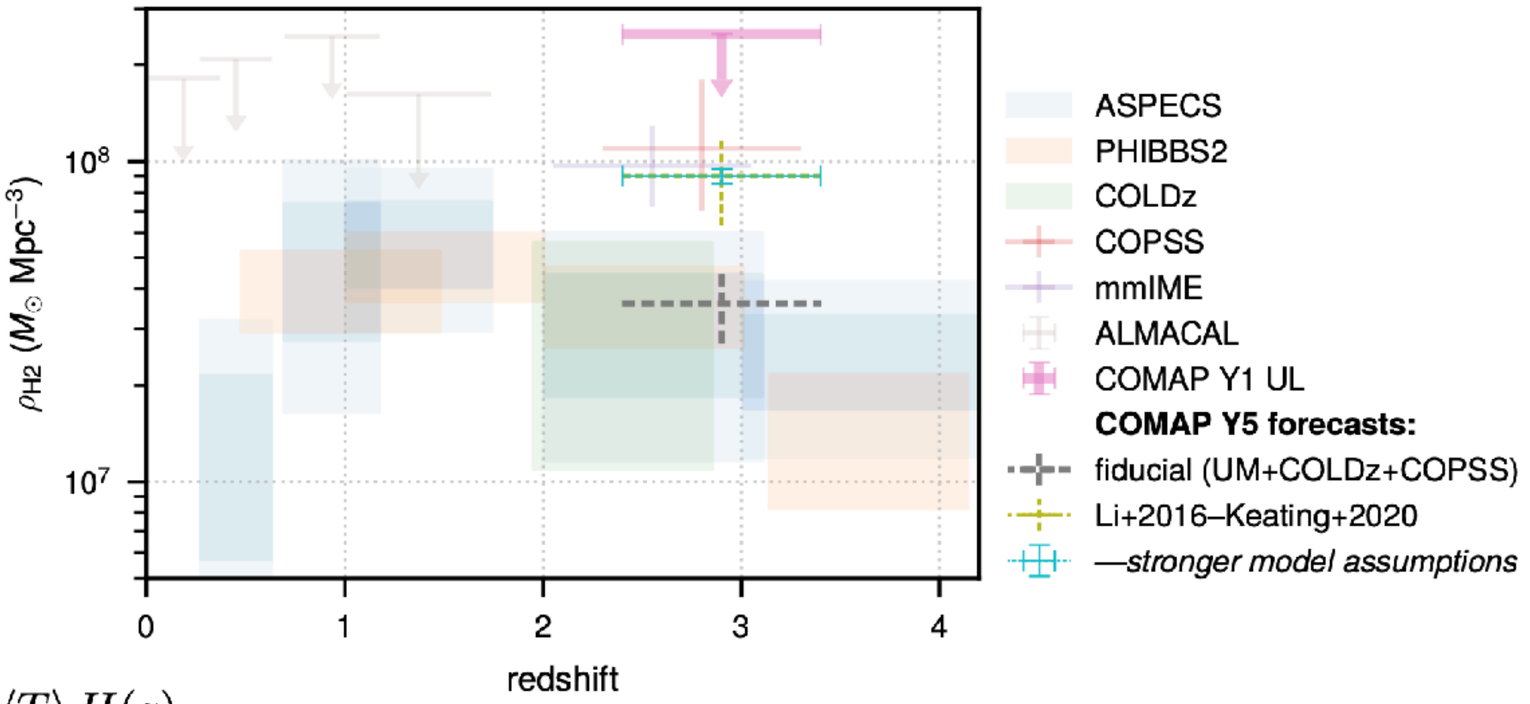
Constraints on Molecular Gas

Current constraints



5yr Forecasts



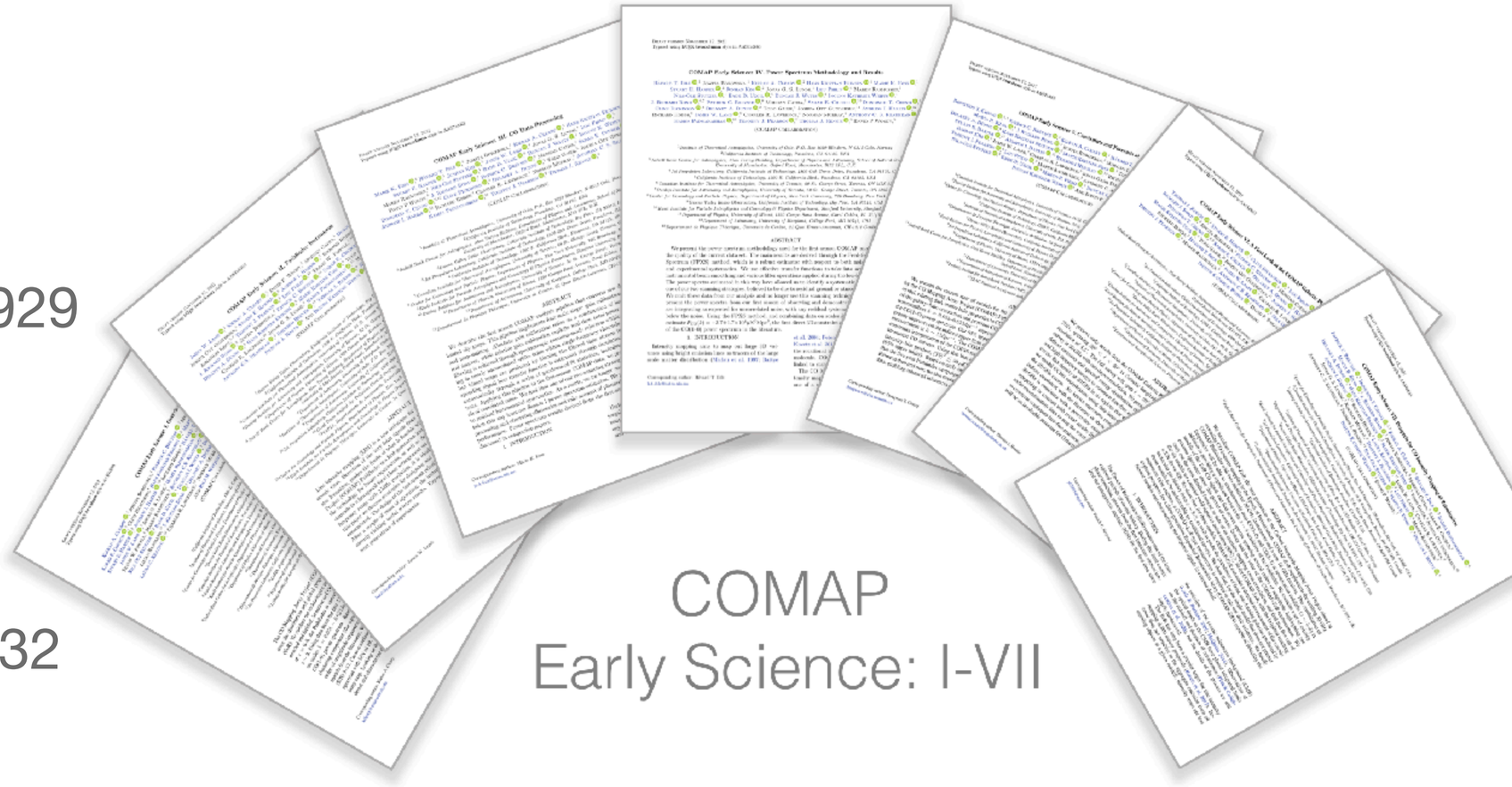
$$\rho_{\rm H2} = \frac{\alpha_{\rm CO}\,\langle T\rangle\,H(z)}{(1+z)^2}.$$

arXiv:2111.05931 Chung et al.

COMAP Pathfinder

Recent Papers

- Overview: 2111.05927
- Instrument: 2111.05928
- Data Processing: 2111.05929
- Results: 2111.05930
- Forecasts: 2111.05931
- Galactic Survey: 2111.05932
- EoR: 2111.05933



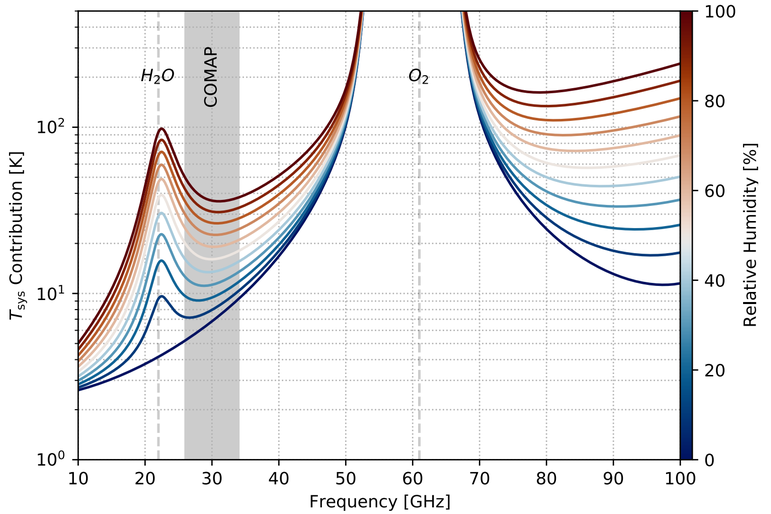
COMAP Pathfinder
Systematics

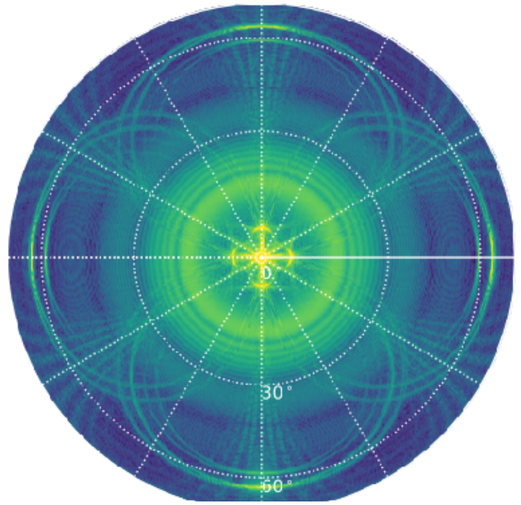
✦Main systematics:

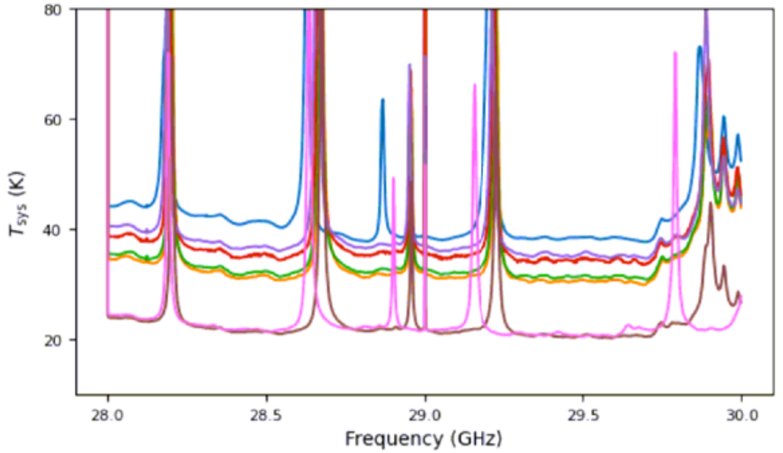
- Atmosphere
- Ground pickup
- Correlated noise
- Sidelobes
- Unique COMAP problems 🤷

✦Less of an issue:

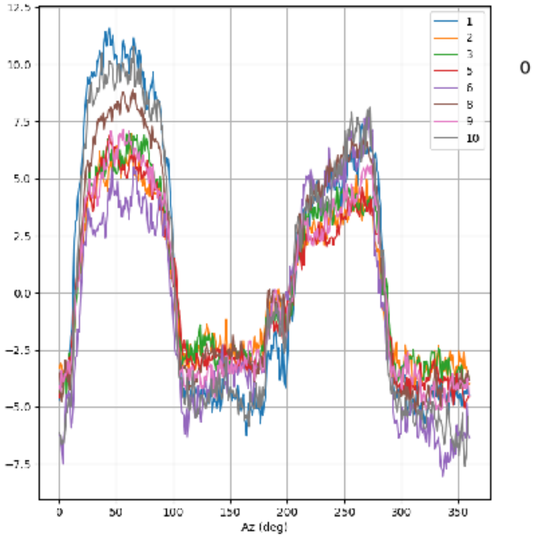
- RFI (for now!)
- Galactic foregrounds







K



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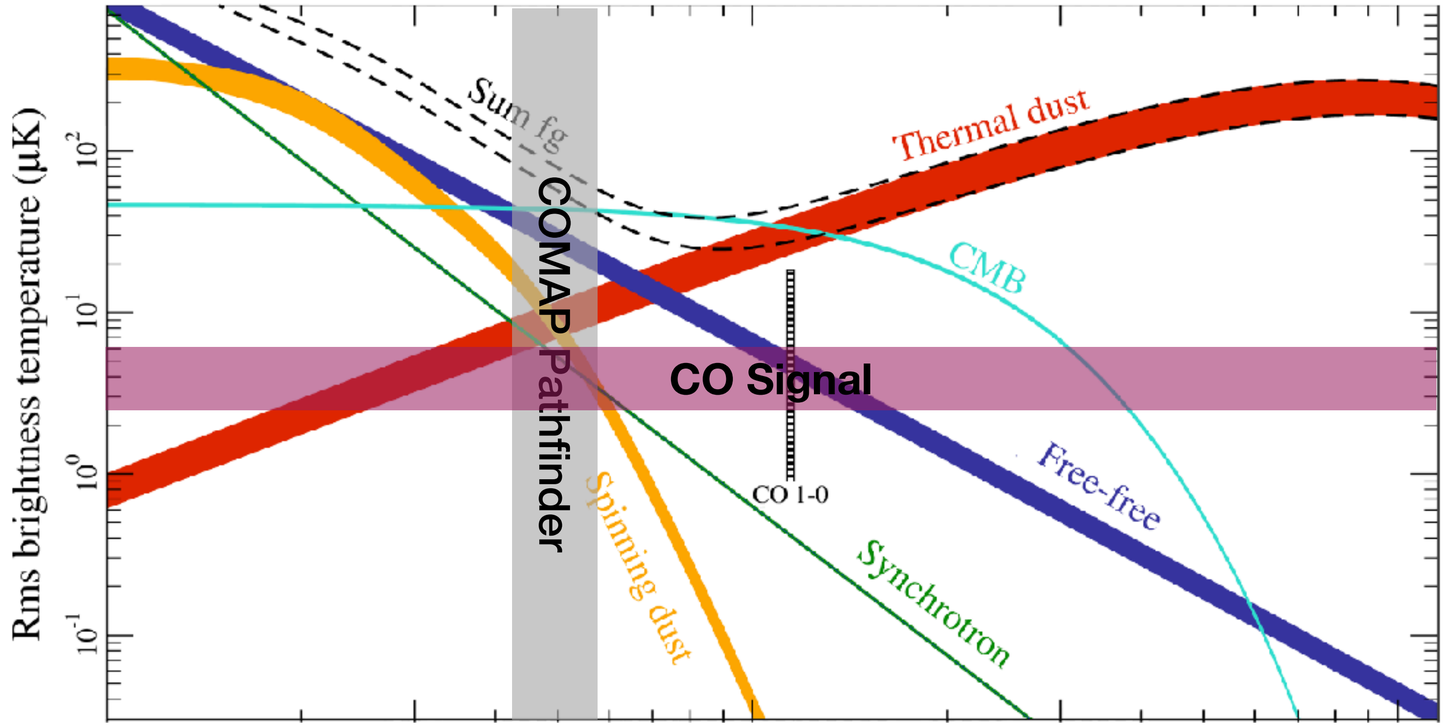
COMAP Pathfinder

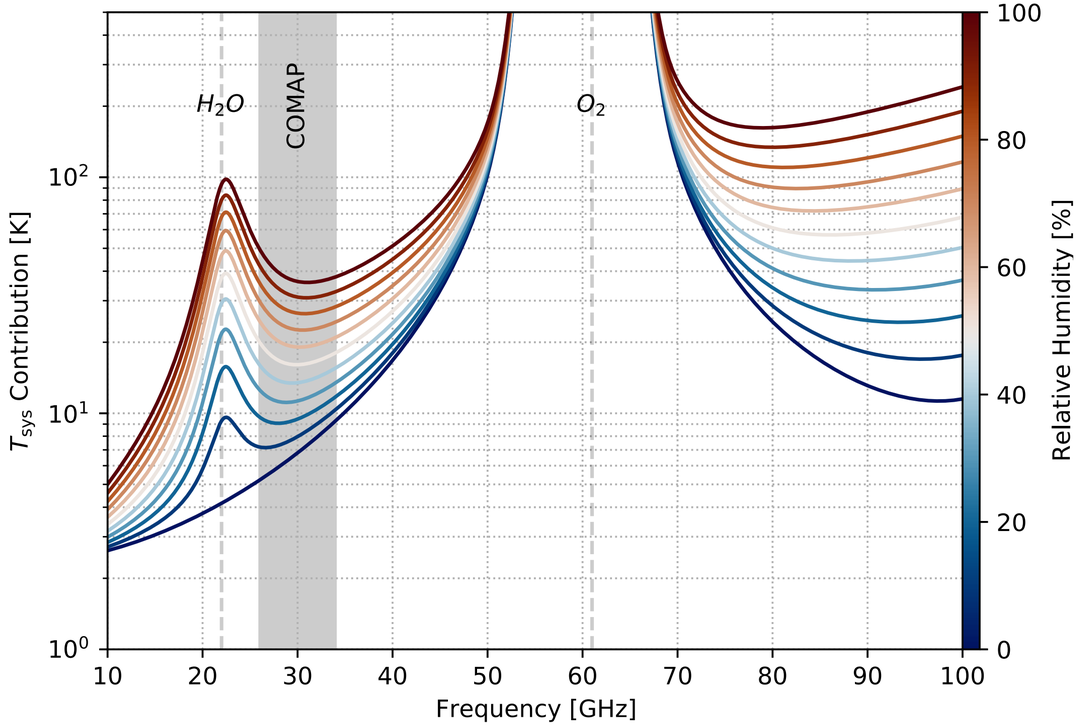
Systematics: Foregrounds

- Galactic foregrounds are very low around 30GHz
- High latitudes mostly just one component.
- Few bright extra-galactic sources.

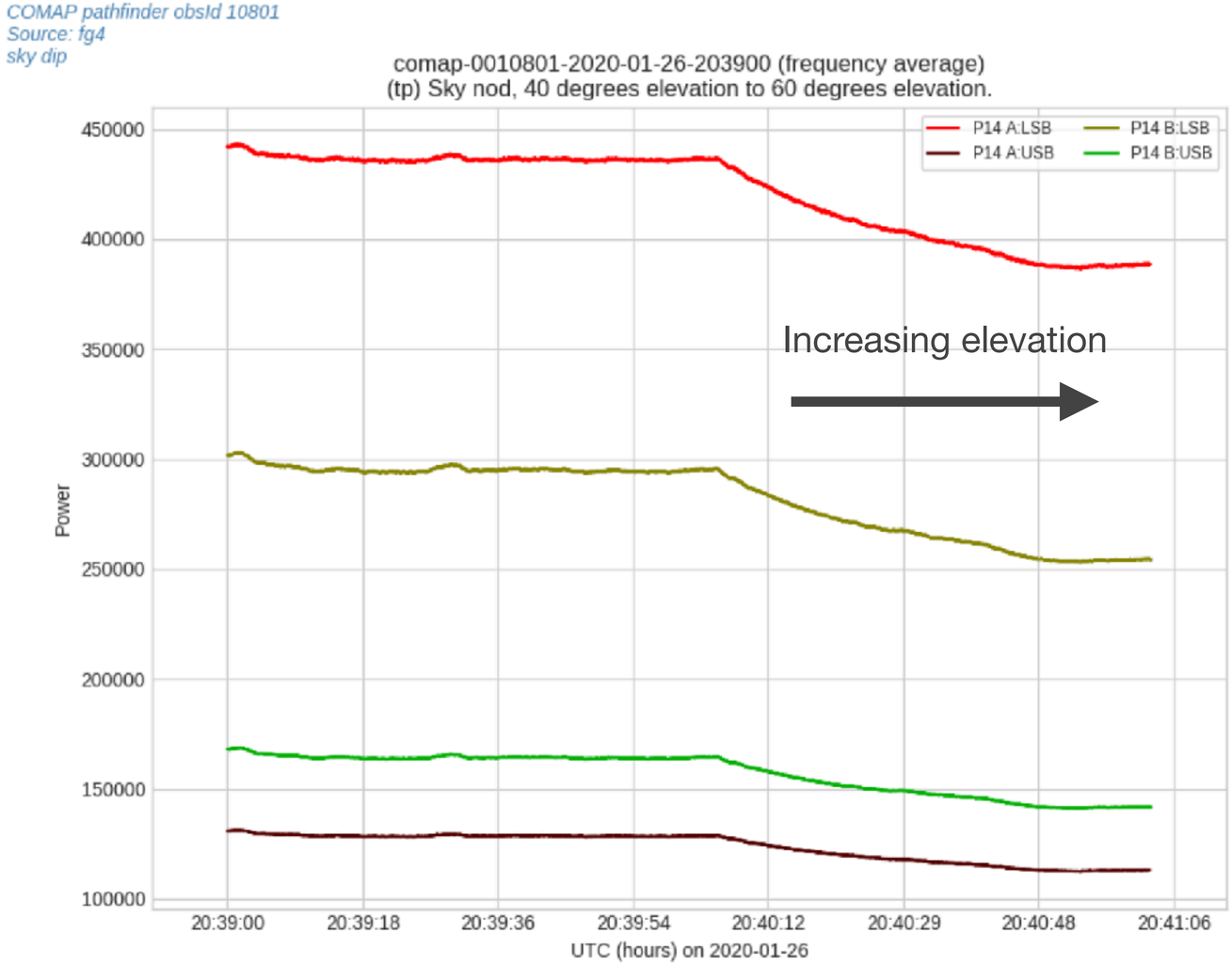


COMAP Pathfinder

Systematics: Atmosphere



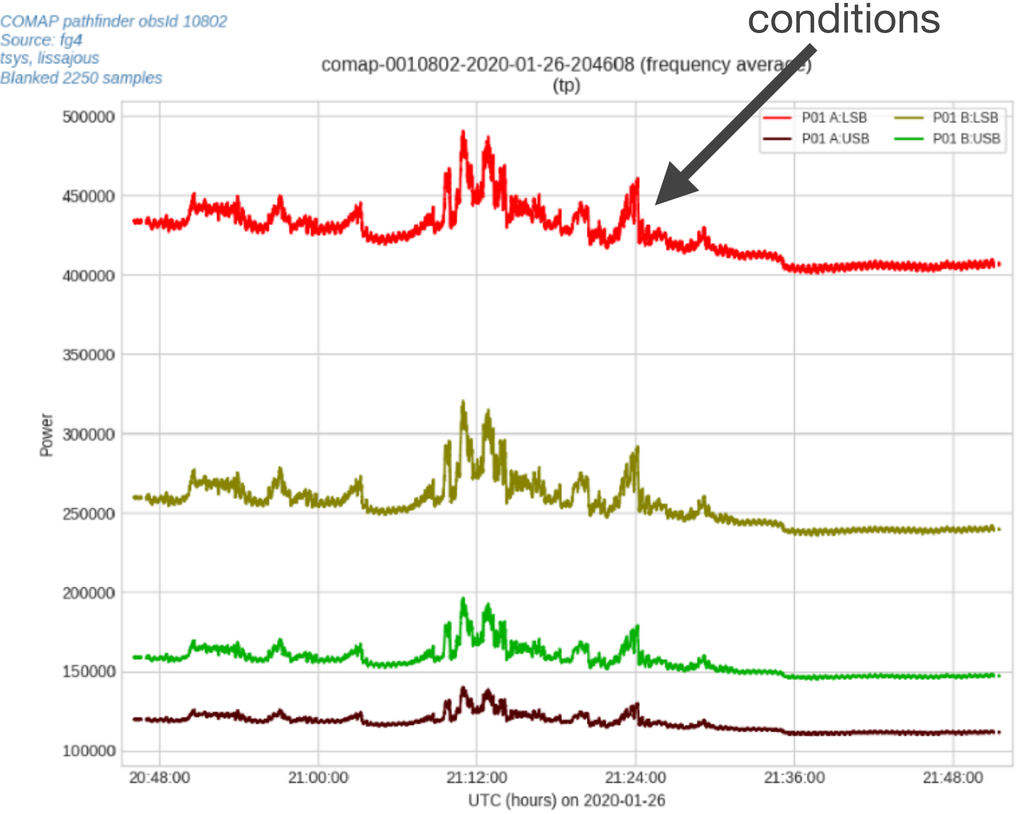
$$d \approx \frac{g}{\sin\left(\mathrm{El}(t)\right)}$$



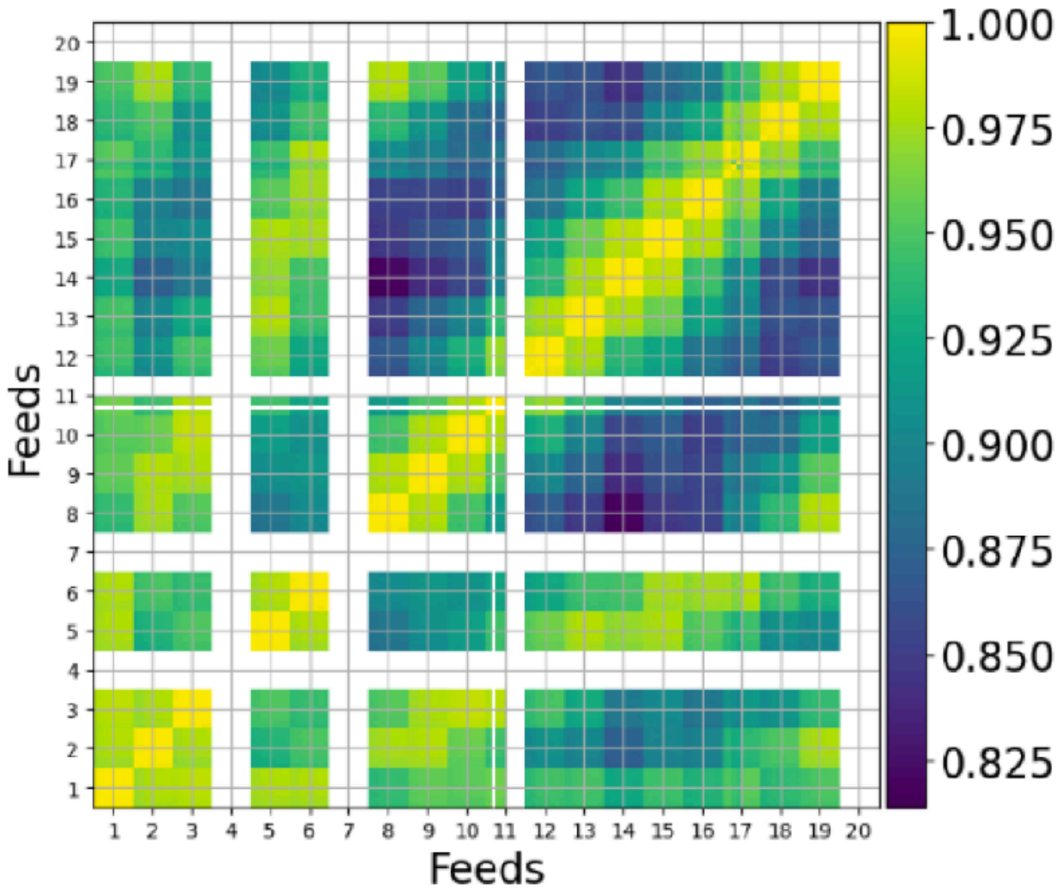
COMAP Pathfinder

Systematics: Atmosphere (A very bad example!)

Turbulent atmospheric conditions



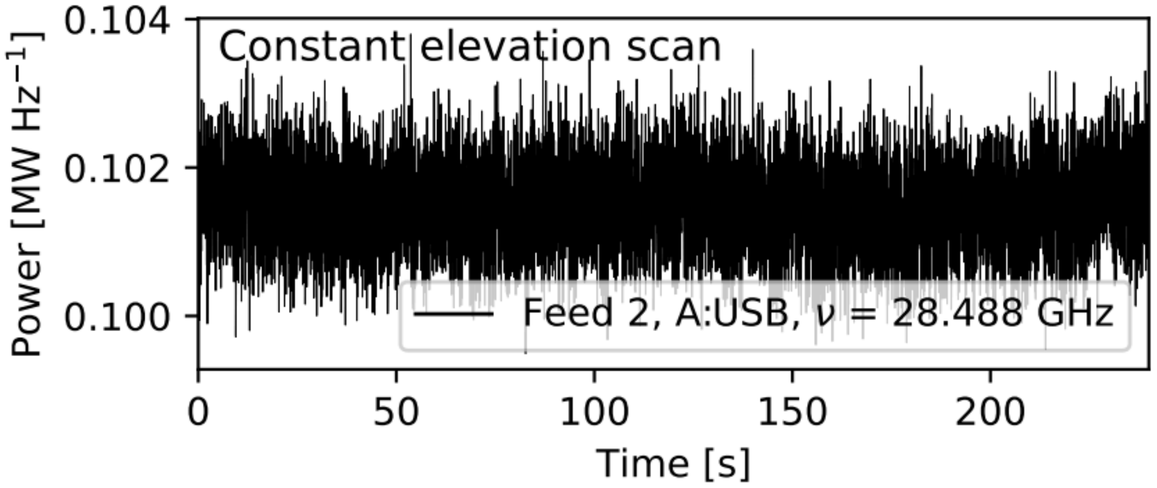
Fluctuations correlated between pixels



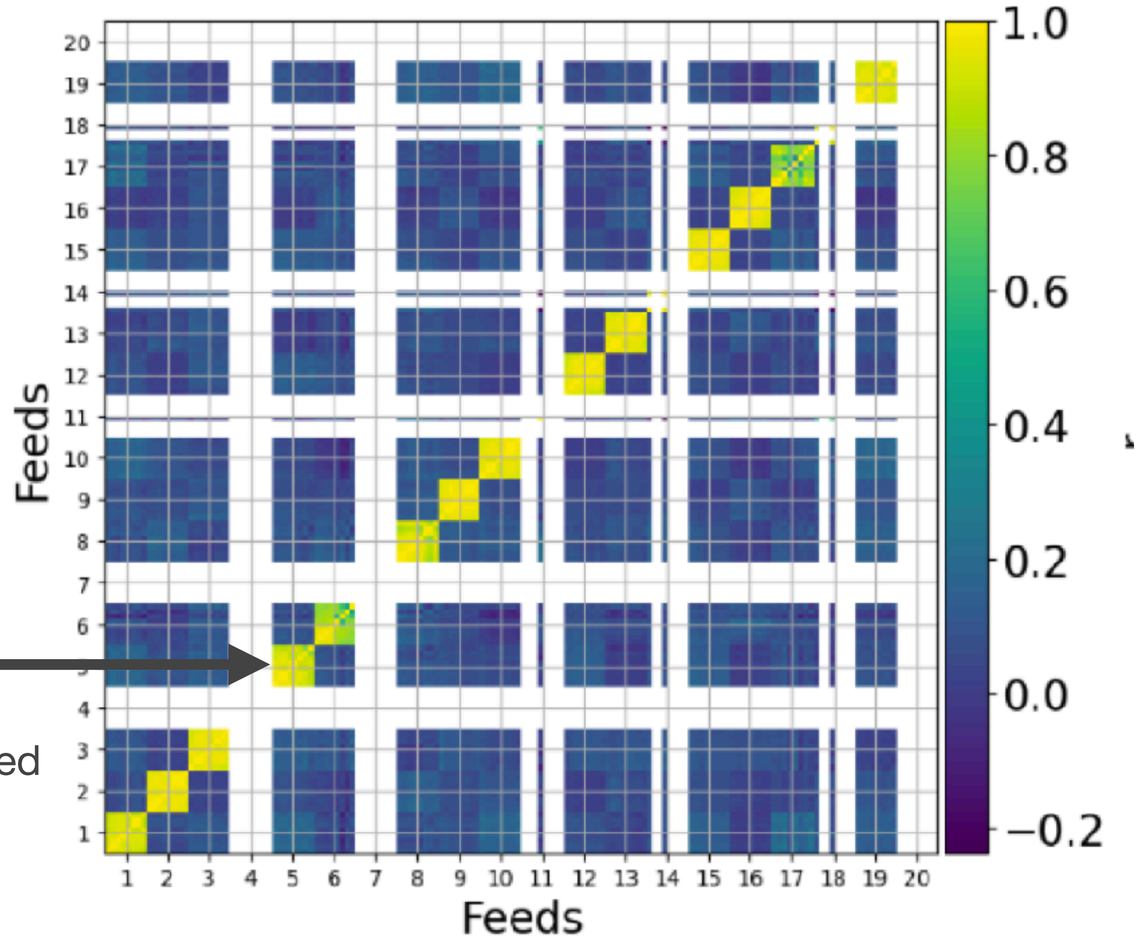
COMAP Pathfinder

Data Analysis: 1/f Noise

More typical “clean” data



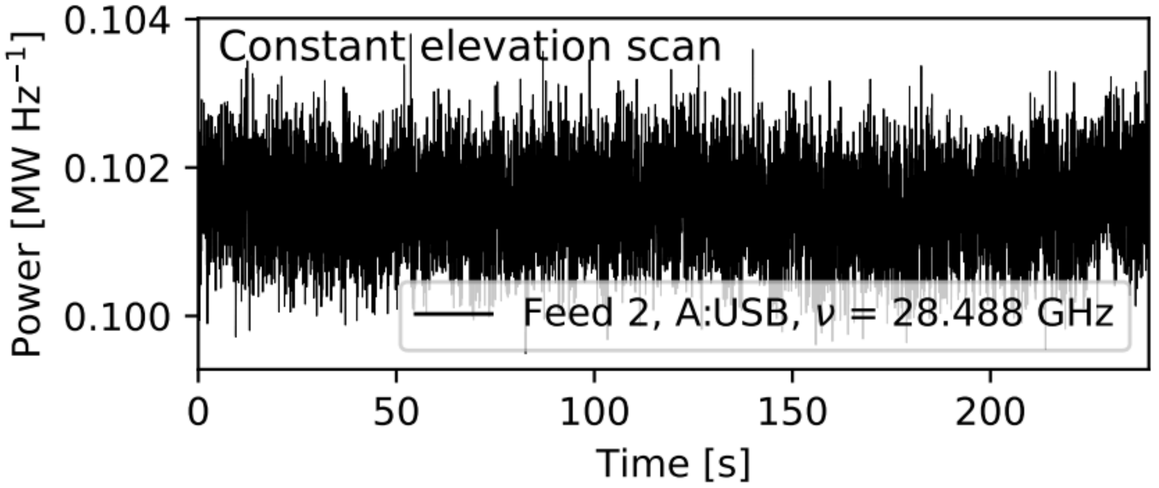
Receiver 1/f dominates correlated noise



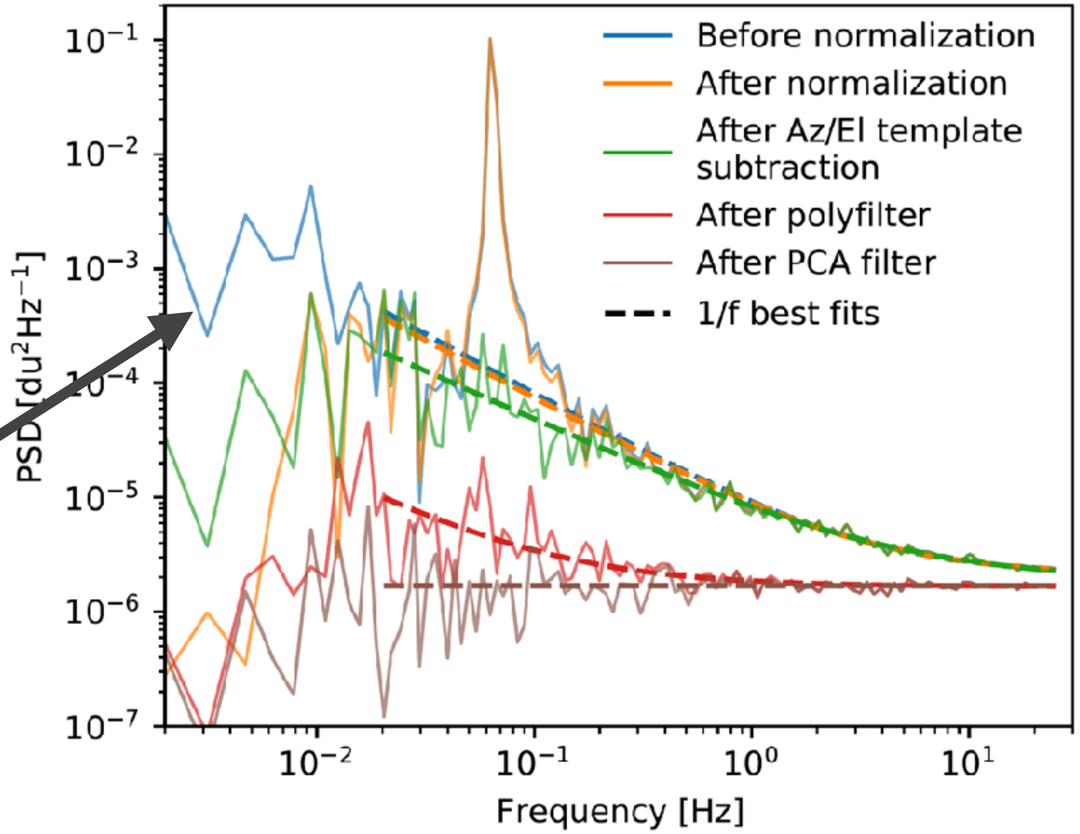
arXiv:2111.05929 Foss et al.

COMAP Pathfinder
Data Analysis: 1/f Noise

More typical “clean” data



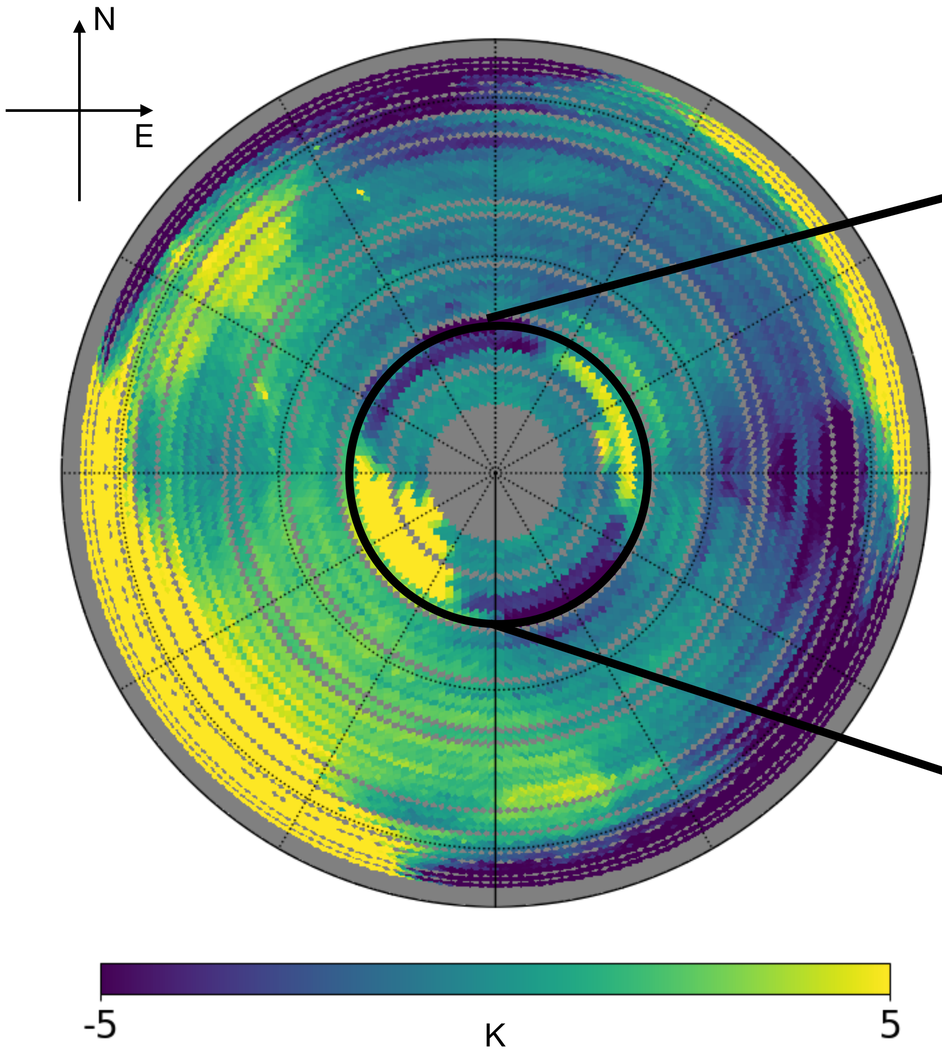
But we can still see there is plenty of correlated noise (blue line!)

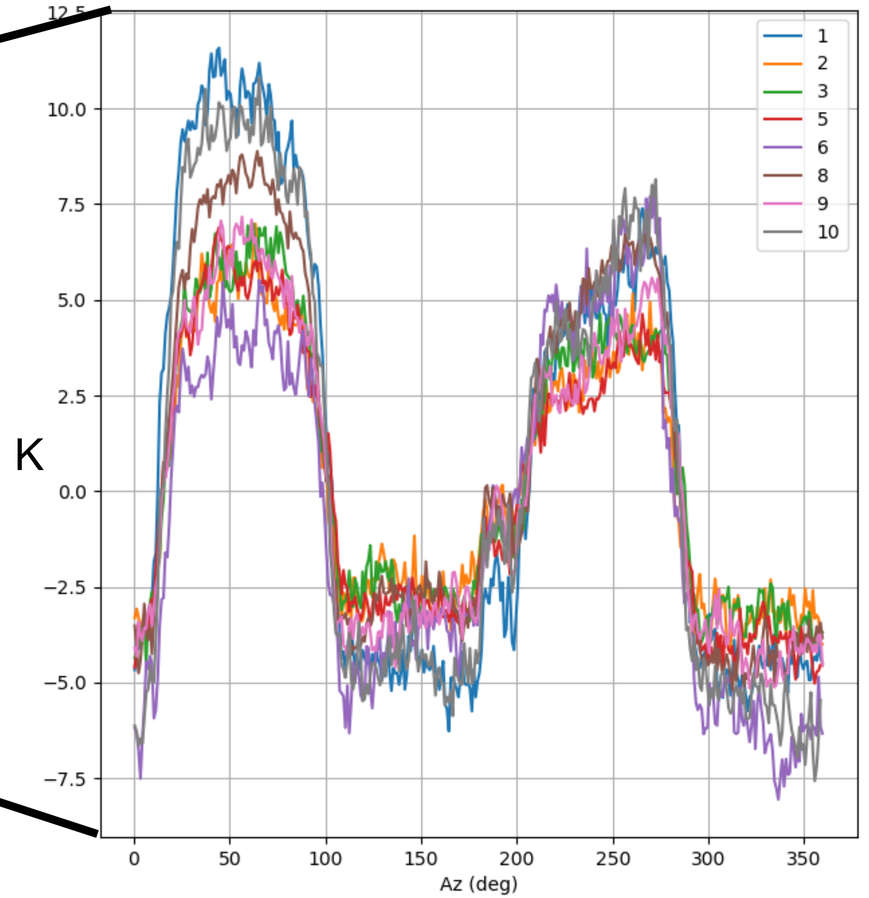


arXiv:2111.05929 Foss et al.

COMAP Pathfinder

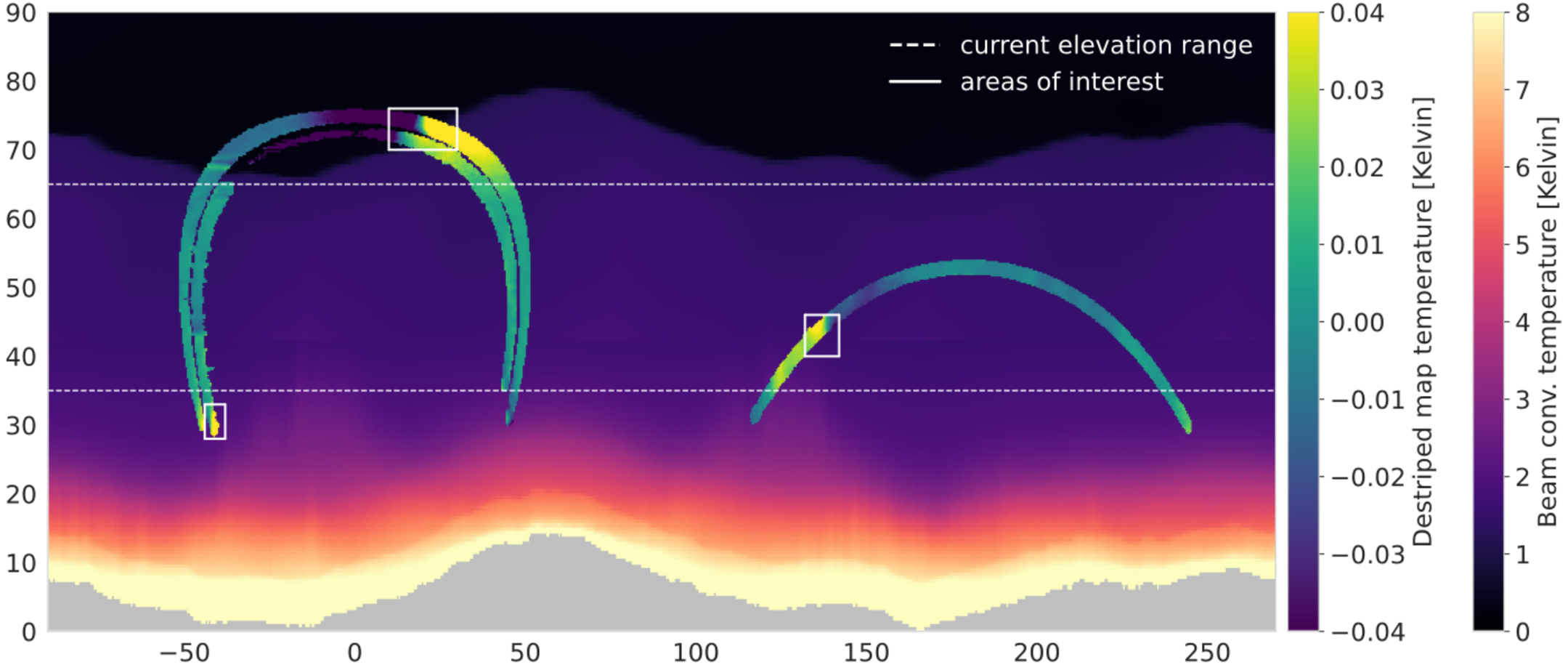
Ground Pickup





COMAP Pathfinder

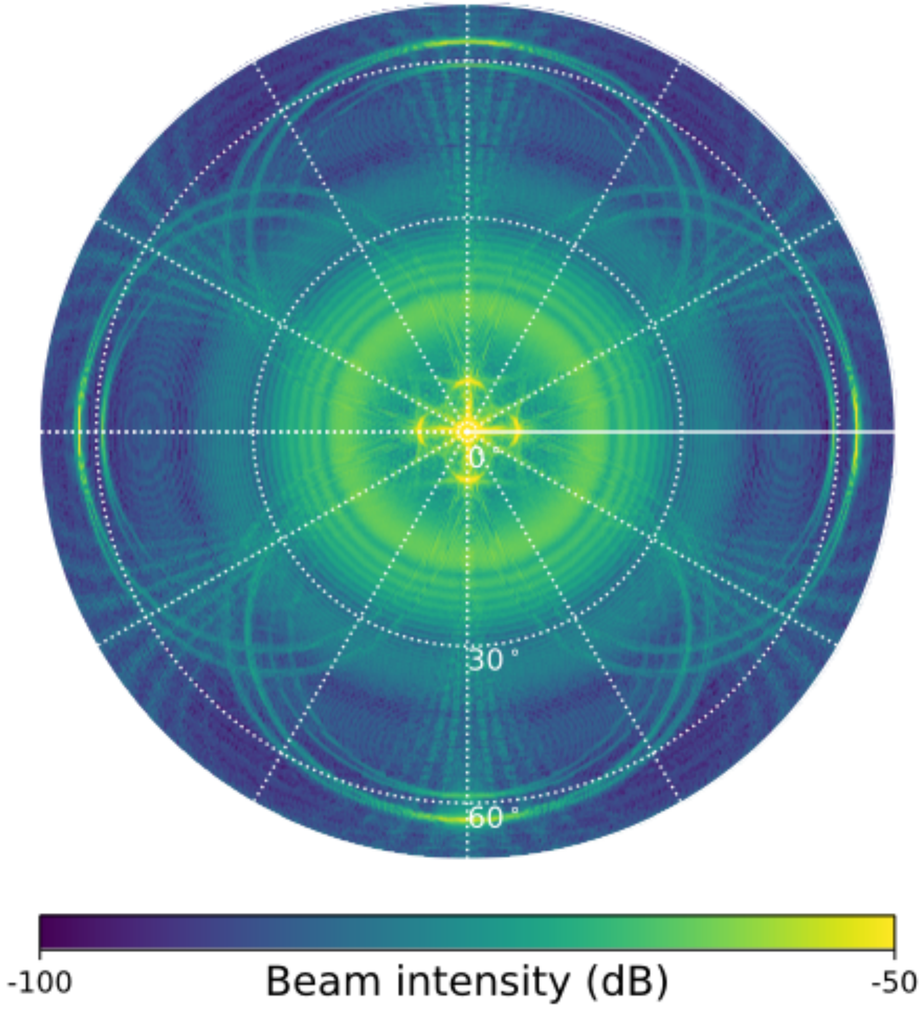
Ground Pickup

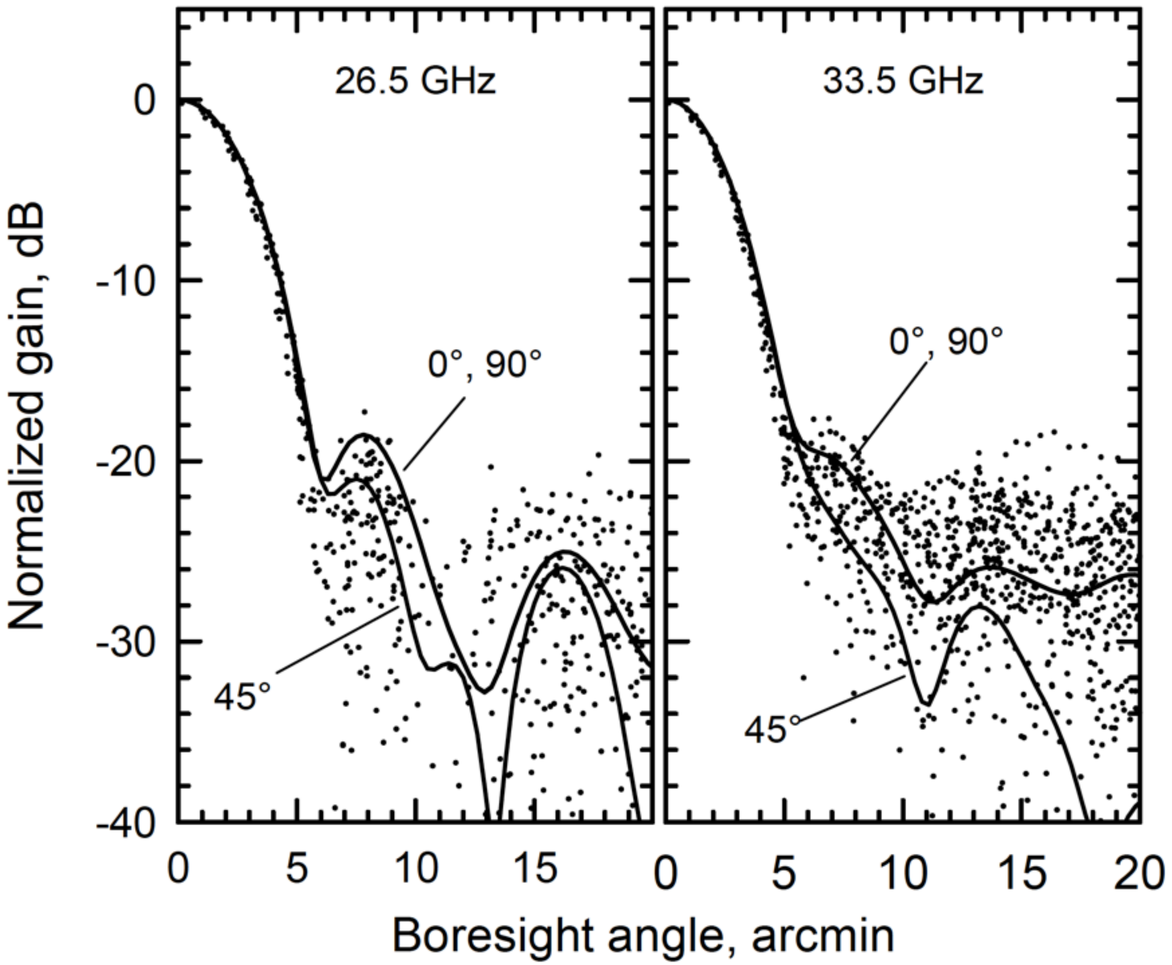


Credit: J. S. Lunde

COMAP Pathfinder

Beams

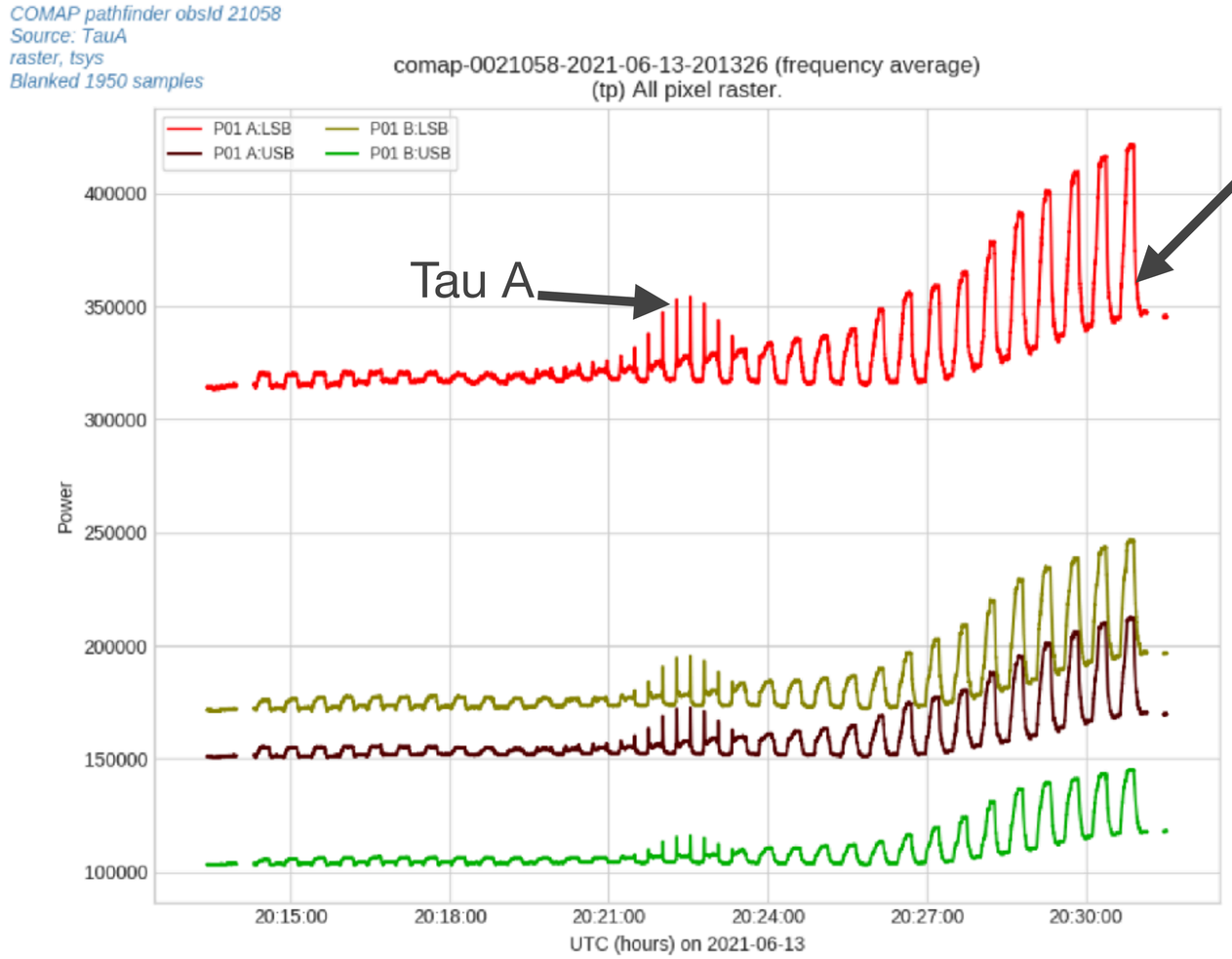




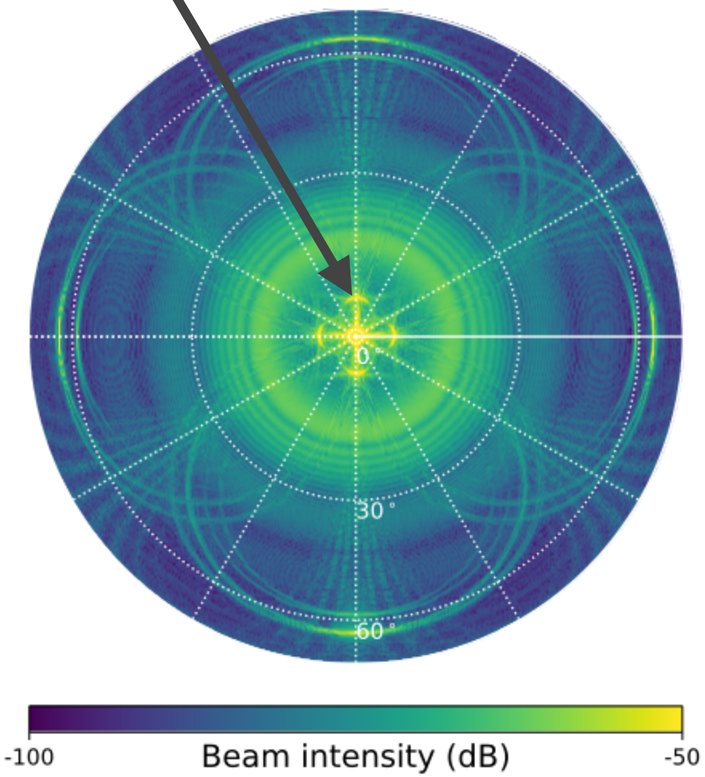
arXiv:2111.05928 Lamb et al.

COMAP Pathfinder

Beams - Solar sidelobes



Pickup of Sun a few degrees from field



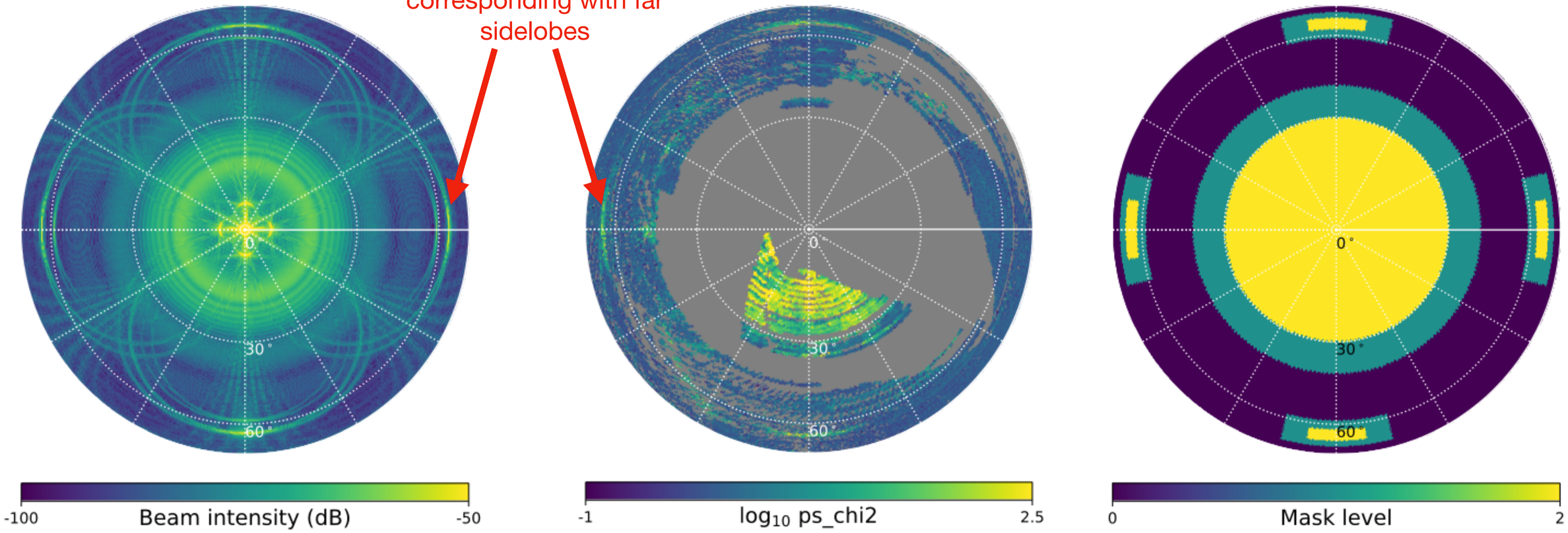
COMAP Pathfinder

Beams - Solar sidelobes

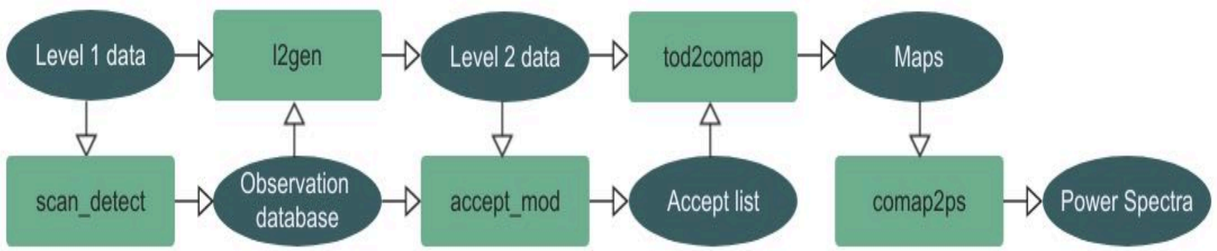
Excess noise after cleaning in regions corresponding with far sidelobes

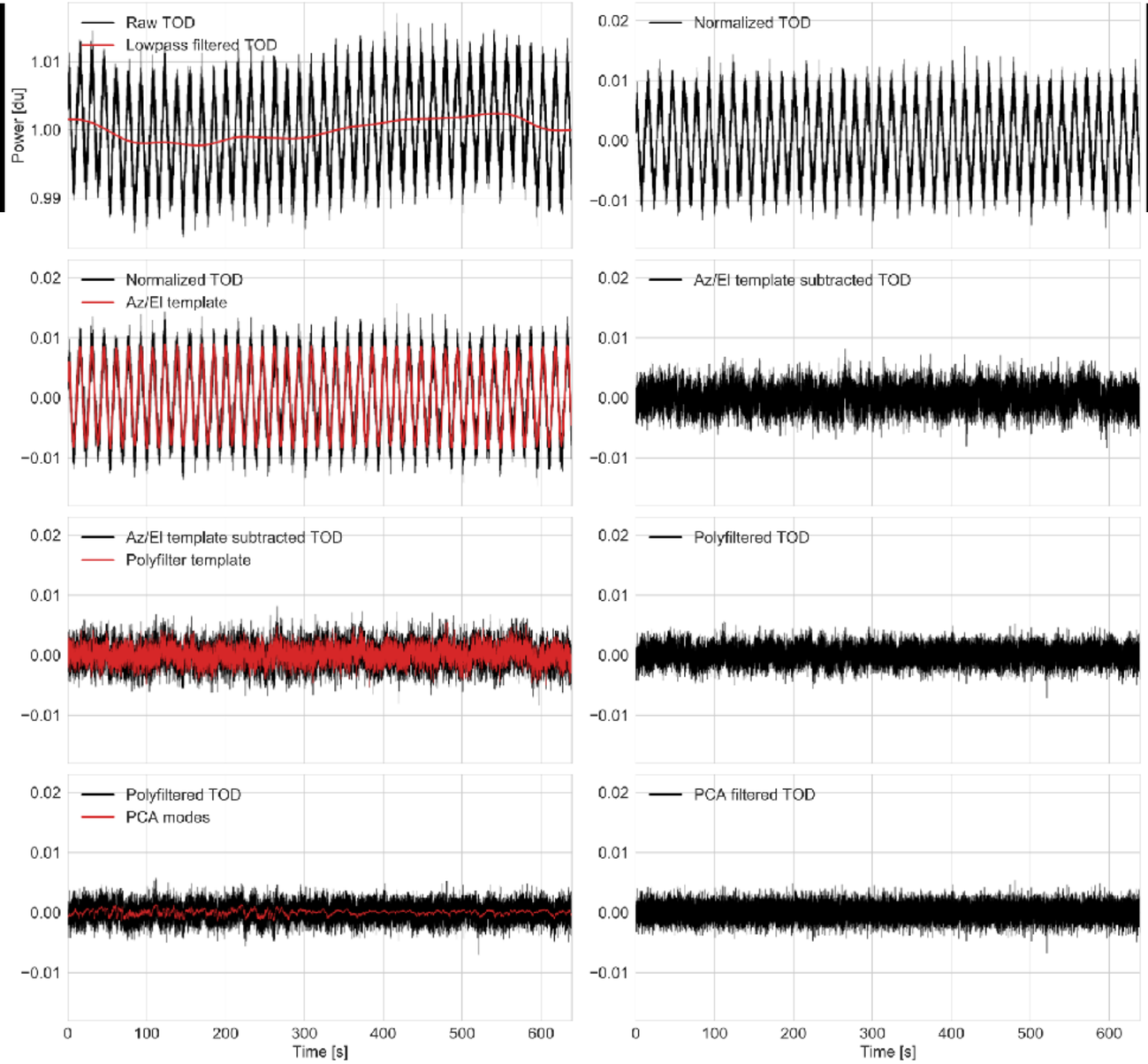
Sun centred projection

Solar sidelobe mask



COMAP Pathfinder
Data Analysis

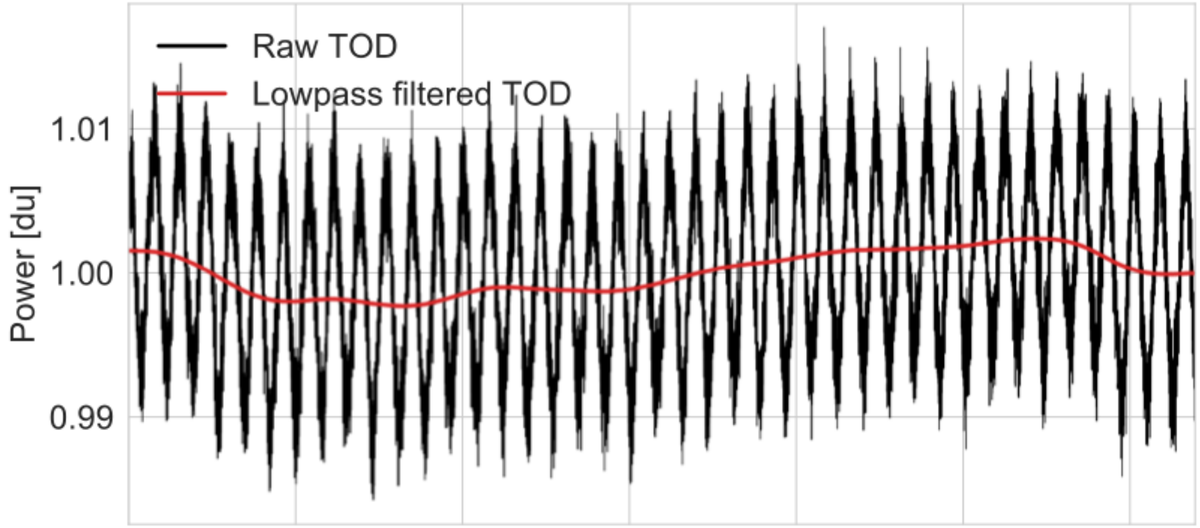


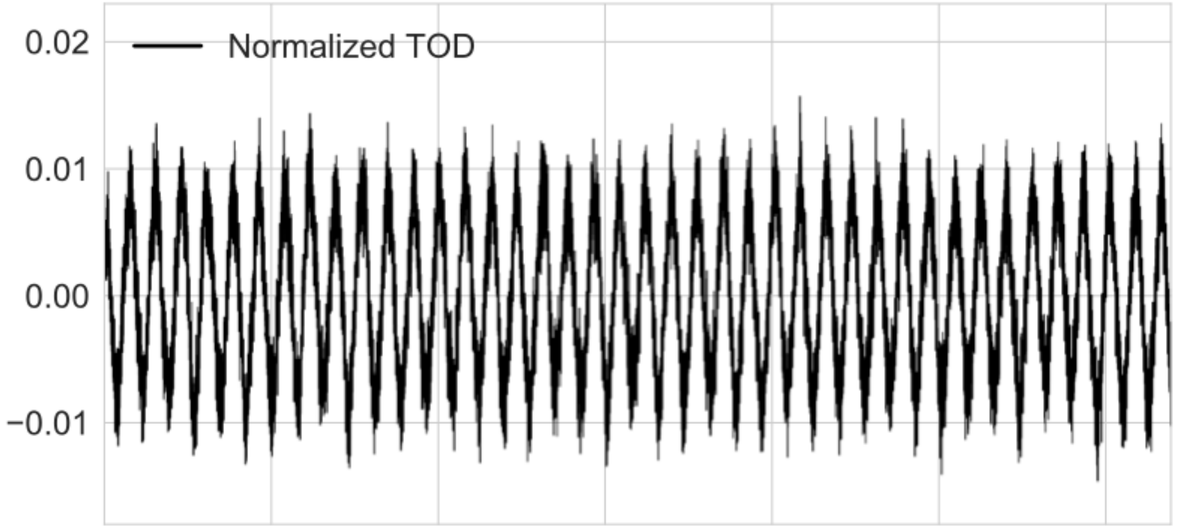


Credit: J. S. Lunde

COMAP Pathfinder

Data Analysis : Normalization





$$d_{\text{after}} \approx \left\langle G^i_\nu(t) \right\rangle \left\langle T^i{}_{\text{sys},\nu}(t) \right\rangle \left(1 + A\,\Delta\tau(\text{El}) + \Delta s_{\text{cont}} + \Delta s_{\text{gnd}} + n^{G,\,i}_{\text{corr}}(t) + n^{\text{SW}}_{\text{corr},\nu}(t) + n^{\text{atm}}_{\text{corr}}(t) + n^{\nu,i}_{\text{w}}(t)\right)$$

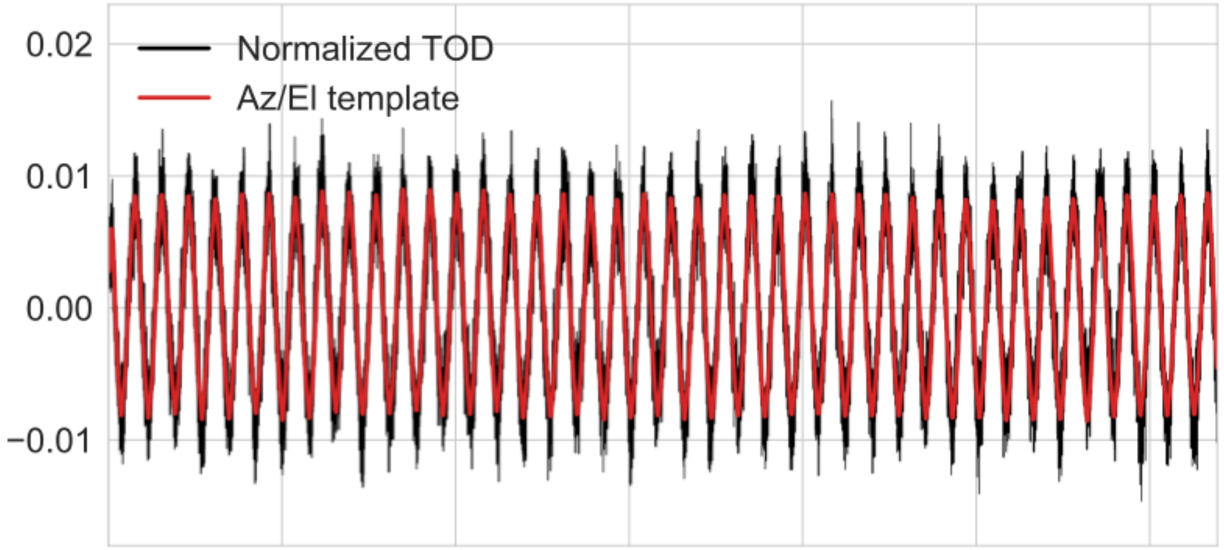
$$d_{\text{after}} = \frac{d_{\text{before}}}{\left\langle d_{\text{before}} \right\rangle} - 1$$

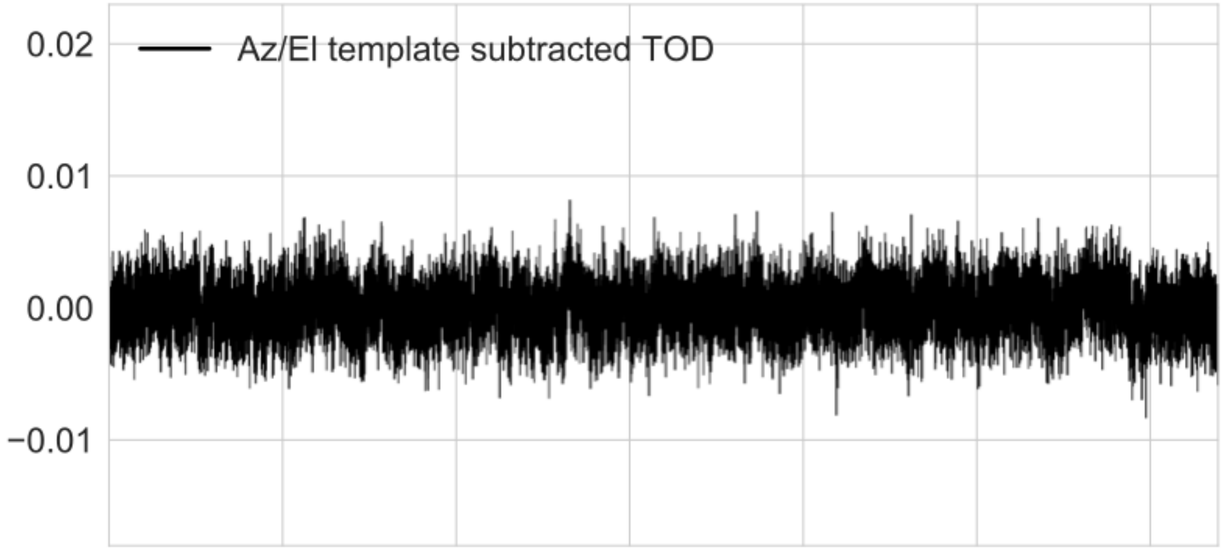
$$d_{\text{after}} \approx \left(1 + A\,\Delta\tau(\text{El}) + \Delta s_{\text{cont}} + \Delta s_{\text{gnd}} + n^{G,\,i}_{\text{corr}}(t) + n^{\text{SW}}_{\text{corr},\nu}(t) + n^{\text{atm}}_{\text{corr}}(t) + n^{\nu,i}_{\text{w}}(t)\right)$$

$$= A\,\Delta\tau(\text{El}) + \Delta s_{\text{cont}} + \Delta s_{\text{gnd}} + n^{G,\,i}_{\text{corr}}(t) + n^{\text{SW}}_{\text{corr},\nu}(t) + n^{\text{atm}}_{\text{corr}}(t) + n^{\nu,i}_{\text{w}}(t)$$

COMAP Pathfinder

Data Analysis : Az/El-Template Removal





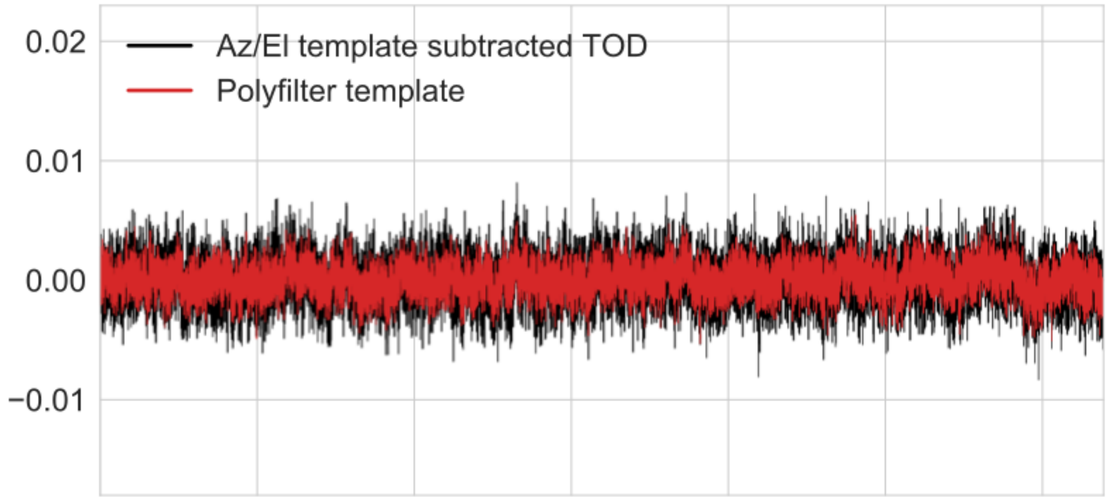
$$d \approx \frac{g}{\sin\left(\mathrm{El}(t)\right)} + a\,\mathrm{Az}(t) + c$$

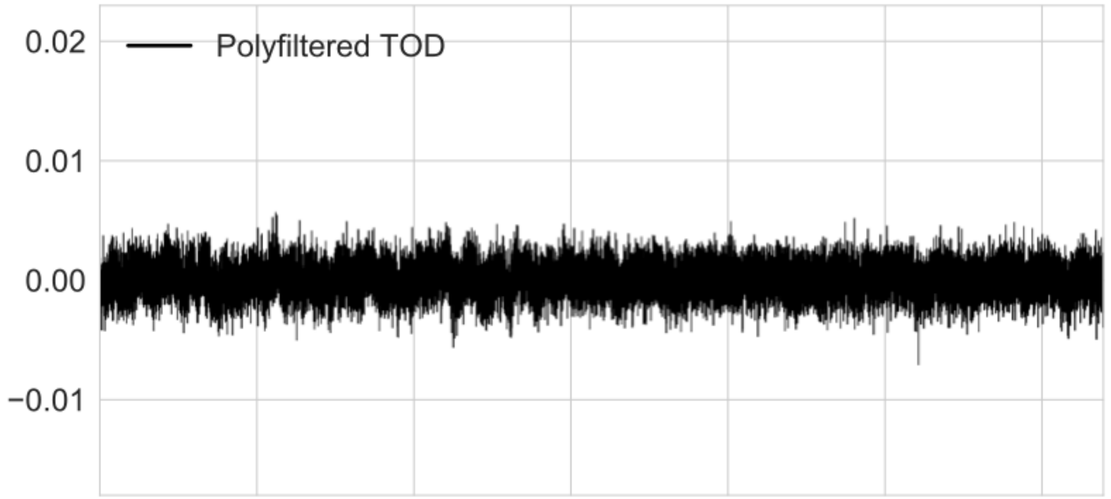
$$d_{\mathrm{after}} \approx A\,\Delta\,\tau\left(\mathrm{El}\right) + \Delta s_{\mathrm{cont}} + \Delta s_{\mathrm{gnd}} + n_{\mathrm{corr}}^{G,\,i}(t) + n_{\mathrm{corr},\nu}^{\mathrm{SW}}(t) + n_{\mathrm{corr}}^{\mathrm{atm}}(t) + n_{\mathrm{w}}^{\nu,i}(t)$$

$$= \Delta s_{\mathrm{cont}} + n_{\mathrm{corr}}^{G,\,i}(t) + n_{\mathrm{corr},\nu}^{\mathrm{SW}}(t) + n_{\mathrm{corr}}^{\mathrm{atm}}(t) + n_{\mathrm{w}}^{\nu,i}(t)$$

COMAP Pathfinder

Data Analysis : Polynomial Continuum Filter





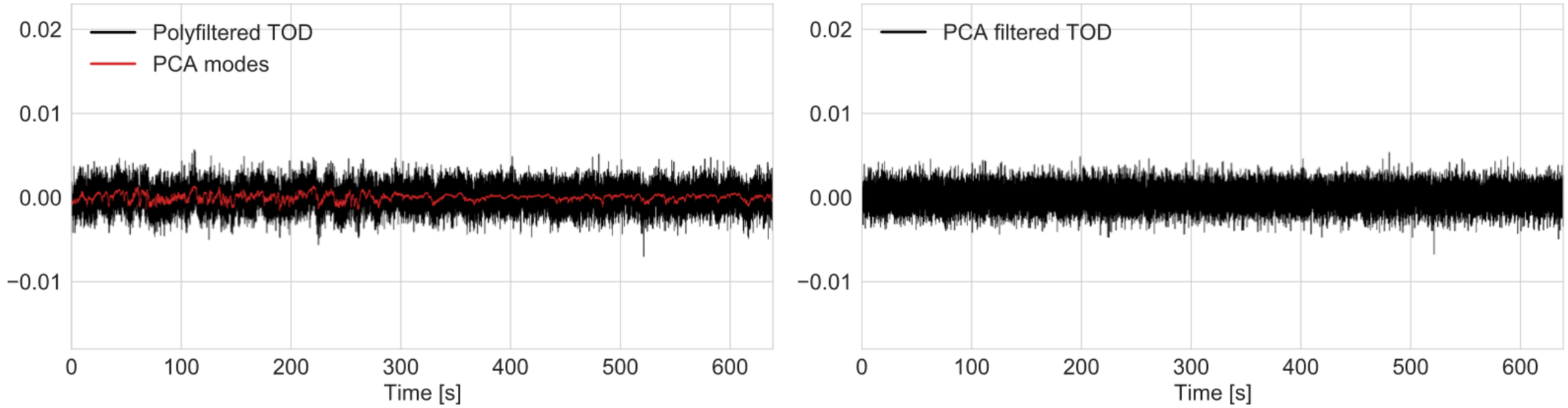
$$d_\nu \approx c_0 + c_1 \nu$$

Frequency correlated modes

$$d_{\text{after}} \approx \boxed{\Delta s_{\text{cont}}} + \boxed{n_{\text{corr}}^{G,\,i}(t)} + n_{\text{corr},\nu}^{\text{SW}}(t) + \boxed{n_{\text{corr}}^{\text{atm}}(t)} + n_{\text{w}}^{\nu,i}(t)$$

COMAP Pathfinder

Data Analysis : Feed-Feed PCA Filter



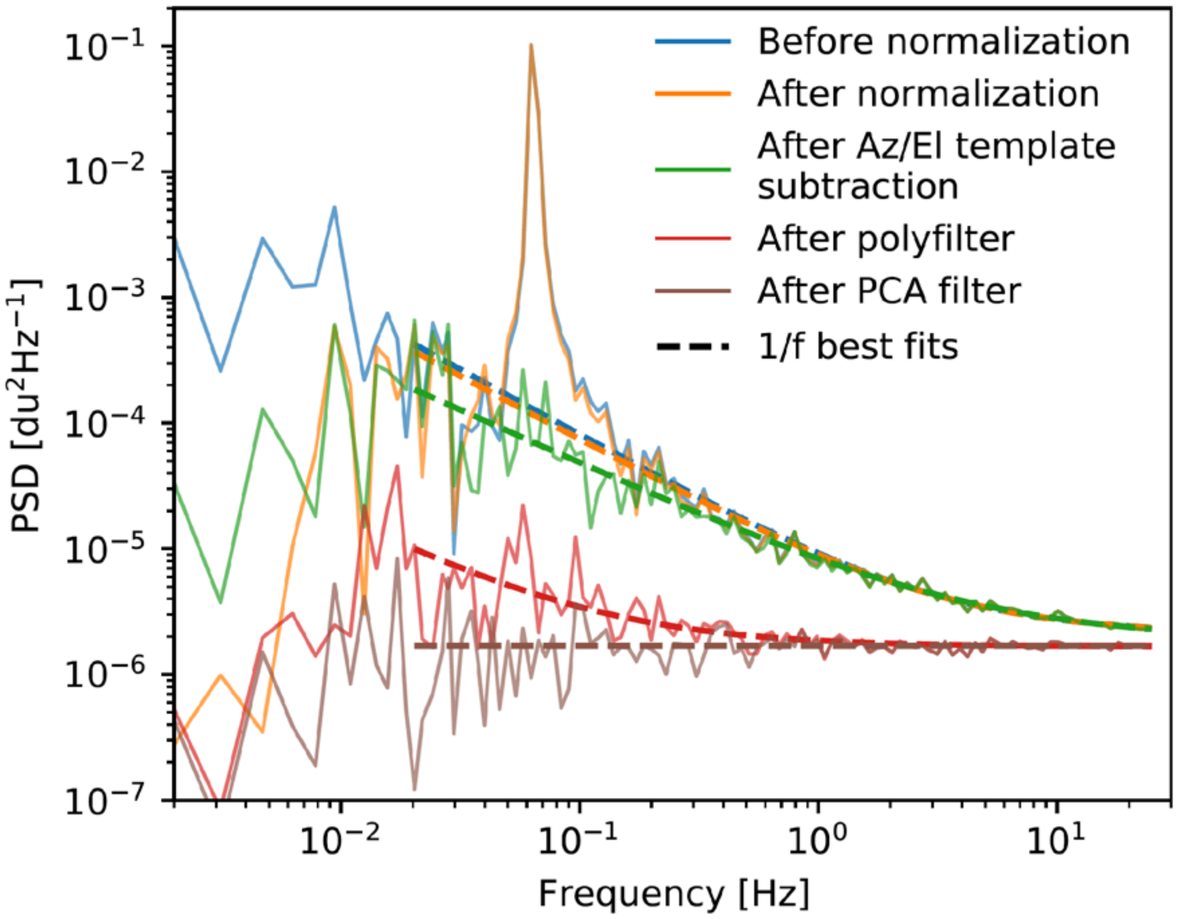
$$d_{\text{after}} = d_{\text{before}} - \sum_{i=1}^{4} a_i \, v_i(t),$$

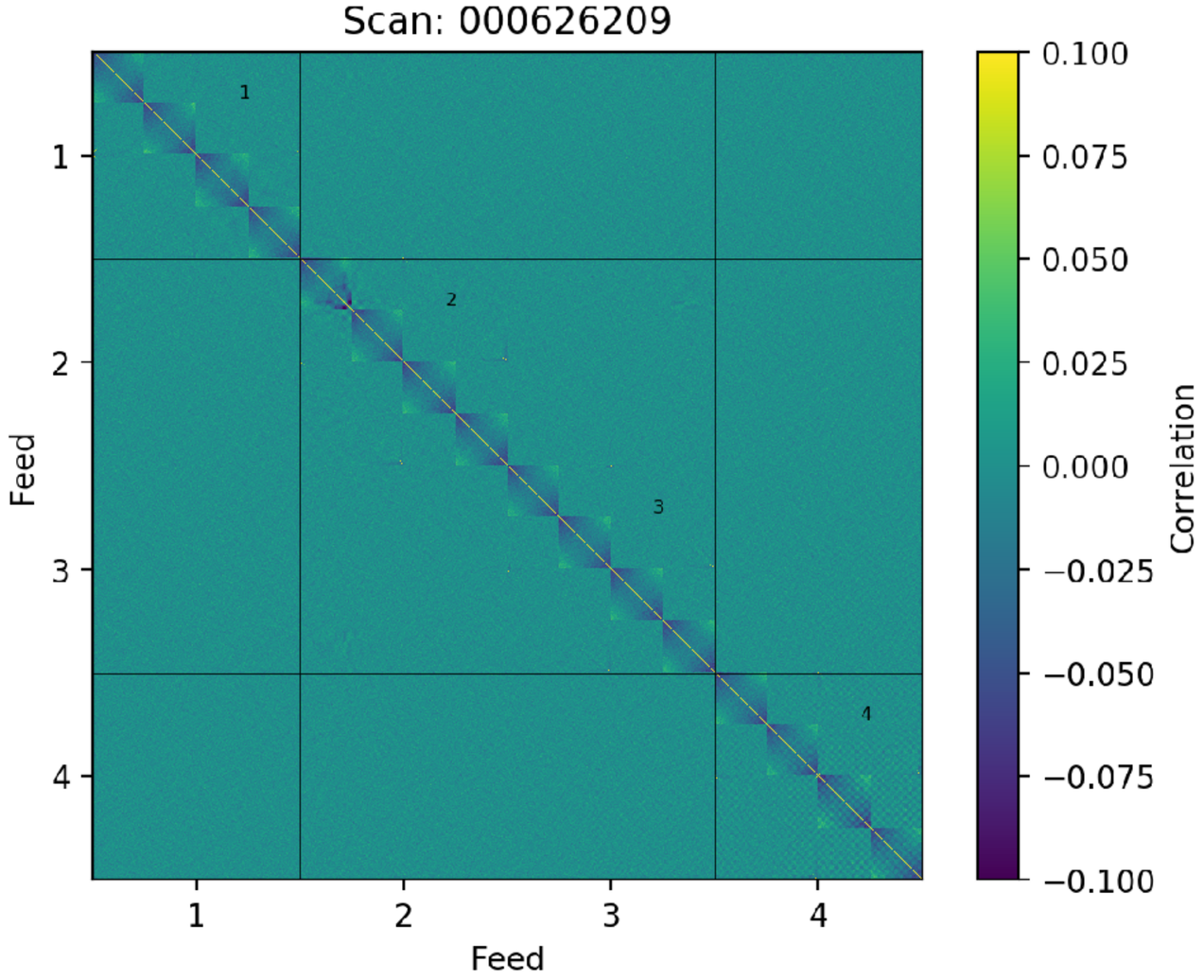
Feed-Feed correlated modes

$$d_{\text{after}} \approx n^{\text{SW}}_{\text{corr},\nu}(t) + n^{\nu,i}_{\text{w}}(t)$$

COMAP Pathfinder

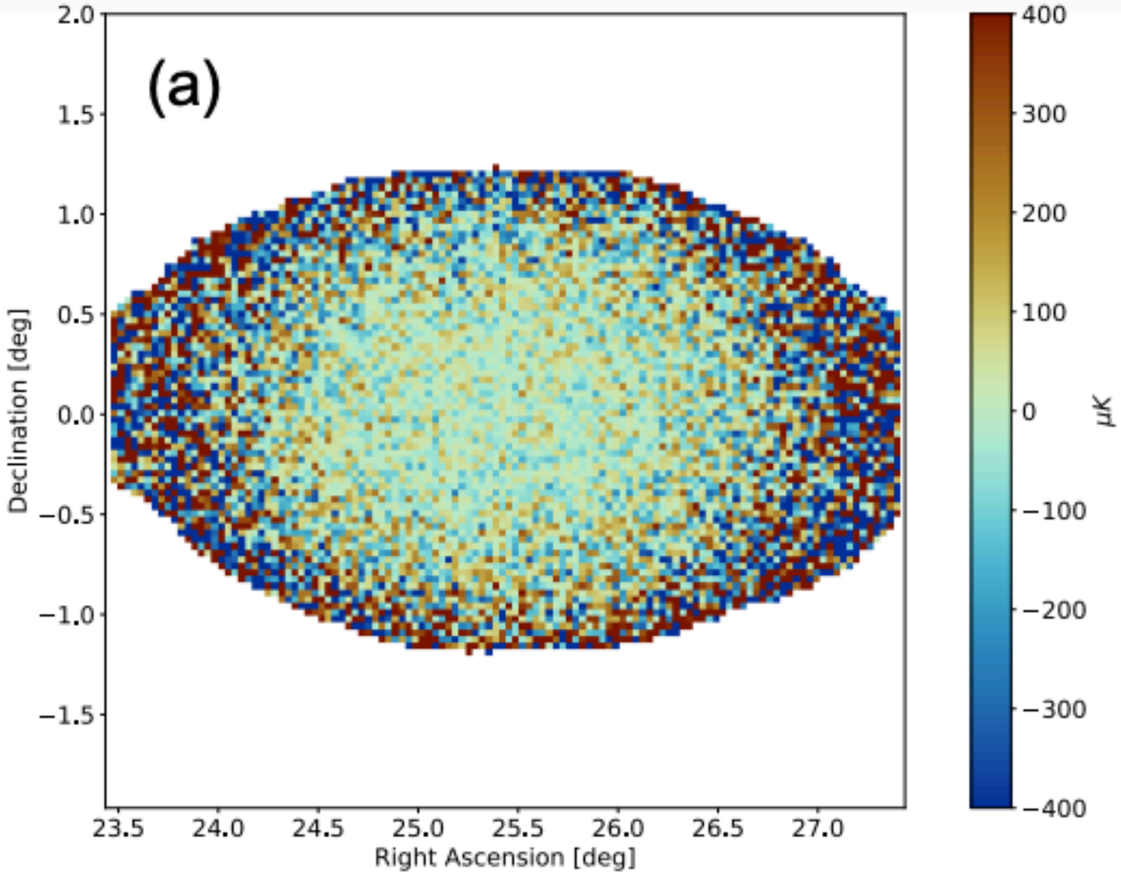
Data Analysis : After cleaning the data…

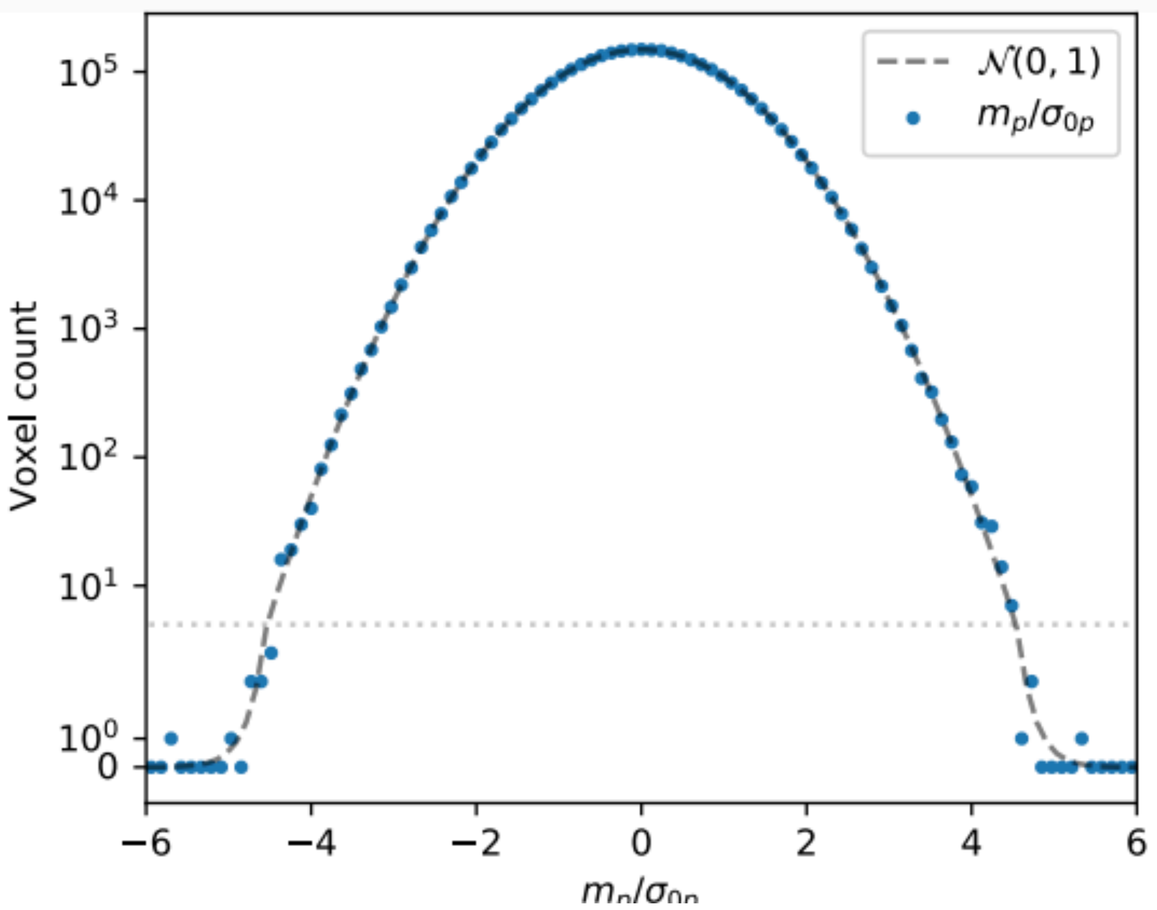




COMAP Pathfinder

CO Field Maps: Field 1



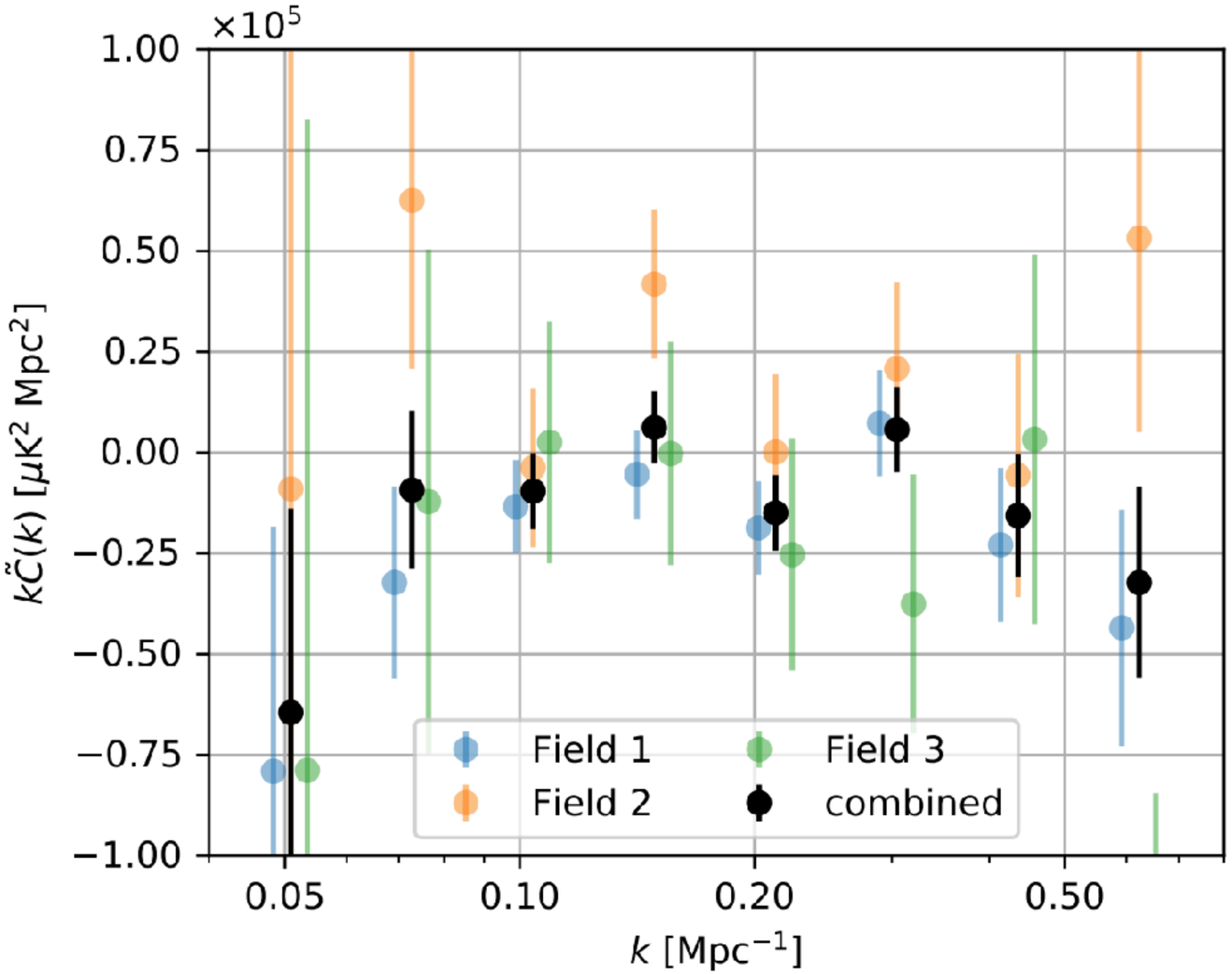


arXiv:2111.05929 Foss et al.

COMAP Pathfinder

CO Field Maps: Power Spectrum

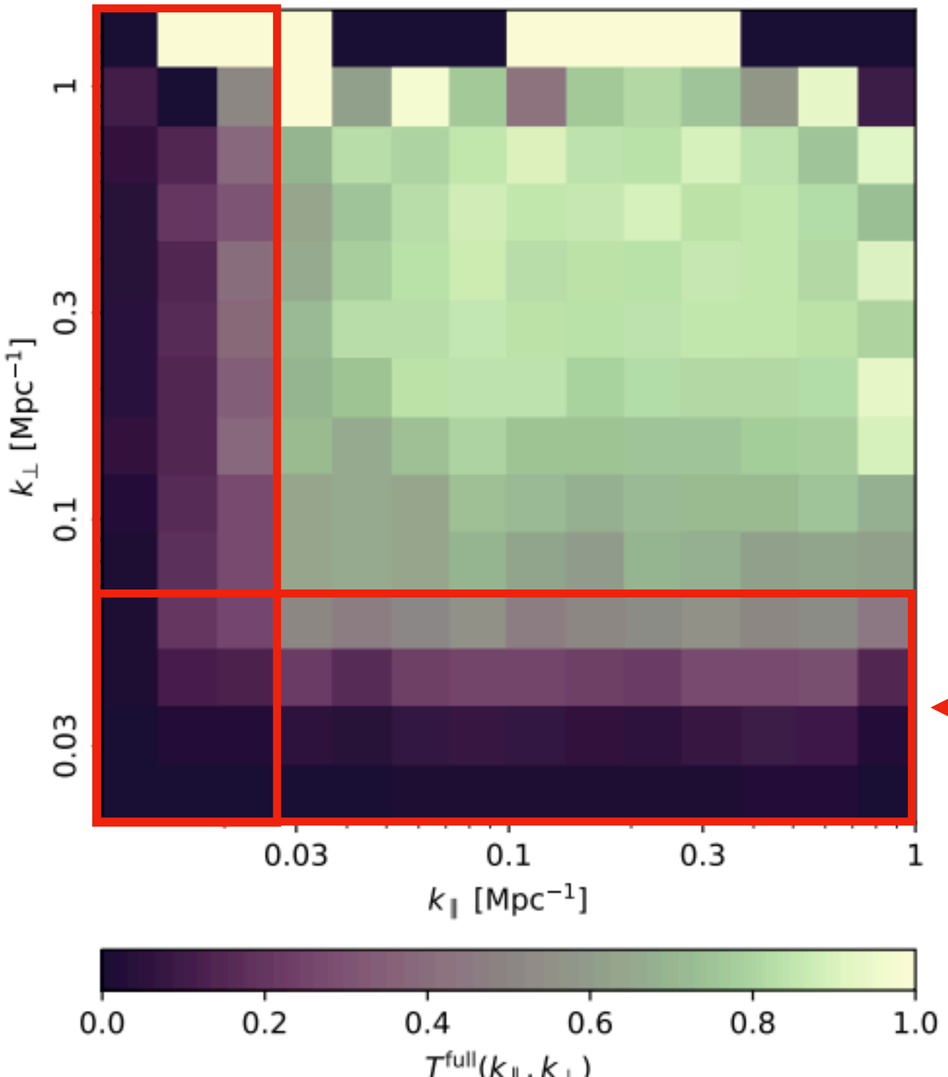
- Spherically averaged power spectrum.
- $P_{\mathrm{CO}}(k) = -2.7 \pm 1.7 \times 10^4 \mu\mathrm{K}^2\mathrm{Mpc}^3$



arXiv:2111.05930 Ihle et al.

COMAP Pathfinder

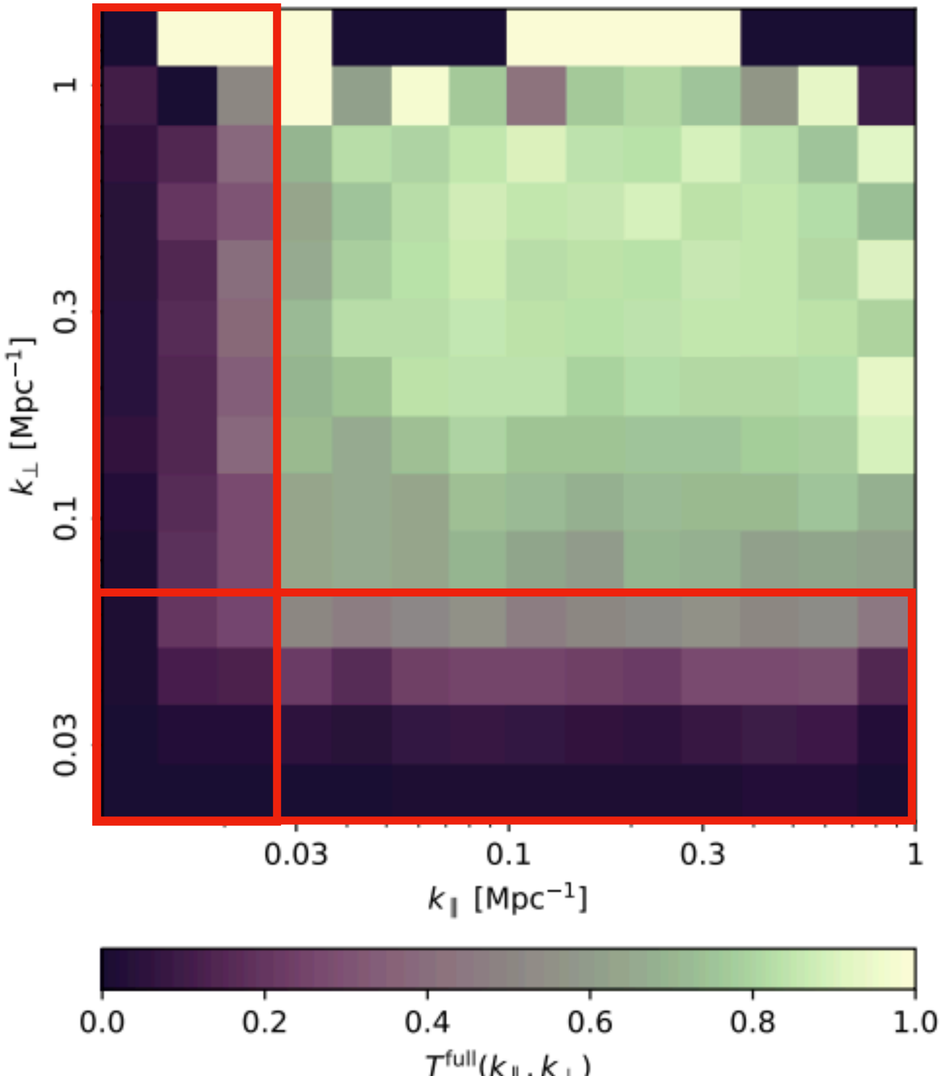
Data Analysis : Transfer Functions



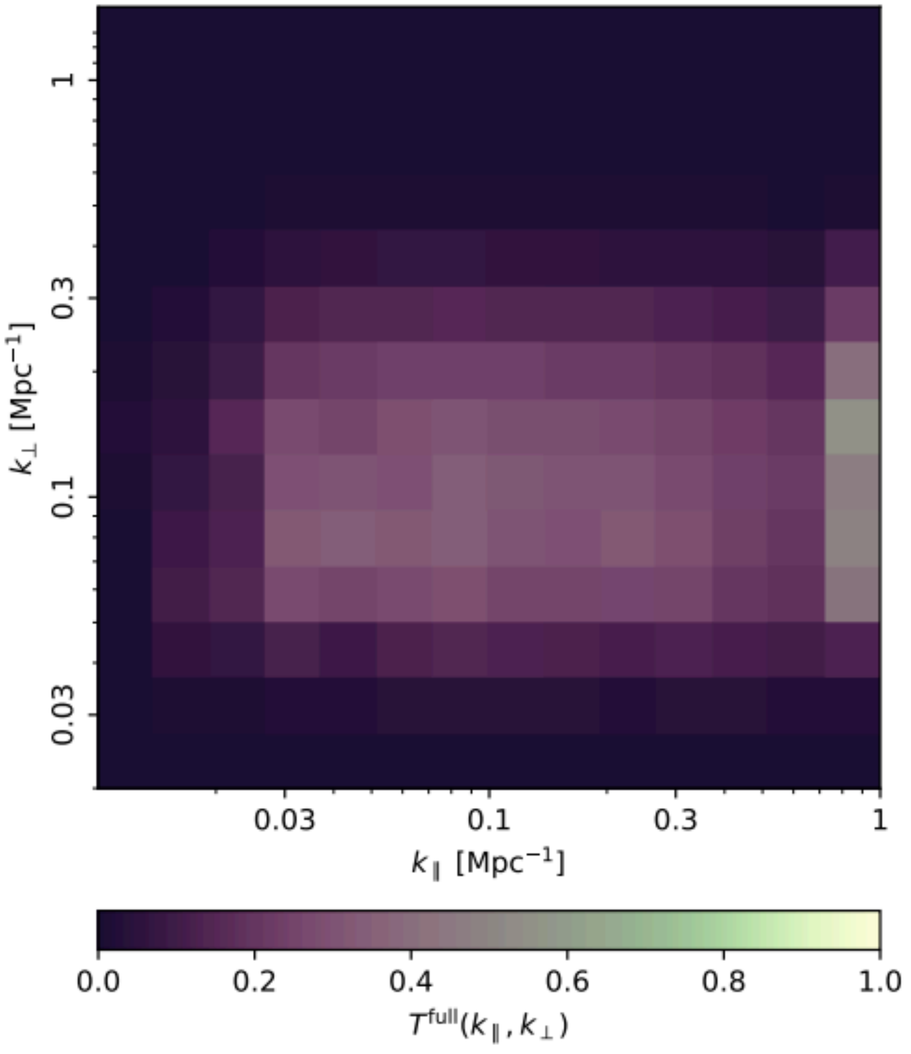
Polyfilter + PCA + Az/El Fits

COMAP Pathfinder

Data Analysis : Transfer Functions



Then we add the effect of the beam…



COMAP Pathfinder

Summary

- COMAP is a CO line intensity mapping experiment probing cold molecular gas from z=3 to z=6 (eventually).
- Systematics are similar to HIIM but the focus is different… not so much Galactic but terrestrial foregrounds are the issue.
- Currently able to clean the data down to the noise level, but the transfer functions show we are filtering a lot of signal.
- We’ve not tried any map-space foreground cleaning methods…

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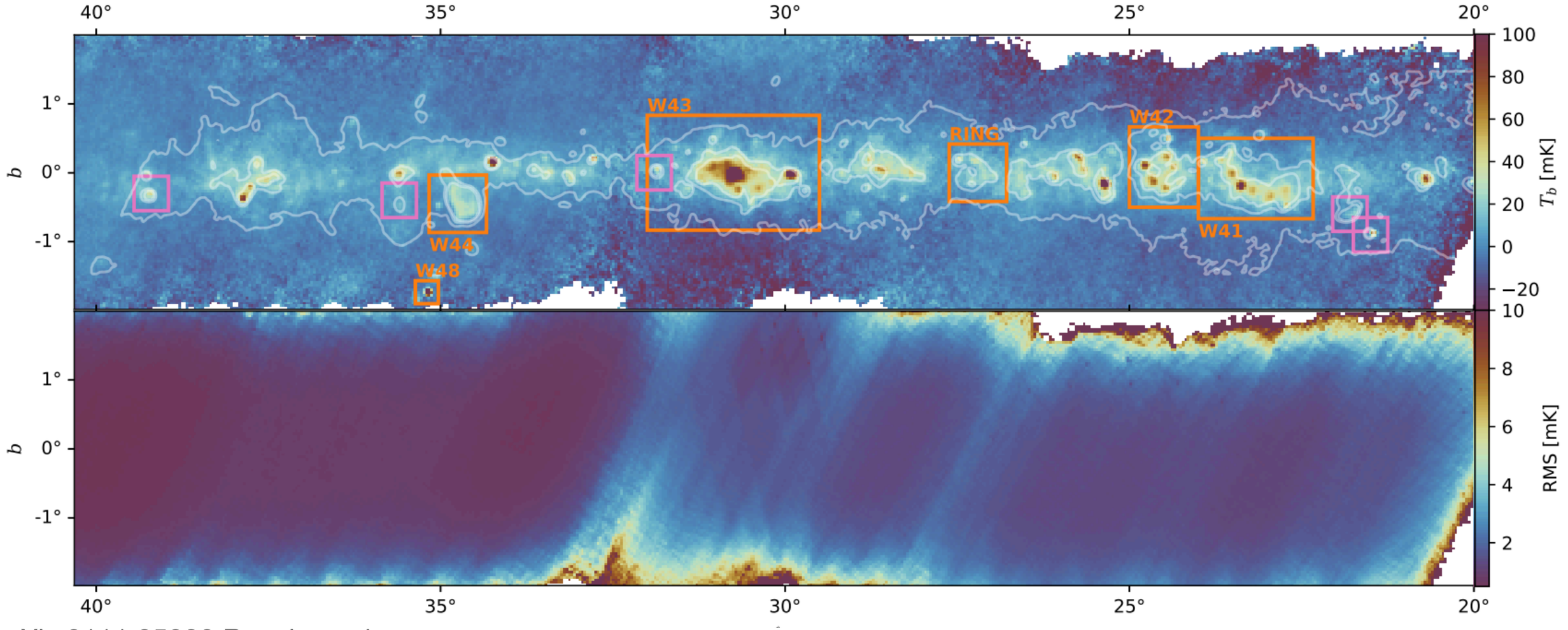
Galactic Plane Survey



arXiv:2111.05932 Rennie et al.

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Observing Strategy