21cm Intensity Mapping with MeerKAT and SKA (autocorrelations)

Prina Patel with Mario Santos

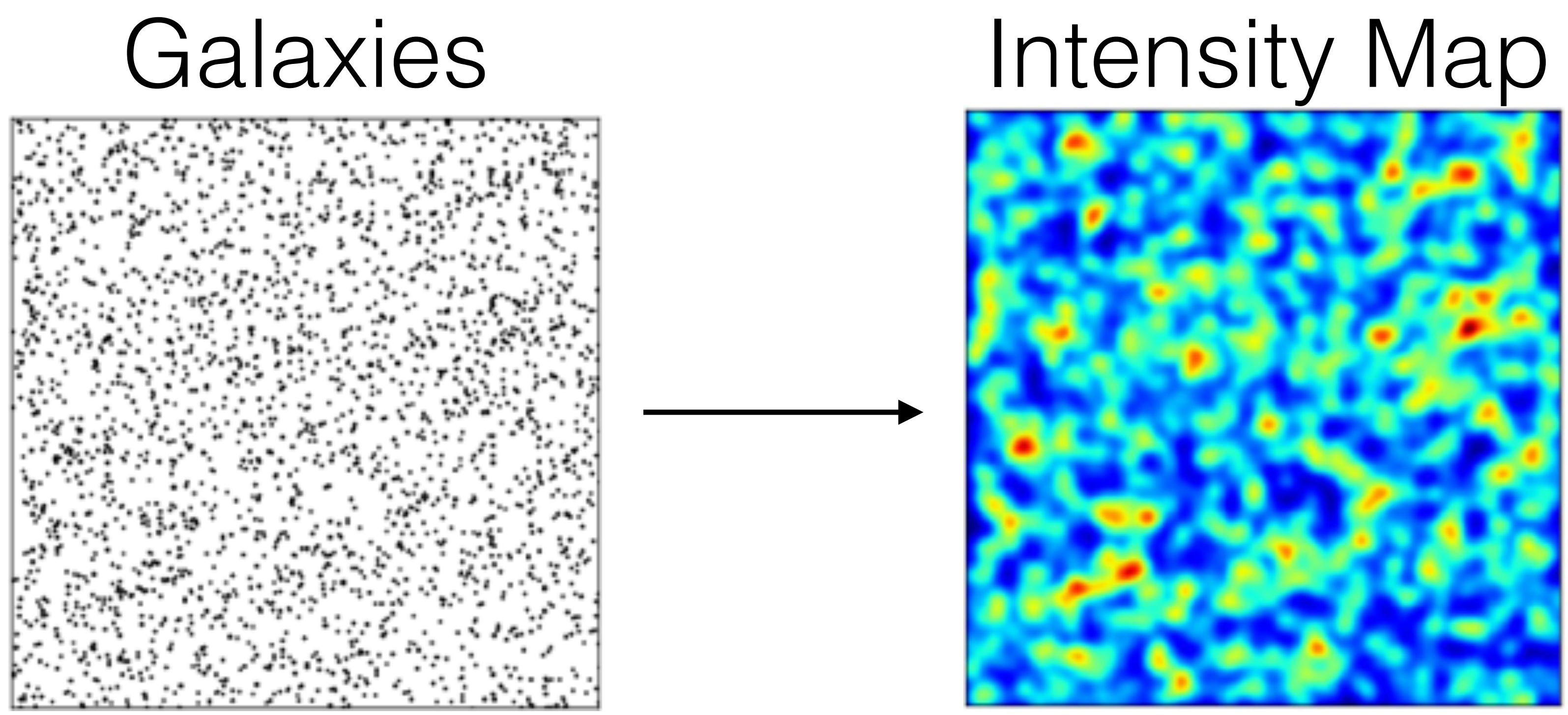
UNIVERSITY of the WESTERN CAPE

UWC ASTROPHYSICS

SKA AFRICA
SQUARE KILOMETRE ARRAY

Cosmology with Next Generation Radio Surveys, 21st June 2016

HI Intensity Mapping?



- Look at the total intensity of a given emission line (21cm in our case) in a large 3d pixel (angle and frequency).
- Each pixel combines the emission of multiple galaxies.

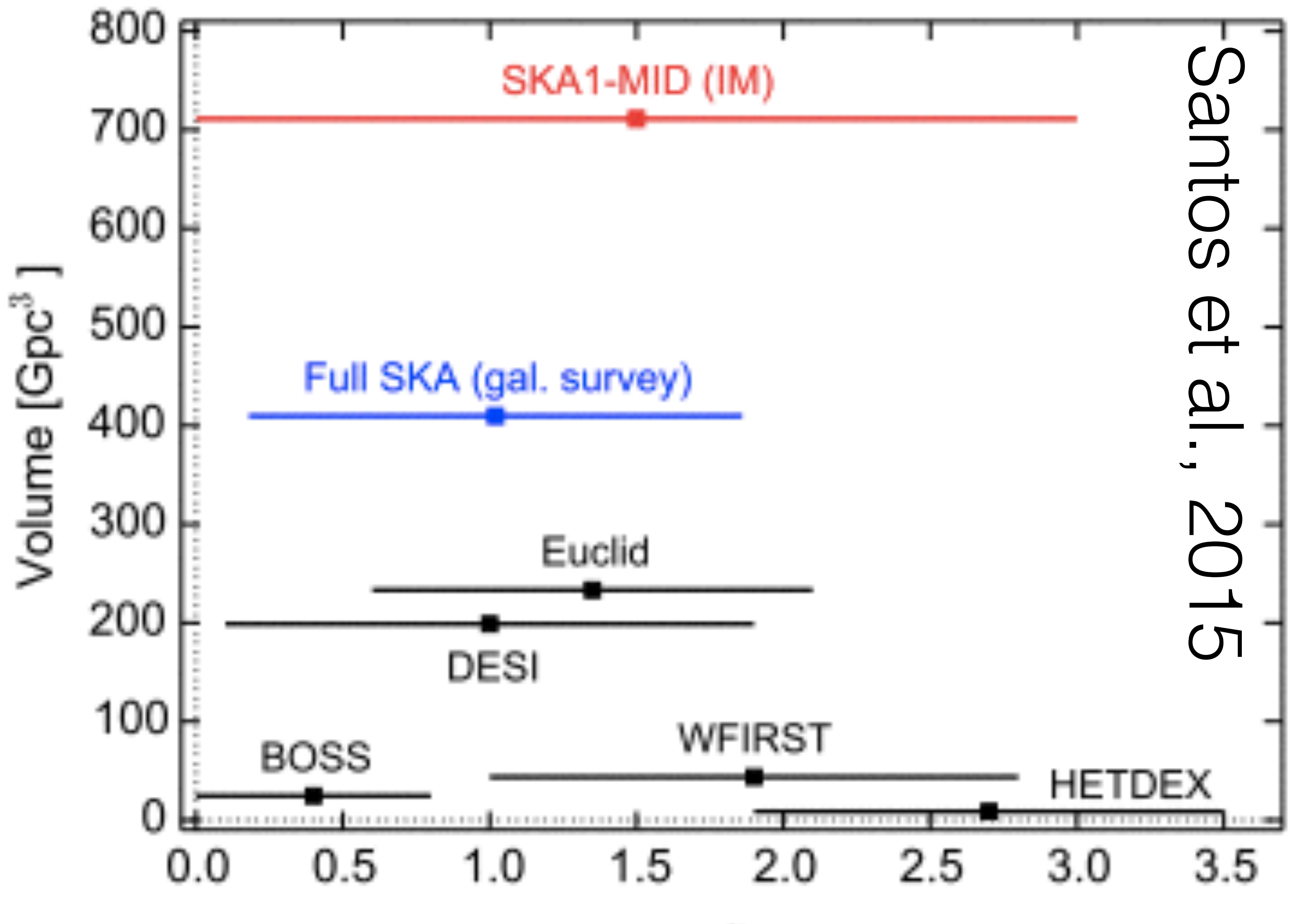
Why HI IM?

HI galaxy surveys are expensive:

SKA1 ~ 10^7 galaxies over 5,000 deg^2

SKA2 ~ 10^9 galaxies over 30,000 deg^2

Cheap way to observe large volumes since you don't need to resolve individual galaxies - ideal for cosmology

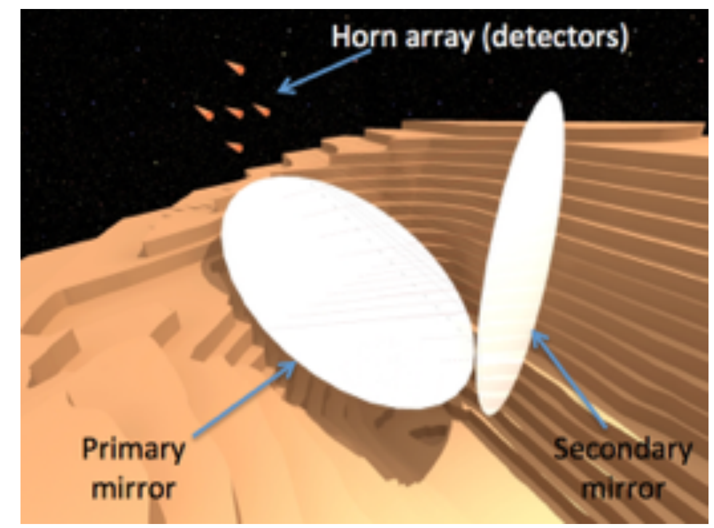


Santos et al., 2015

Current/Planned

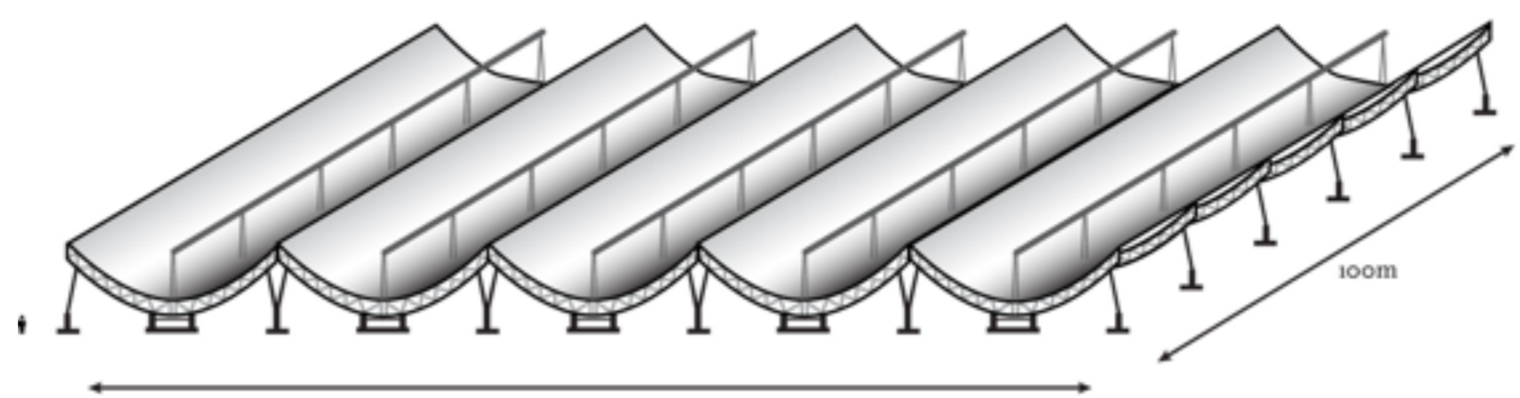
HIRAX, South Africa

BINGO, Uruguay



GBT, USA

CHIME, Canada



MeerKAT

64 dishes in the Karoo, 20 dishes in place, 16 with receivers fitted and operational as an interferometer in the next few months

Precursor that will be incorporated into SKA1-Mid

MeerKLASS

MeerKAT final specs deliver great survey speed (large primary beam and low noise)

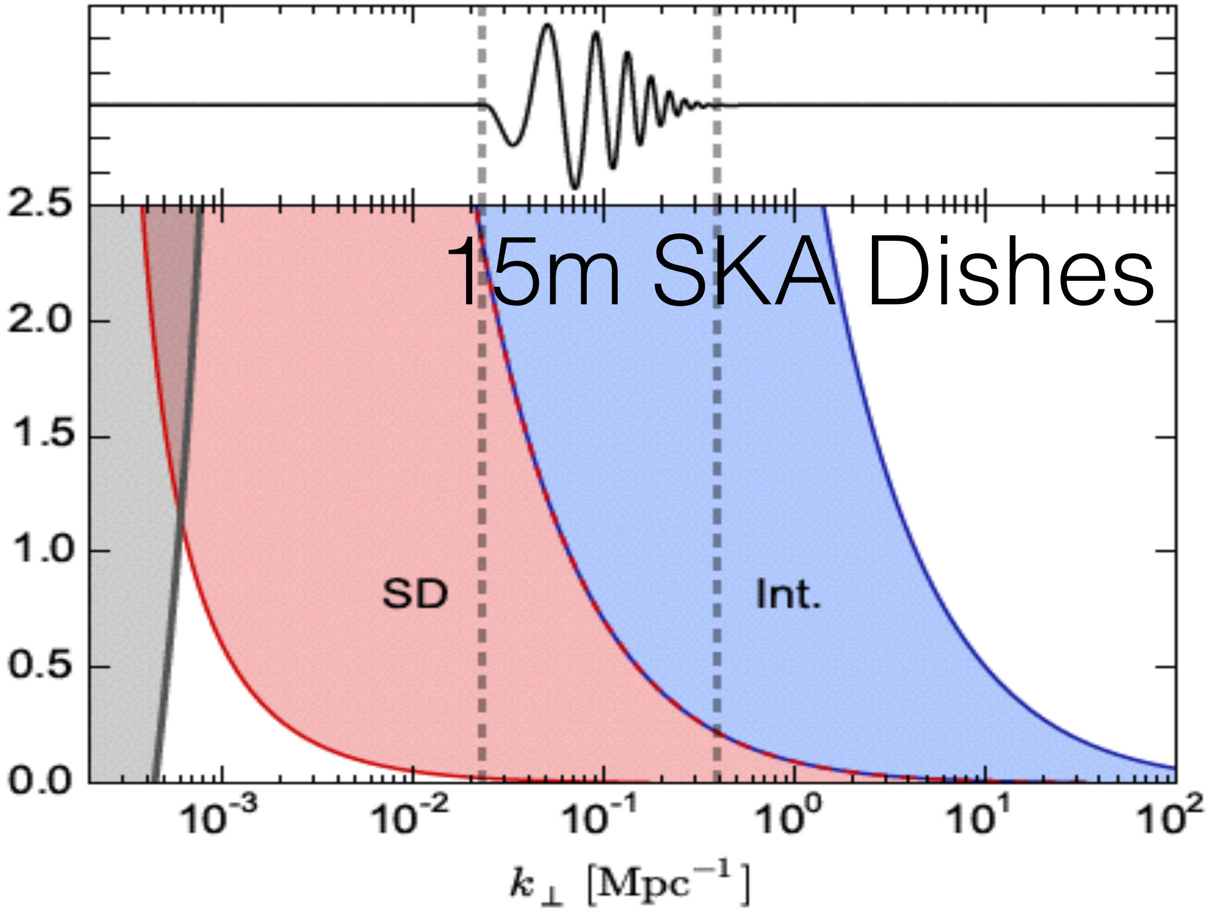
HI Intensity mapping, cosmology and lots of other stuff

~4000 square degrees, 6 microJy rms noise (~4000h)

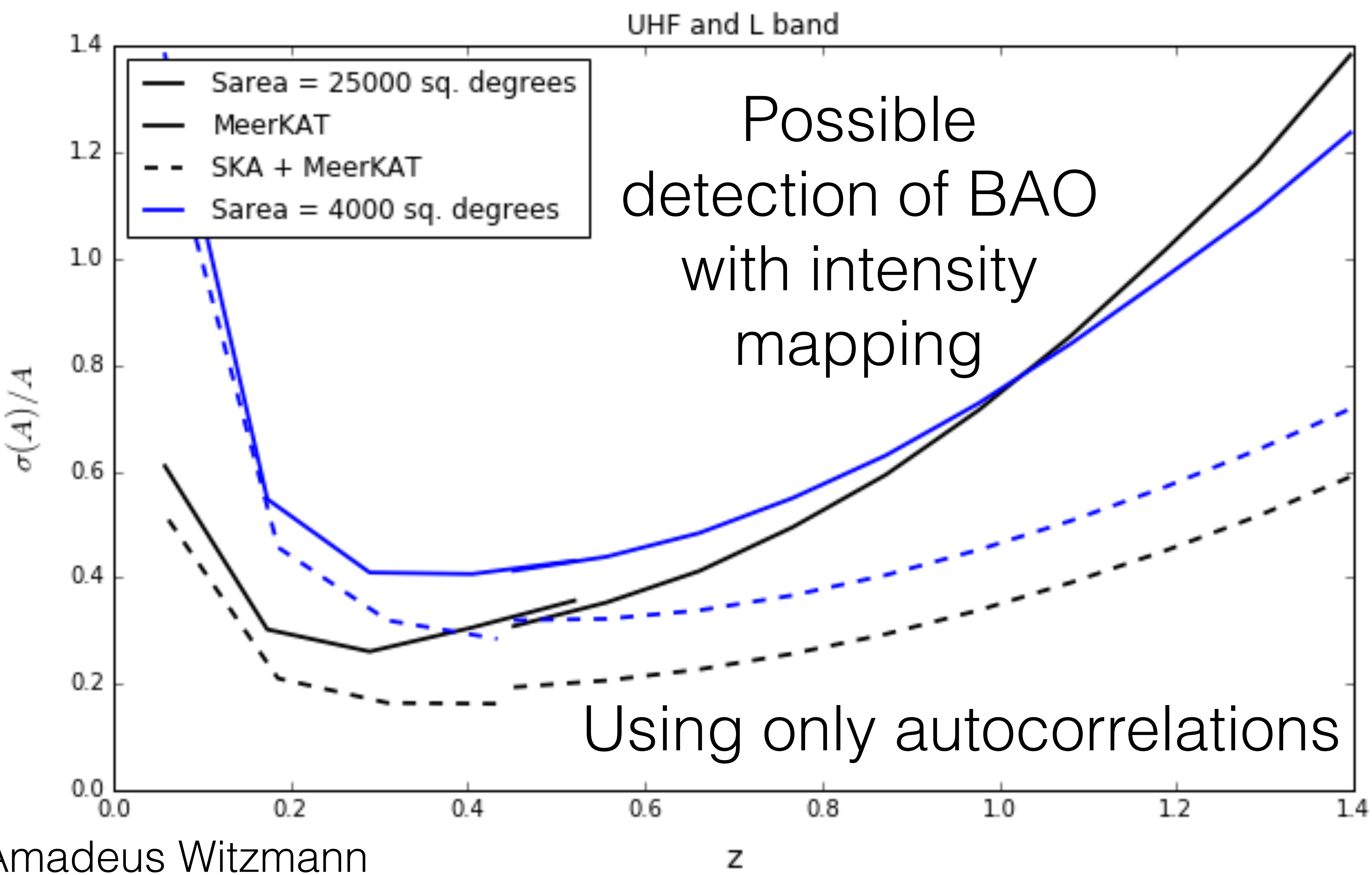
Crucial stepping stone for run up to SKA (especially for intensity mapping)

SKA

- Interferometer baselines not small enough to probe BAO scales, so have to use in single dish mode…also only way to get very largest scales
- Phase 1: ~190 dishes + 64 MeerKAT, ~2023
- Proposal to provide calibrated autocorrelations approved by the SKA office



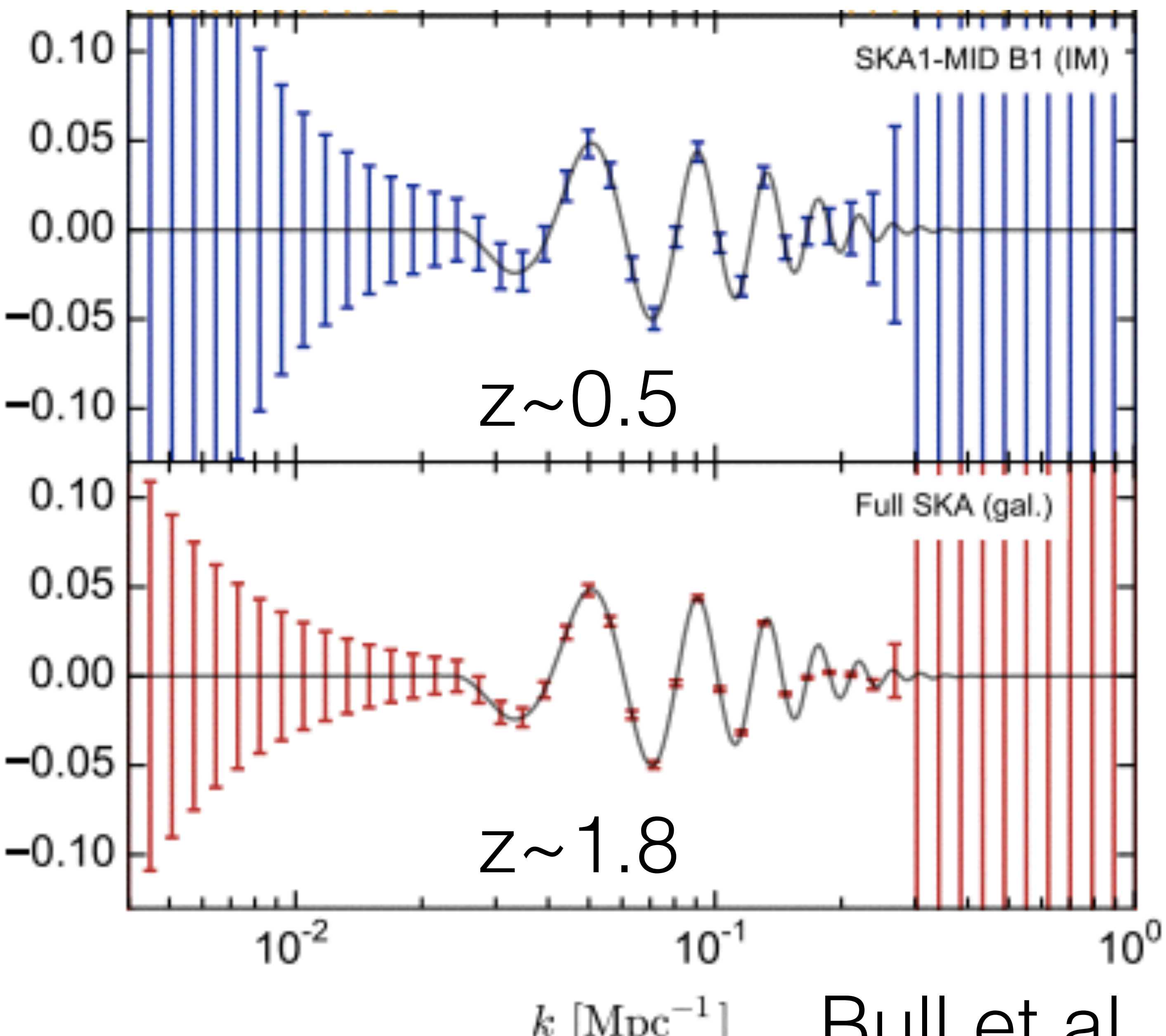
BAO with MeerKAT?



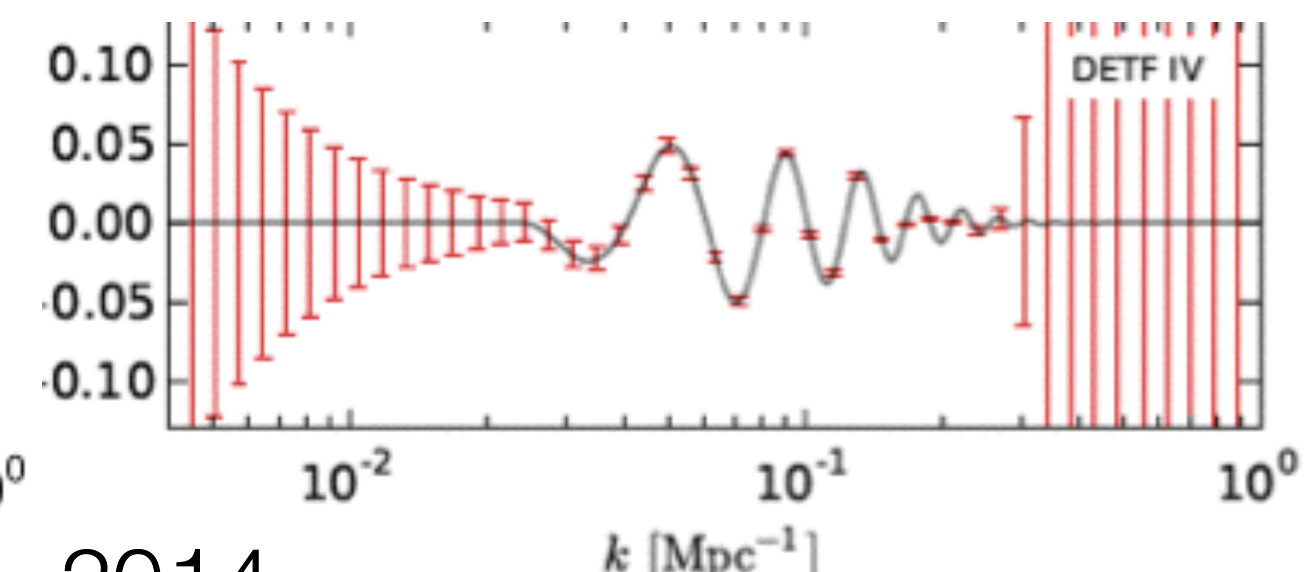
Credit: Amadeus Witzmann

BAO with SKA?

SKA1 Intensity mapping comparable to EUCLID galaxy survey for measuring the BAO wiggles.



Bull et al., 2014



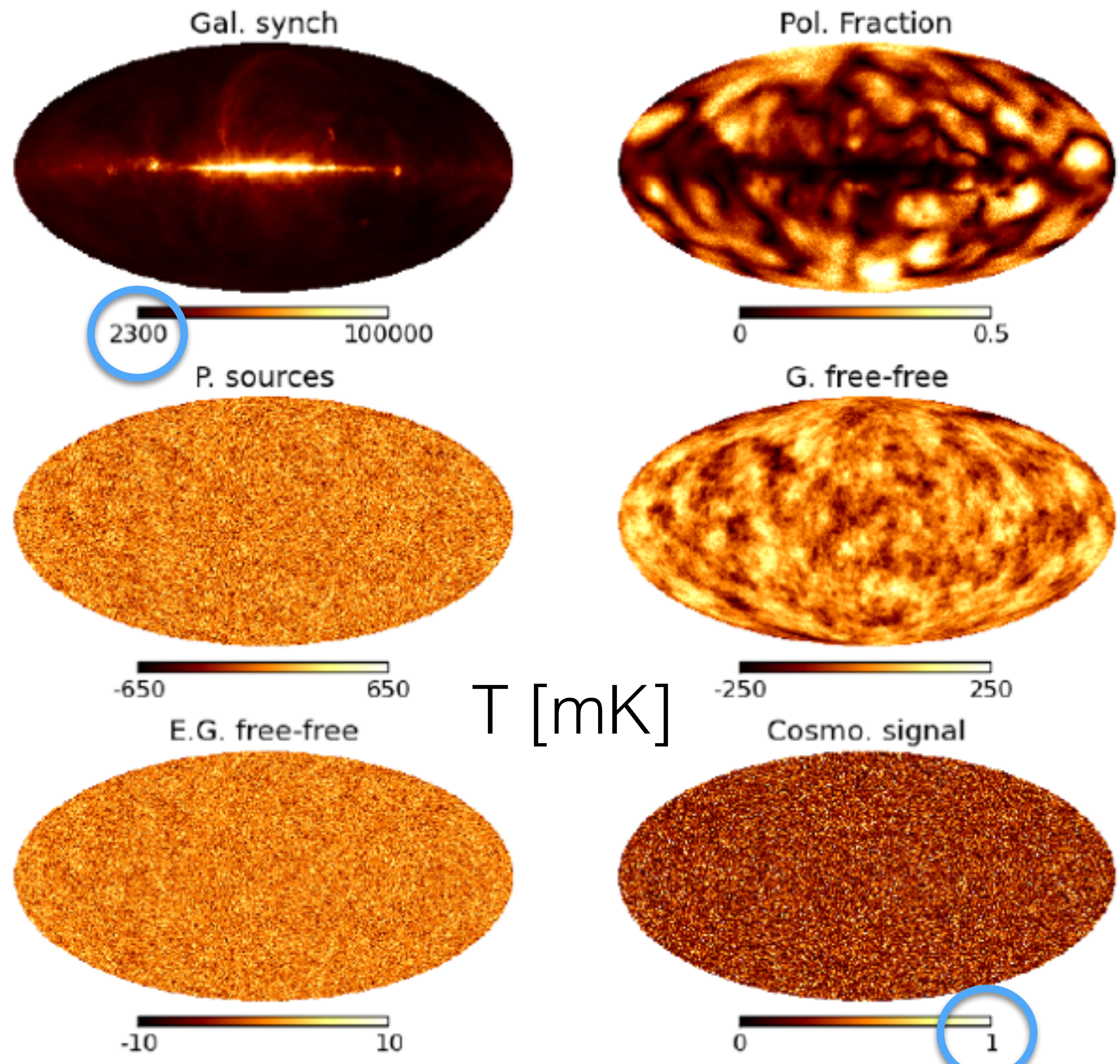
Why is IM hard?

Foregrounds

Orders of magnitude larger than signal

Several contributors

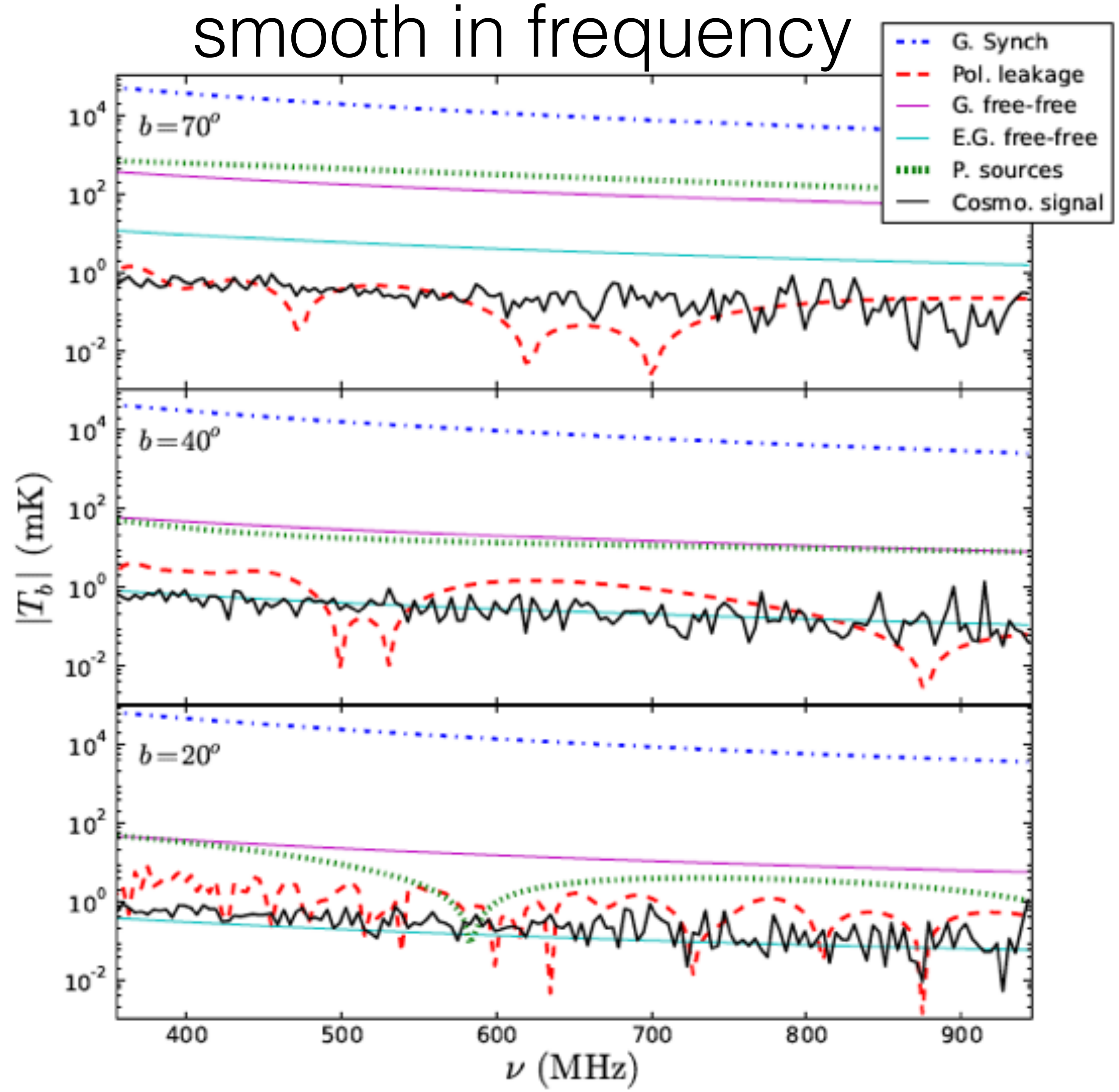
BUT spectrally smooth



Fluctuations in the instruments and their coupling to the foregrounds make cleaning much harder

Cross-correlation with other surveys (e.g. MeerKAT/ DES, SKA/LSST/EUCLID) can also help with this, as demonstrated by the GBT team

Foregrounds are smooth in frequency



Alonso et al., 2014

Noise

$$\Delta T = T_{sys} \left(\frac{1}{\Delta t \Delta \nu} + \left(\frac{\Delta G}{G} \right)^2 \right)^{0.5}$$

White/thermal noise

Pink - 1/f noise

Can model the gain fluctuations in time as:

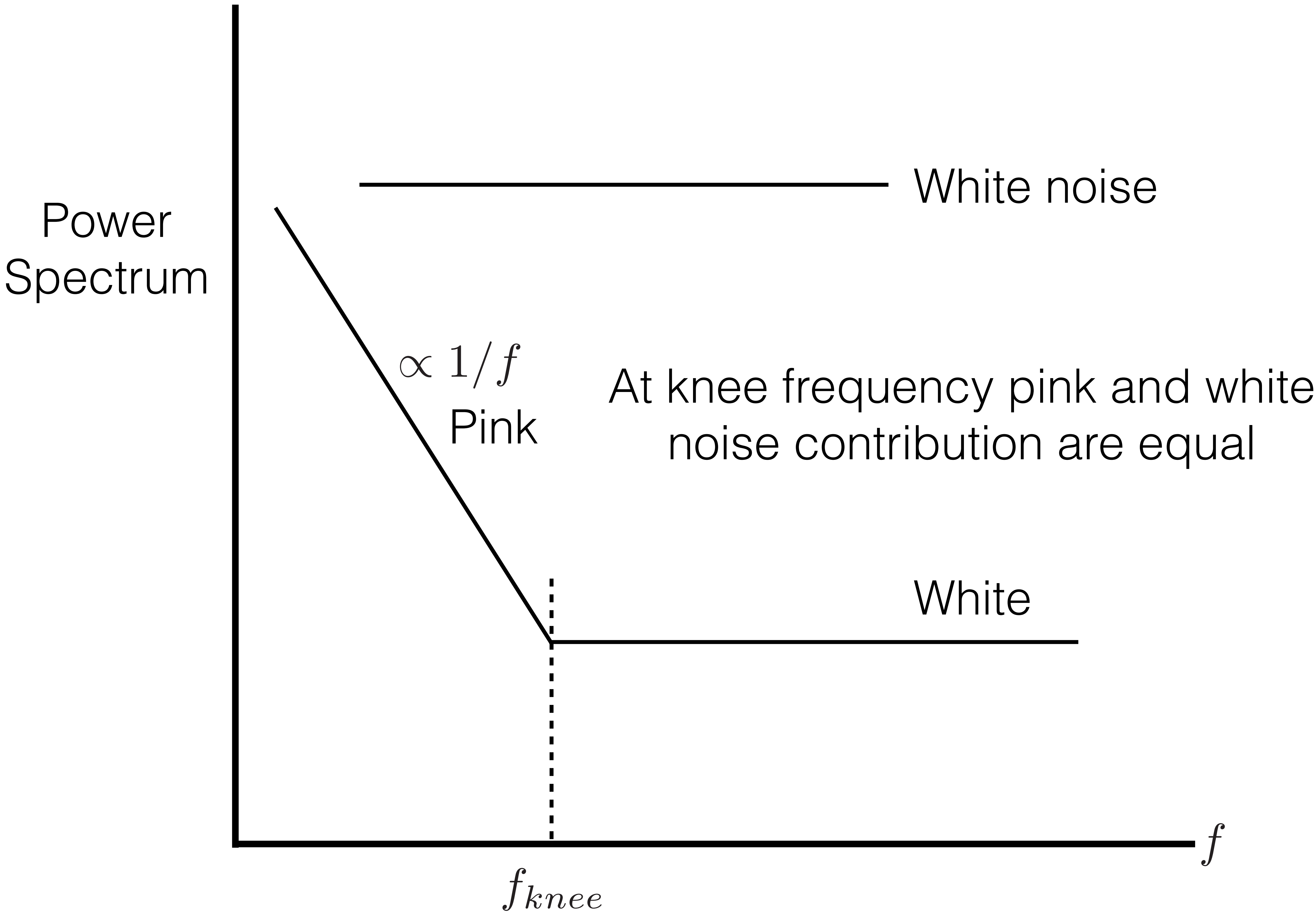
$$\left(\frac{\Delta G}{G} \right)^2 = \gamma_0 + \gamma_1 t$$

Integration time sweet spot:

$$t = \frac{1}{\sqrt{\gamma_1 \Delta \nu}}$$

Integrating longer than this means the 1/f dominates

Power Spectrum in Time…



Testing the calibration of autocorrelations with Noise Injection using KAT7 and MeerKAT

KAT7 Data

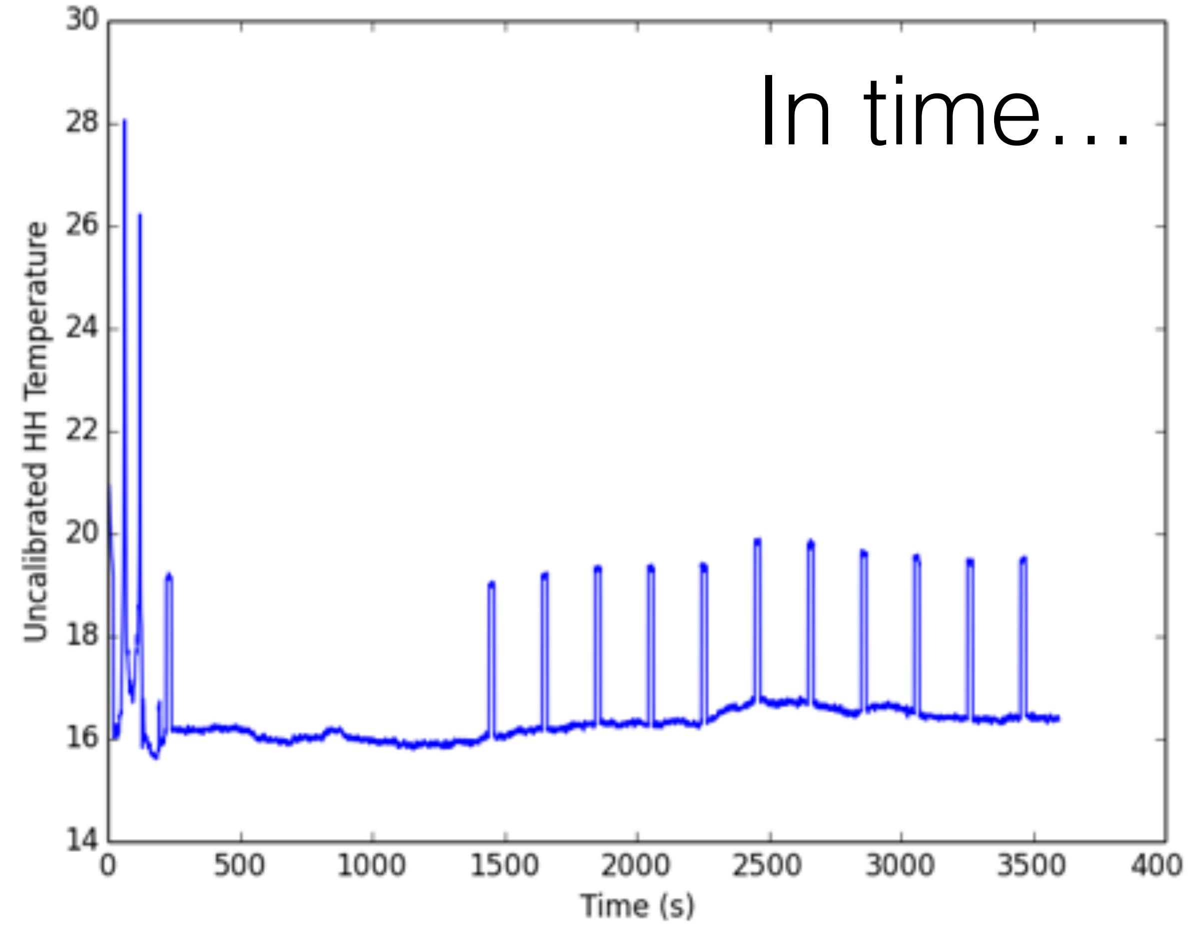
Drift scan observation

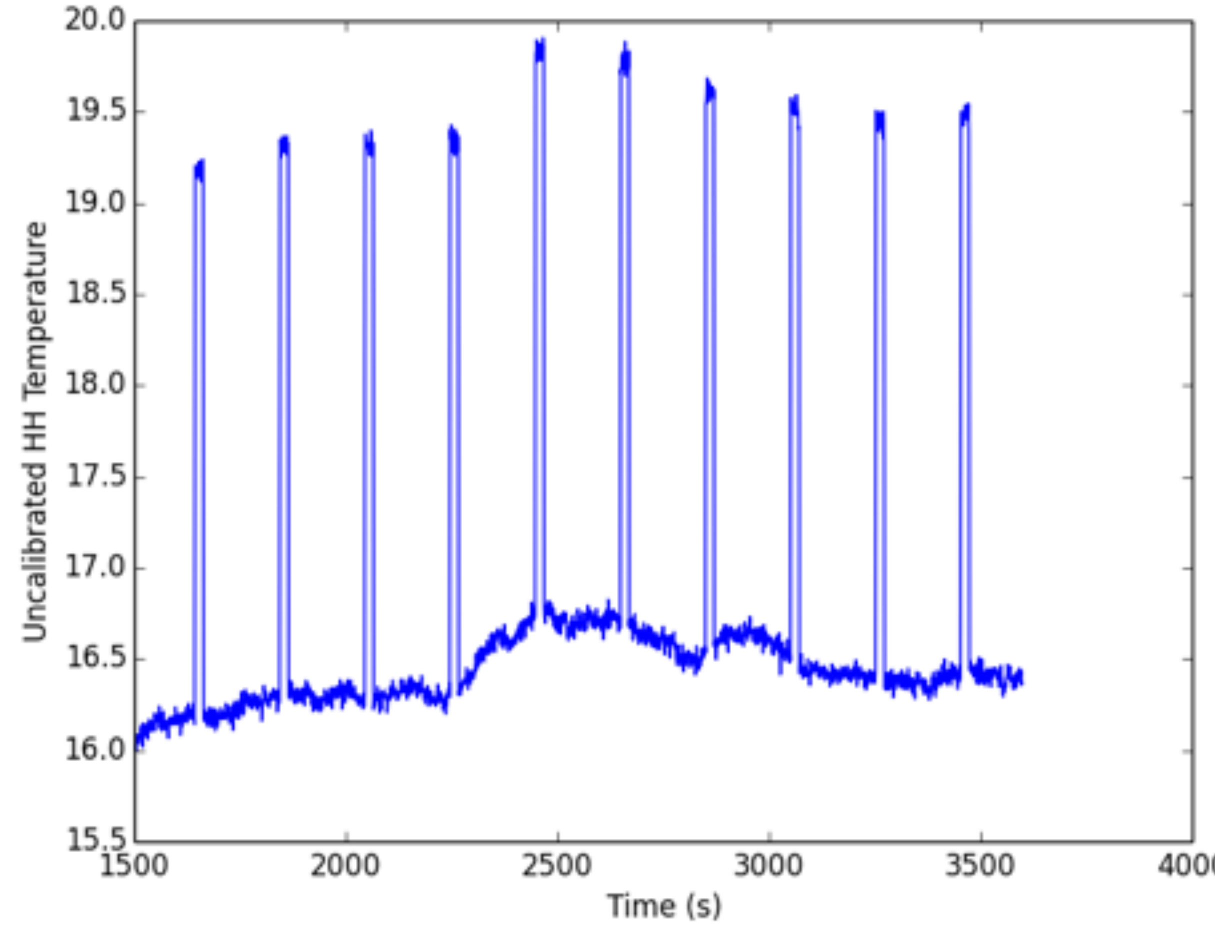
~30 mins of useable data with 1 second integration

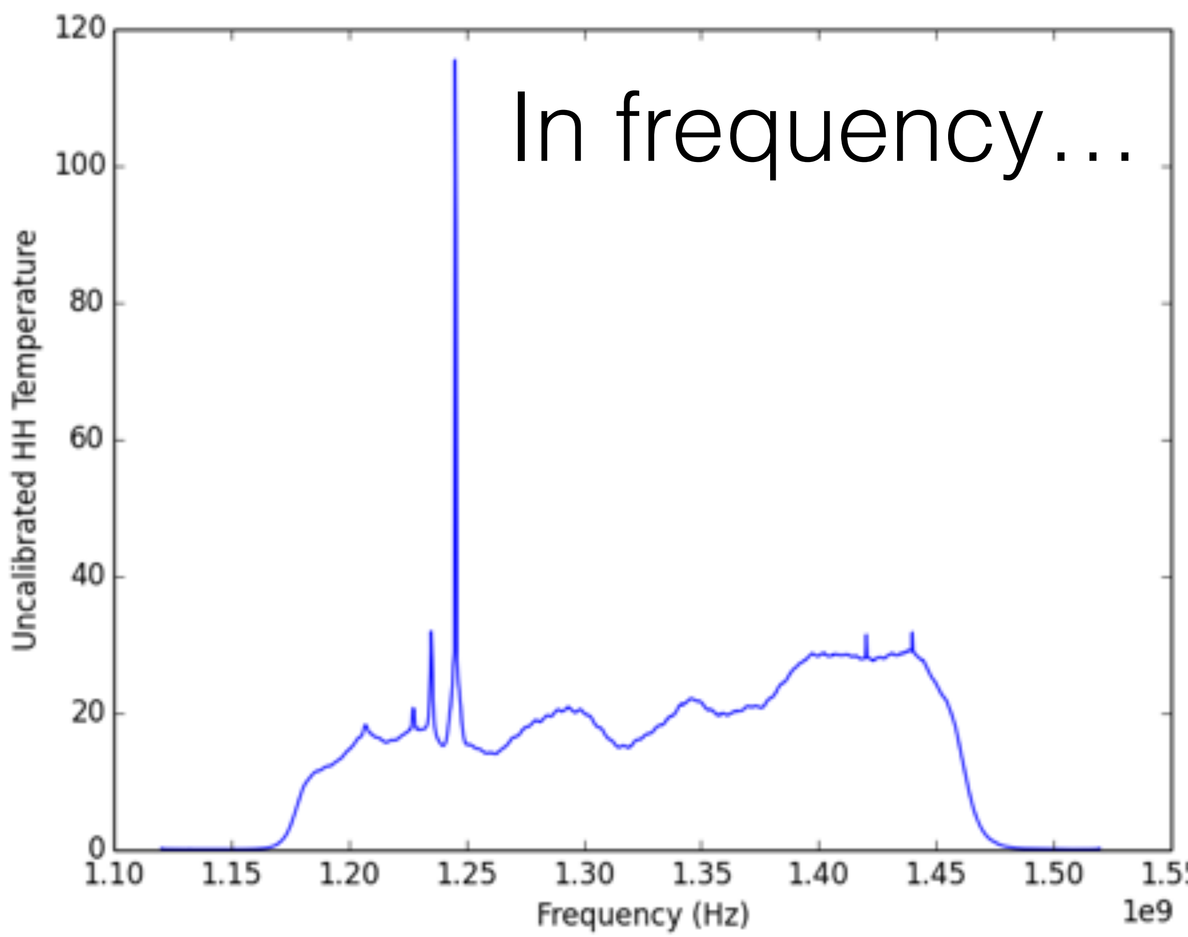
Noise diode fired every 3 minutes

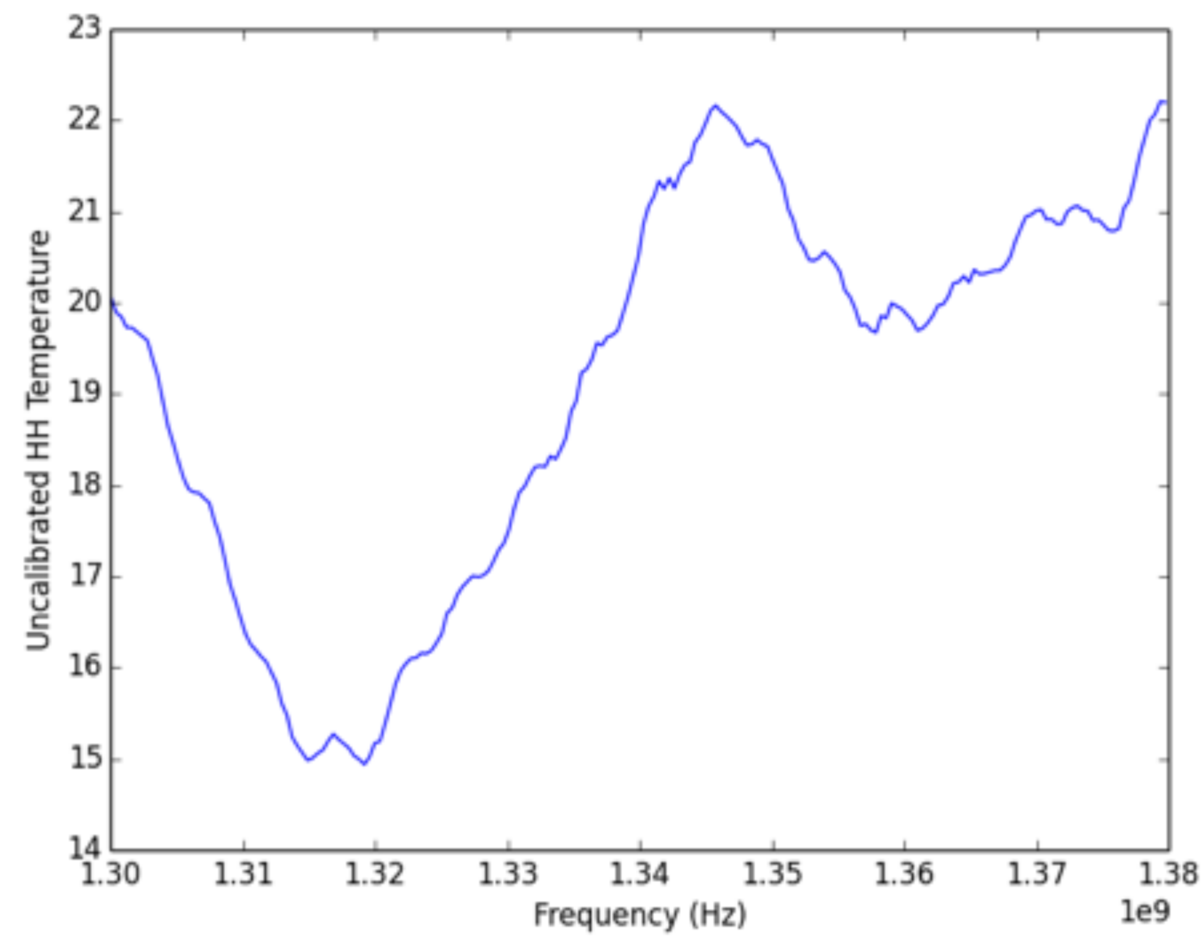
Can we calibrate the autocorrelation to reach T_{RMS}=48mK?

$$T_{rms} = \frac{T_{sys}}{\sqrt{\Delta\nu\tau}} \simeq \frac{30\mathrm{K}}{\sqrt{1\mathrm{s} \times 390.625\mathrm{kHz}}} = 48\mathrm{mK}$$


In time…
Uncalibrated HH Temperature
Time (s)


Uncalibrated HH Temperature
Time (s)


In frequency…
Uncalibrated HH Temperature
Frequency (Hz)
1e9

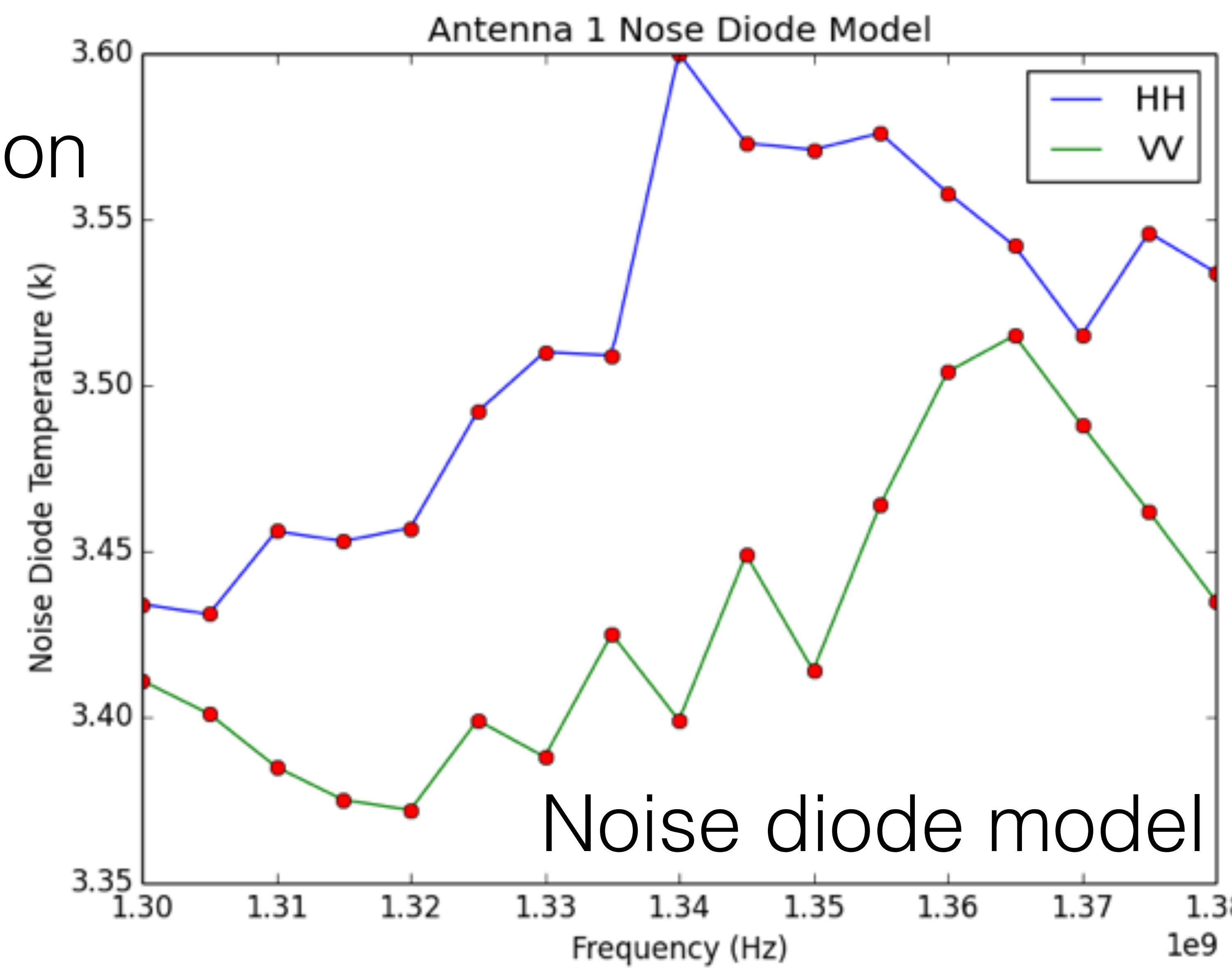

Uncalibrated HH Temperature
Frequency (Hz)
1e9

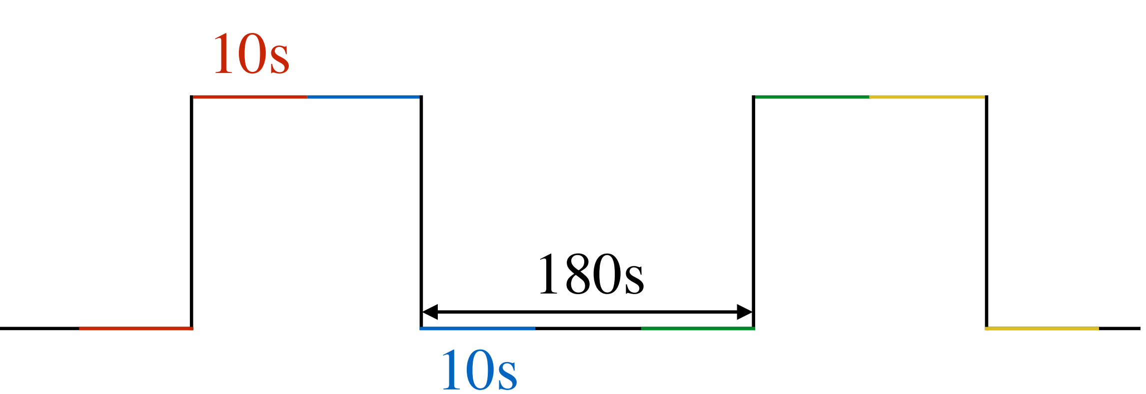
Deriving Gains

$$I_N = G(S + N)$$ When the noise diode is firing

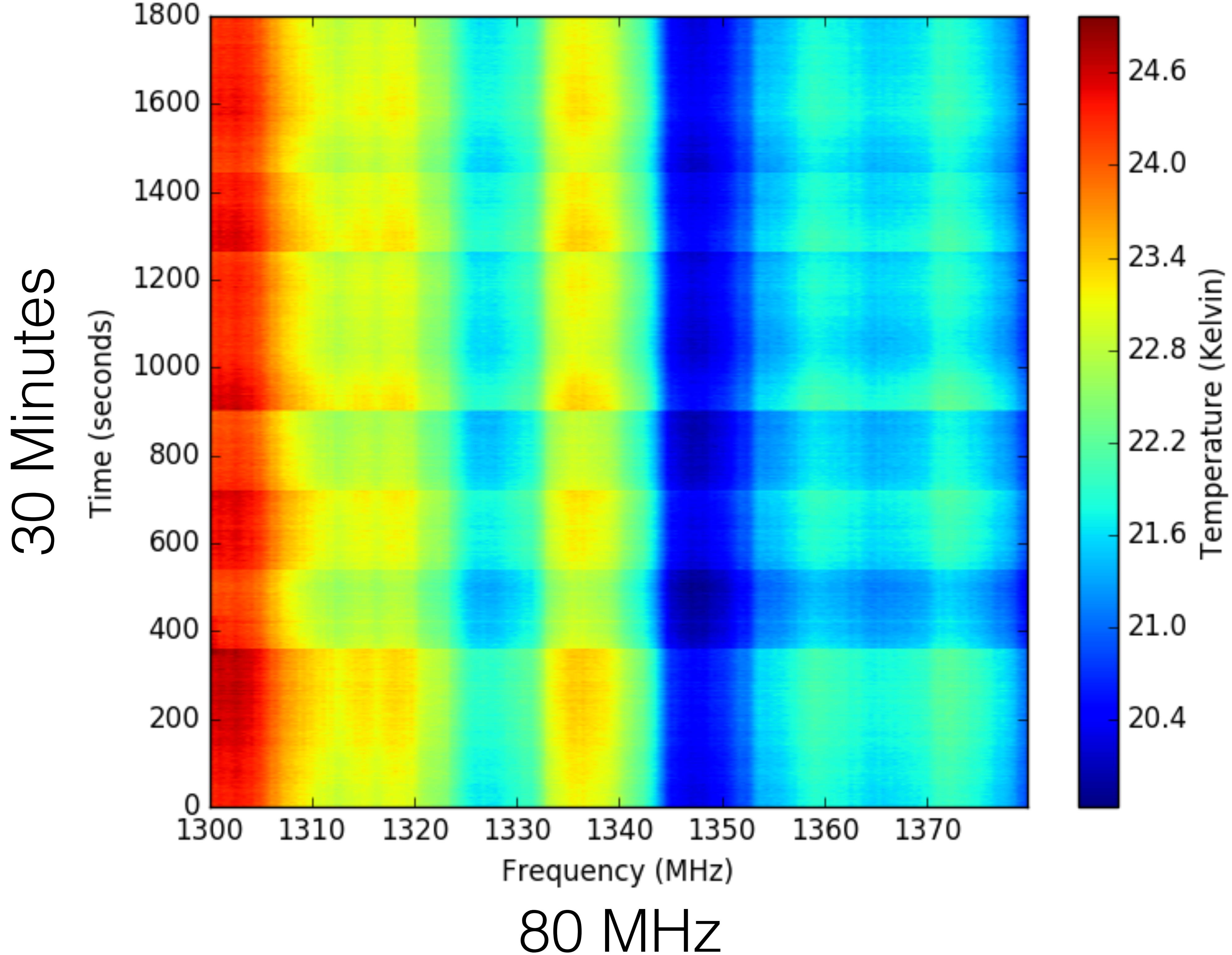
$$I = GS$$ When it's not

$$G = \frac{I_N - I}{N}$$ Solution





Corrected Data



Starting point for foreground cleaning

Foreground Cleaning

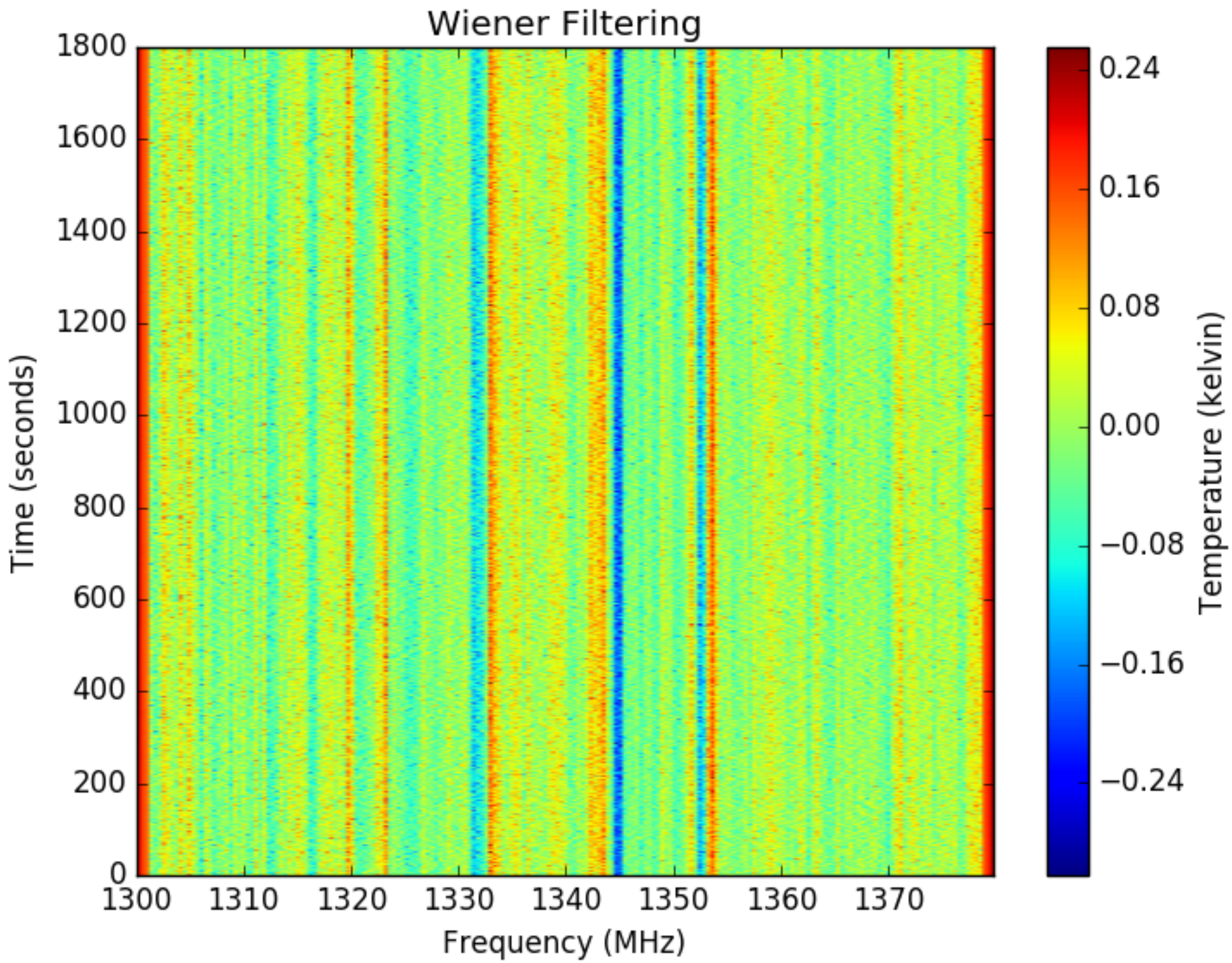
(Along the frequency direction)

Spectral smoothness - fit smooth things to each timestamp.

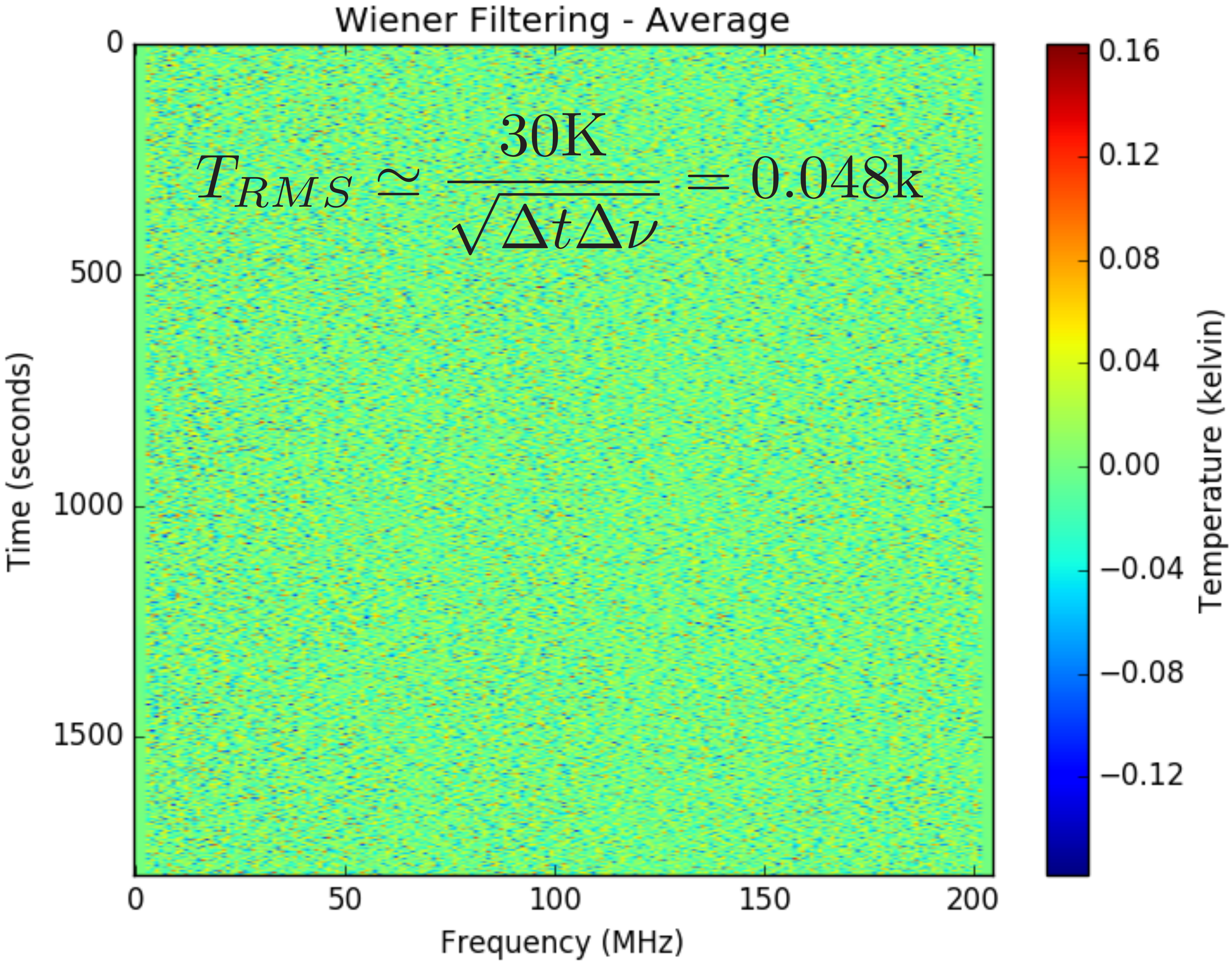
We looked at 3 different approaches: Wiener filtering, Gaussian Processes and SVD.

Are residuals noise like?

Wiener Filtering:



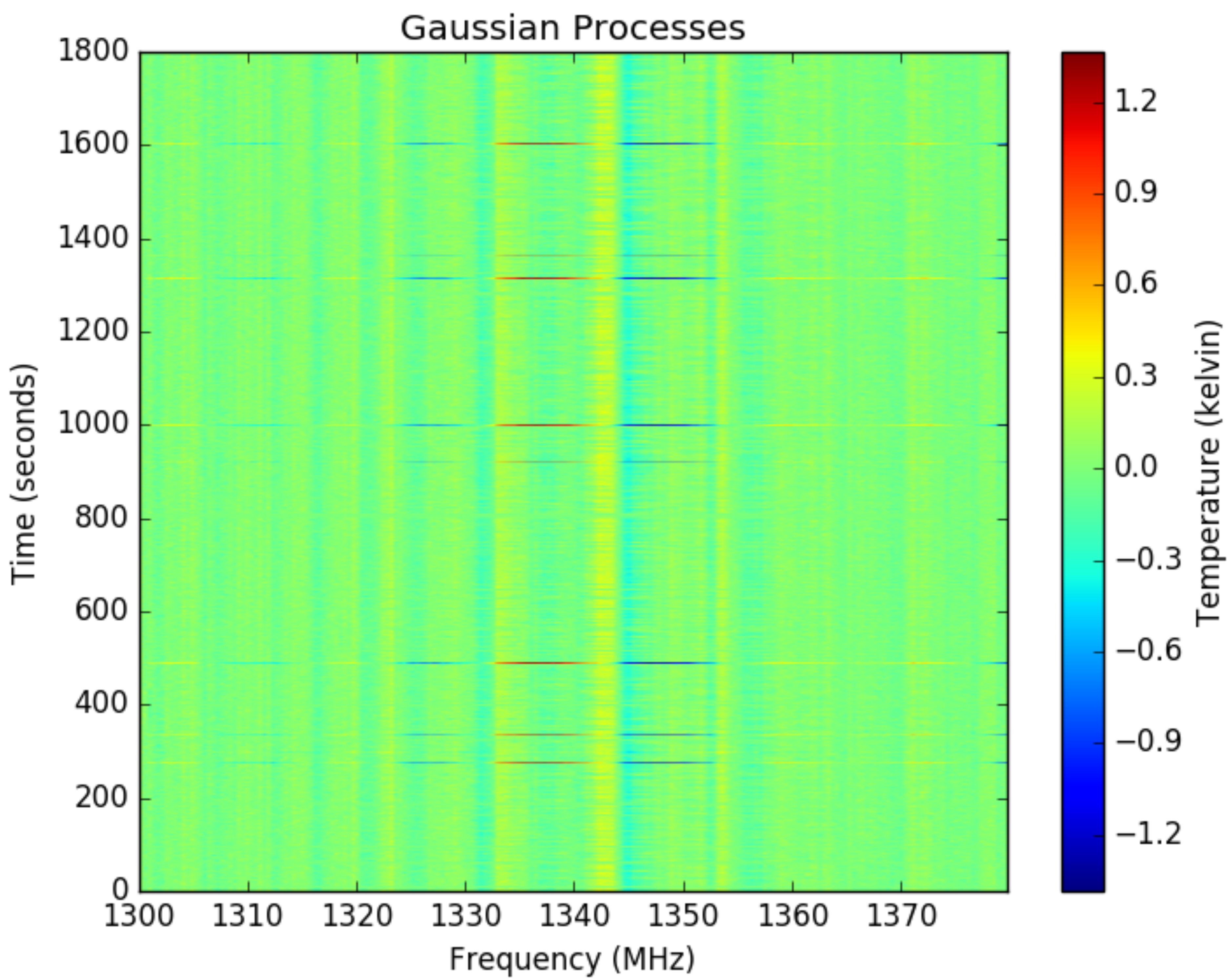
Leaves a very distinct signature in frequency that appears very constant in time

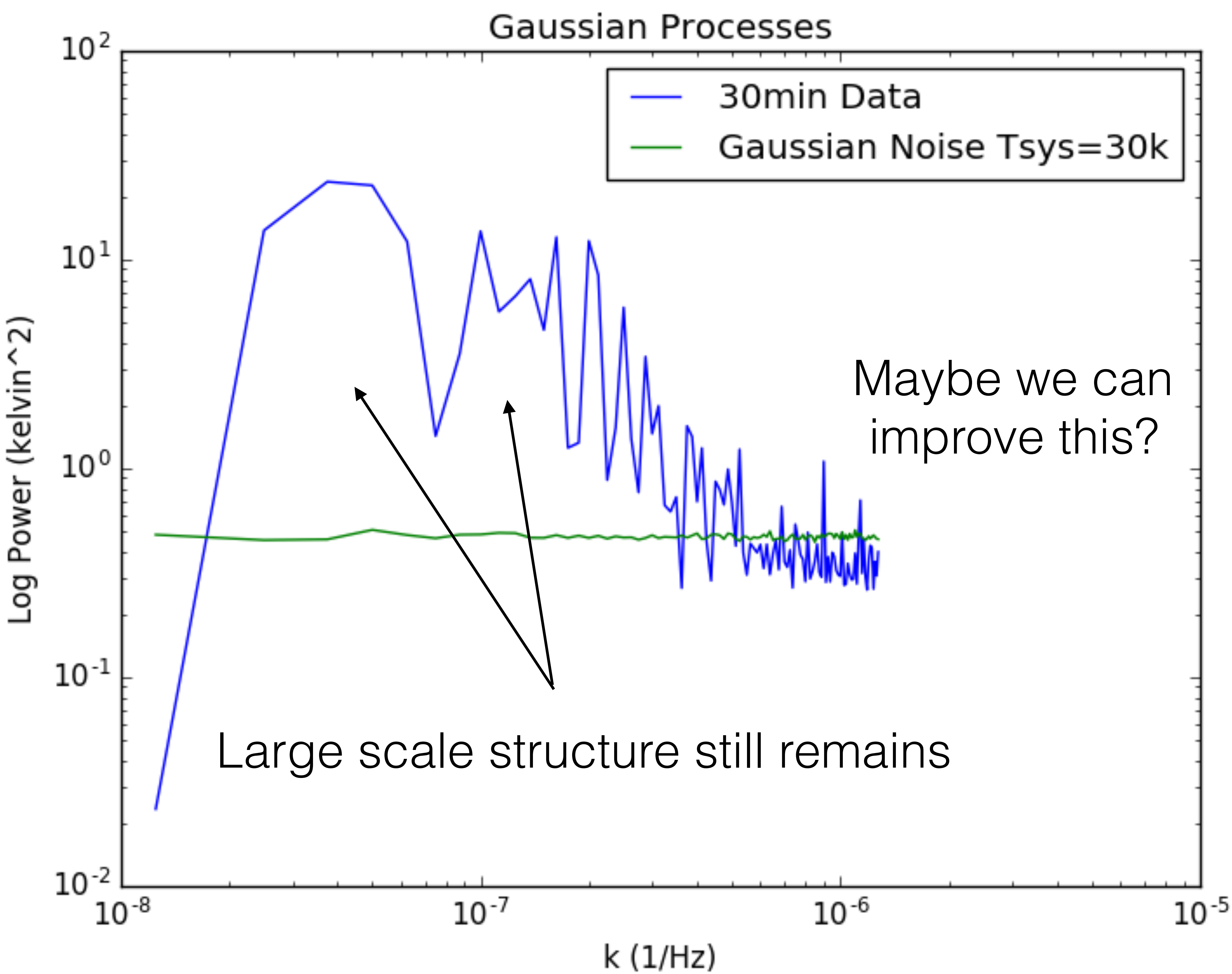


Subtract off this very constant pattern and you're left with noise like residuals (but rms level is below the expected noise)

Gaussian Processes

Much more contamination is removed, but still not perfect!

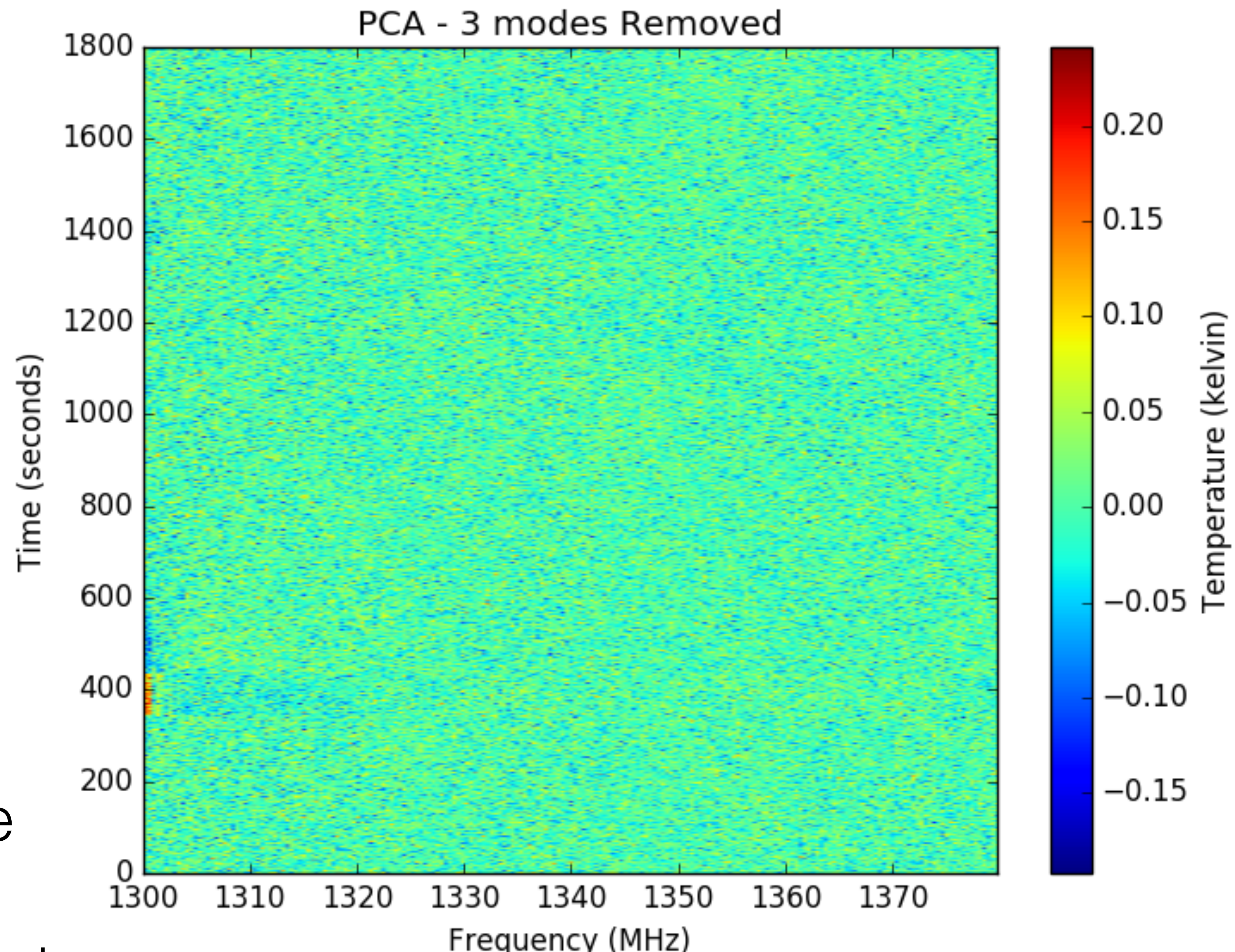



Gaussian Processes
30min Data
Gaussian Noise Tsys=30k
Log Power (kelvin^2)
k (1/Hz)
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
Maybe we can improve this?
Large scale structure still remains

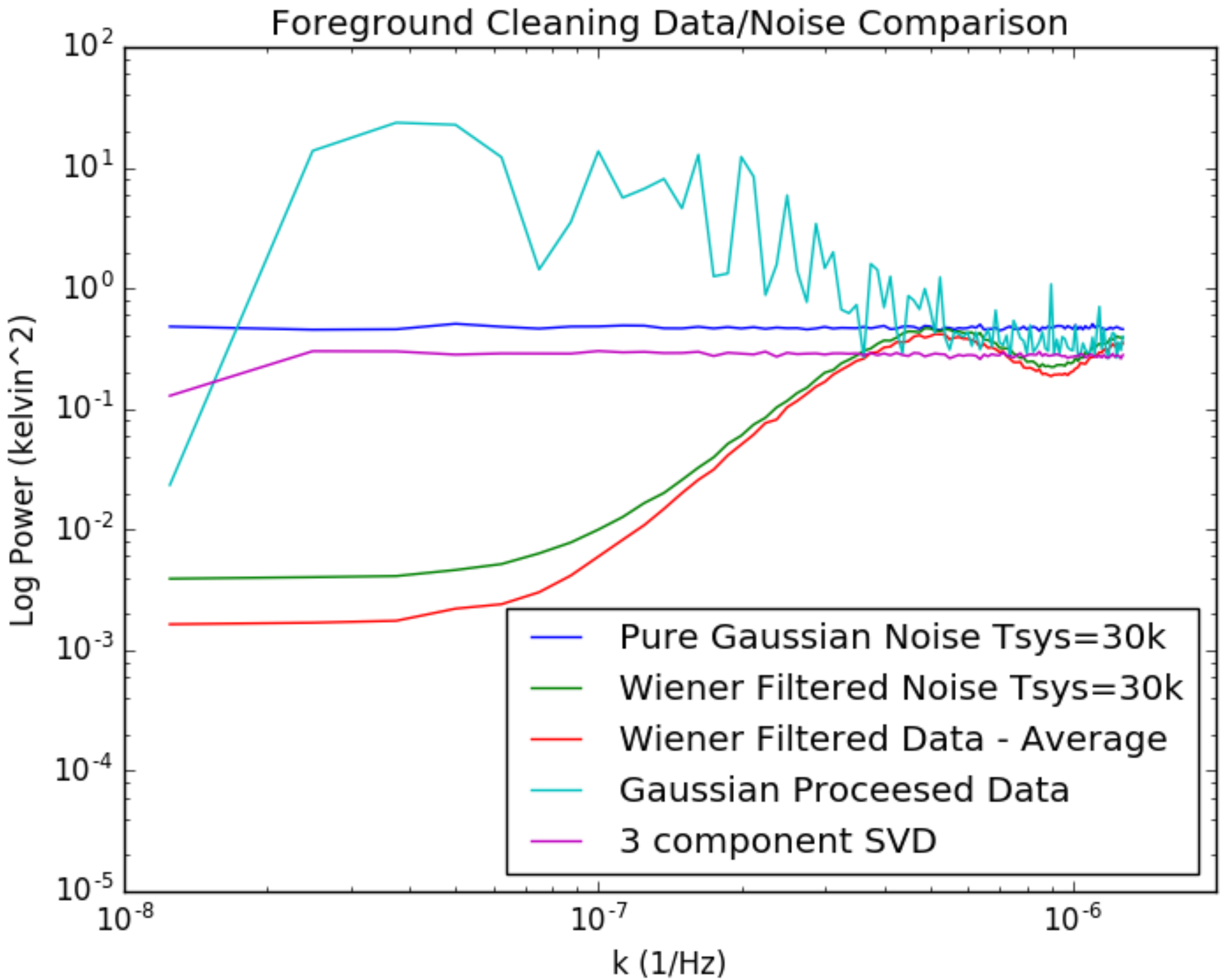
SVD

Factor data matrix A: $A = USV$

U, V - unitary S - Singular values of A



Find that with the removal of 3 components we get noise like residuals

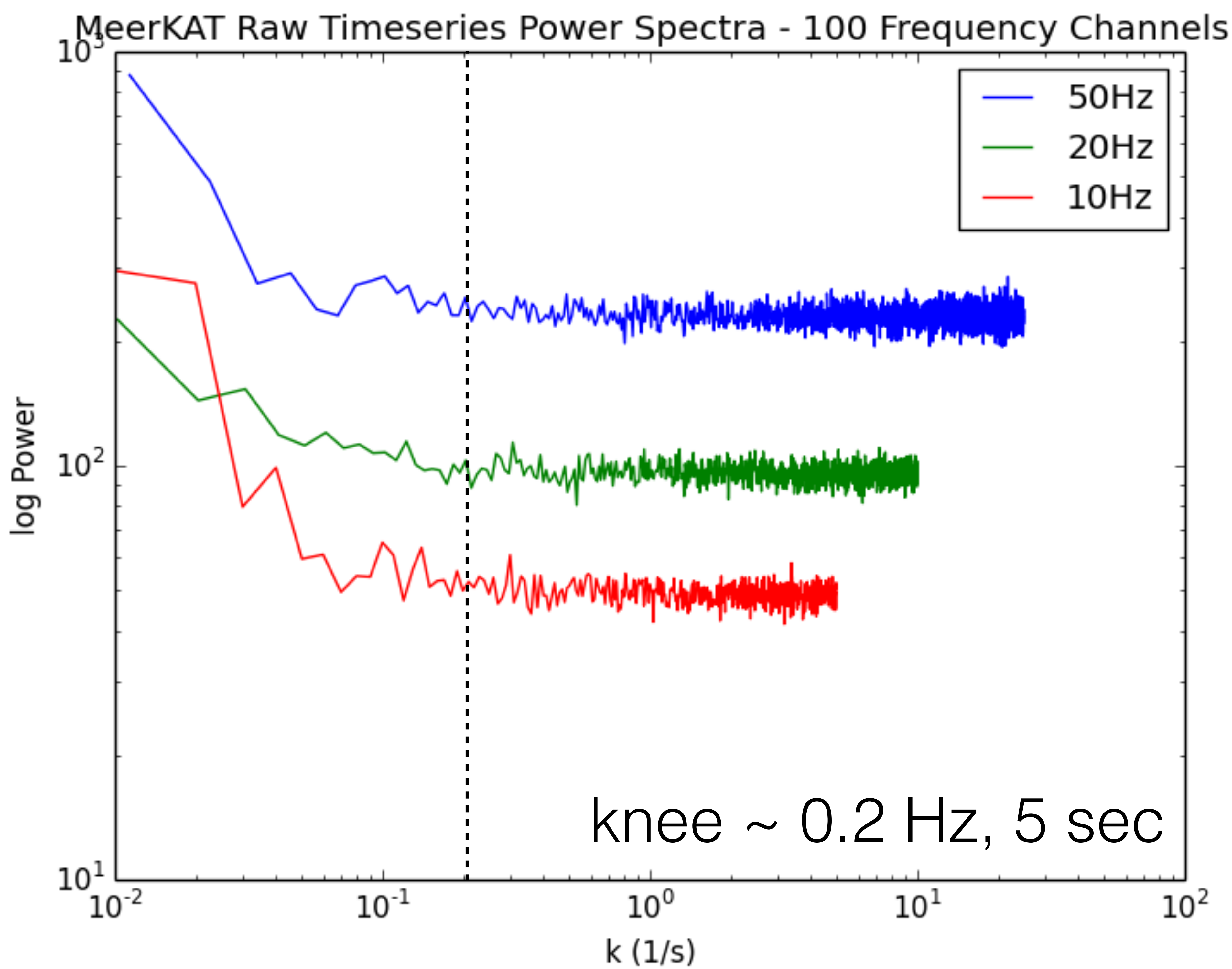


Foreground Cleaning Data/Noise Comparison
Log Power (kelvin^2)
k (1/Hz)
Pure Gaussian Noise Tsys=30k
Wiener Filtered Noise Tsys=30k
Wiener Filtered Data - Average
Gaussian Proceesed Data
3 component SVD

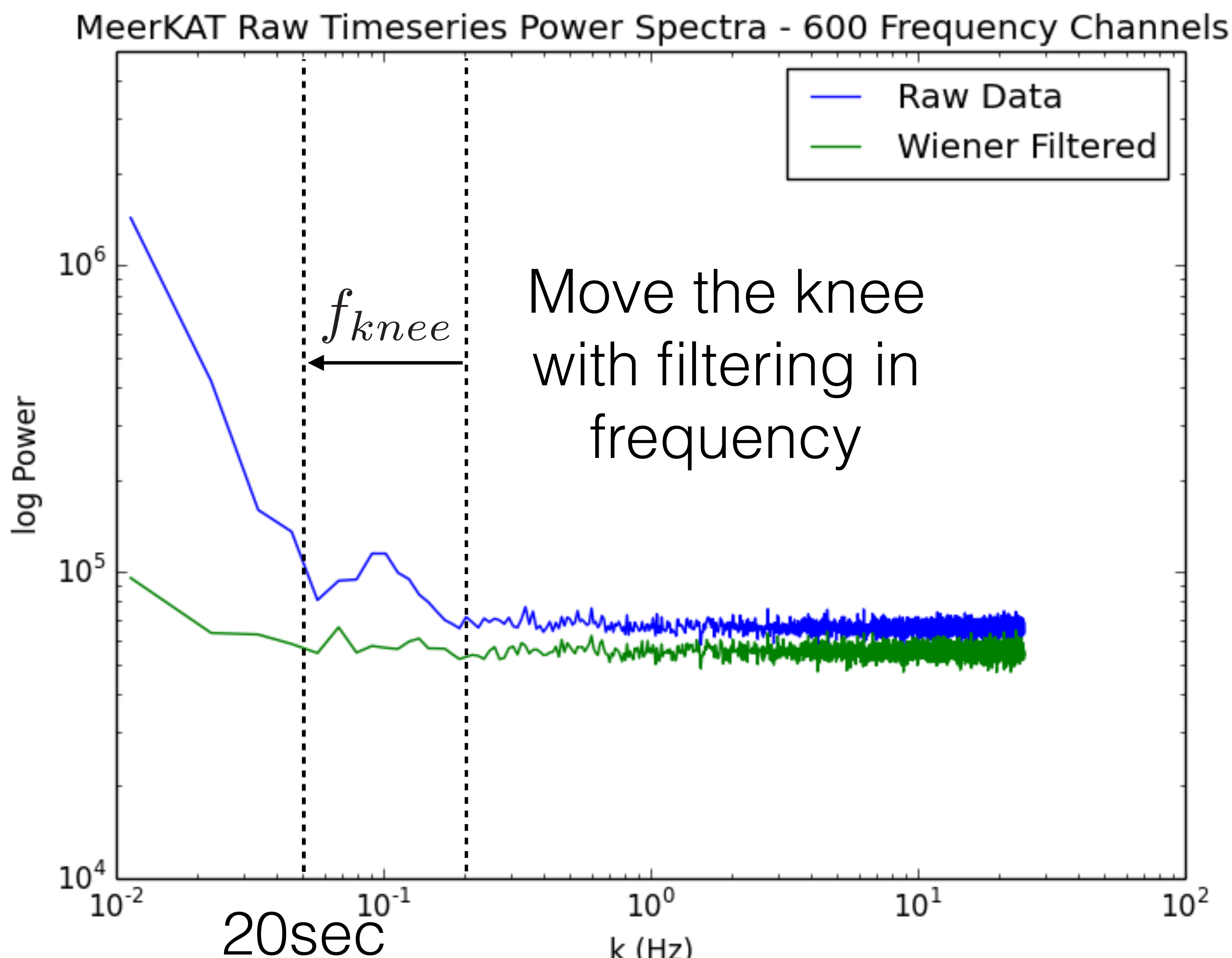
MeerKAT Data - 1/f

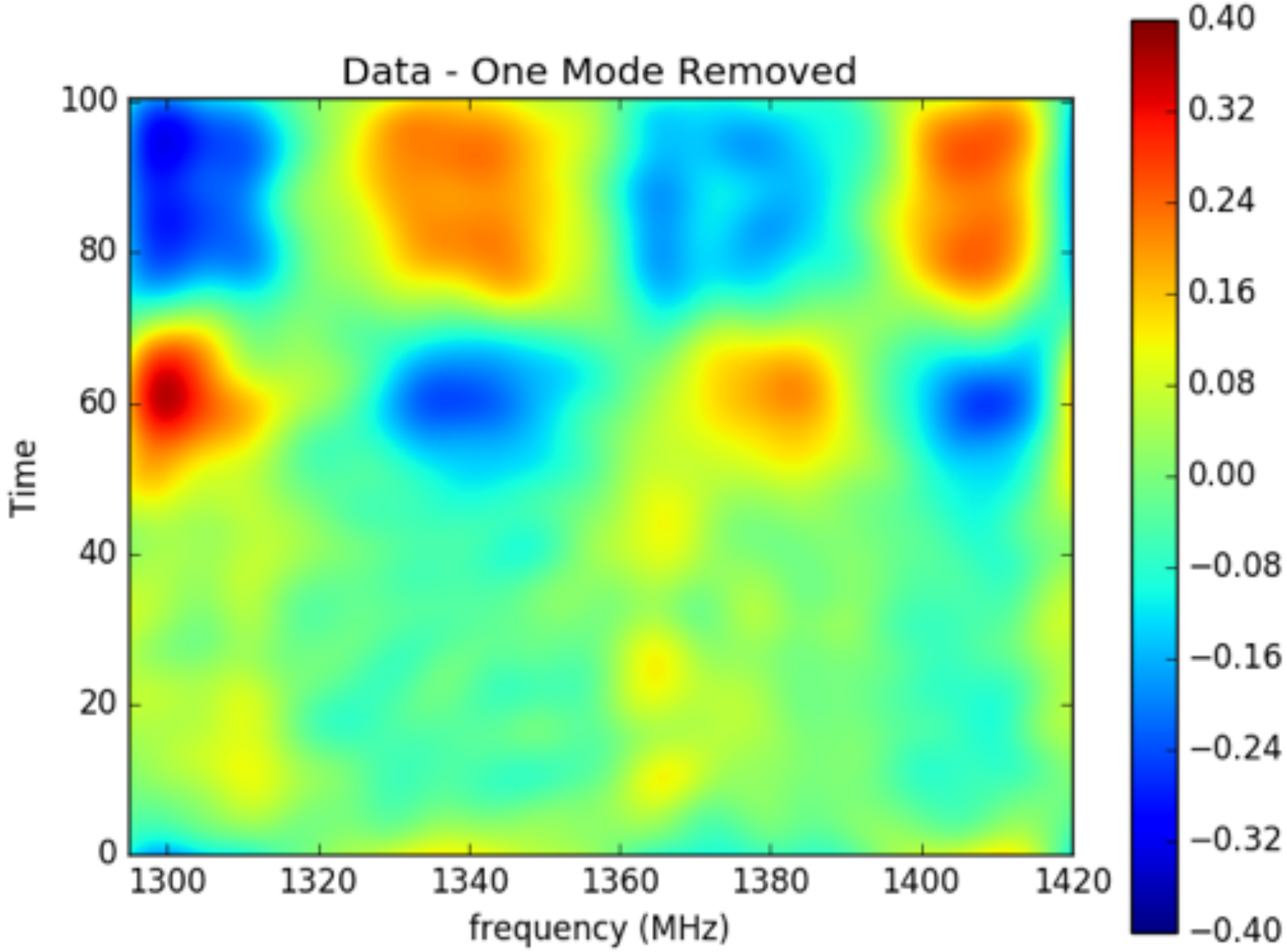
SCP Data with different dump rates, all below 1 second

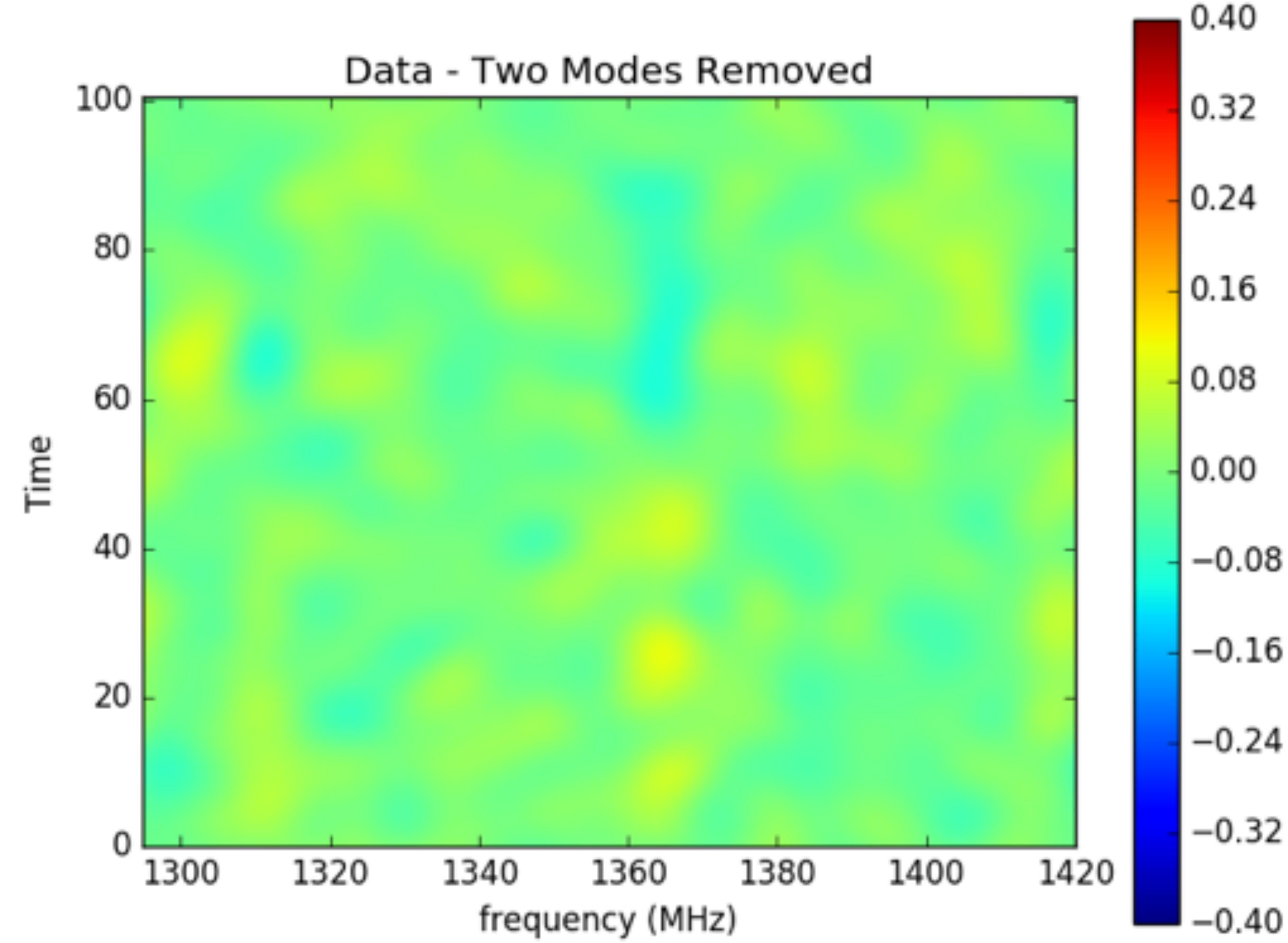
100 second observations

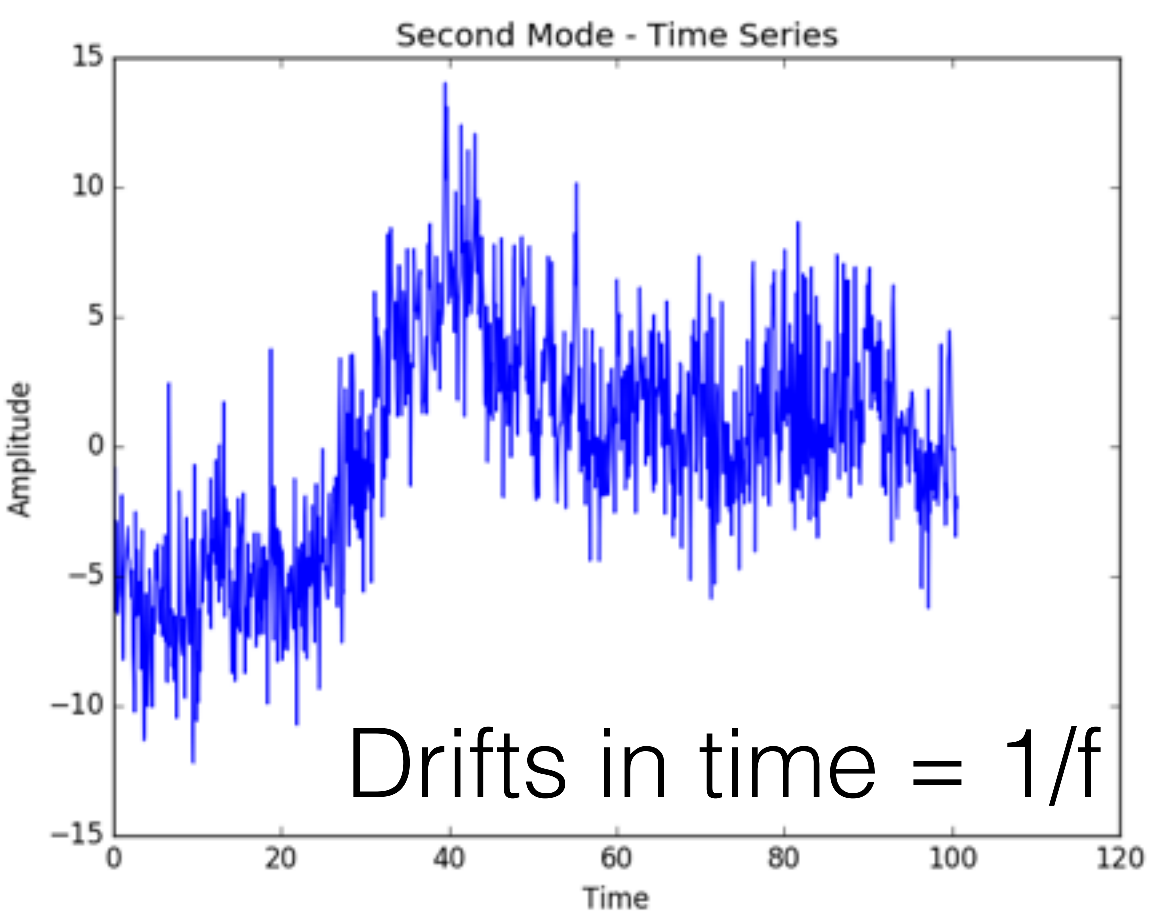


Move the knee









10Hz data SVD - remove two top modes - looks pretty white!

1/f seems to be mostly in the top 2 modes

(Thanks to Jon Sievers)

More MeerKAT Data

Noise injection data to be analysed: noise diodes are available on every dish (very stable: <0.04% RMS over 20 minute intervals)

Longer observations requested for testing the 1/f stability

Scan data with noise injection and sky calibrator also in the works

Conclusions

A large survey with MeerKAT will detect the BAO signal in HI (as well as other science)

Exploring foreground cleaning methods with autocorrelation data from KAT7 & MeerKAT

Looking at how to achieve the optimal 1/f

More MeerKAT data in the pipeline

Everything is a crucial step towards SKA1