APSERA: ARRAY OF PRECISION SPECTROMETERS FOR THE EPOCH OF RECOMBINATION

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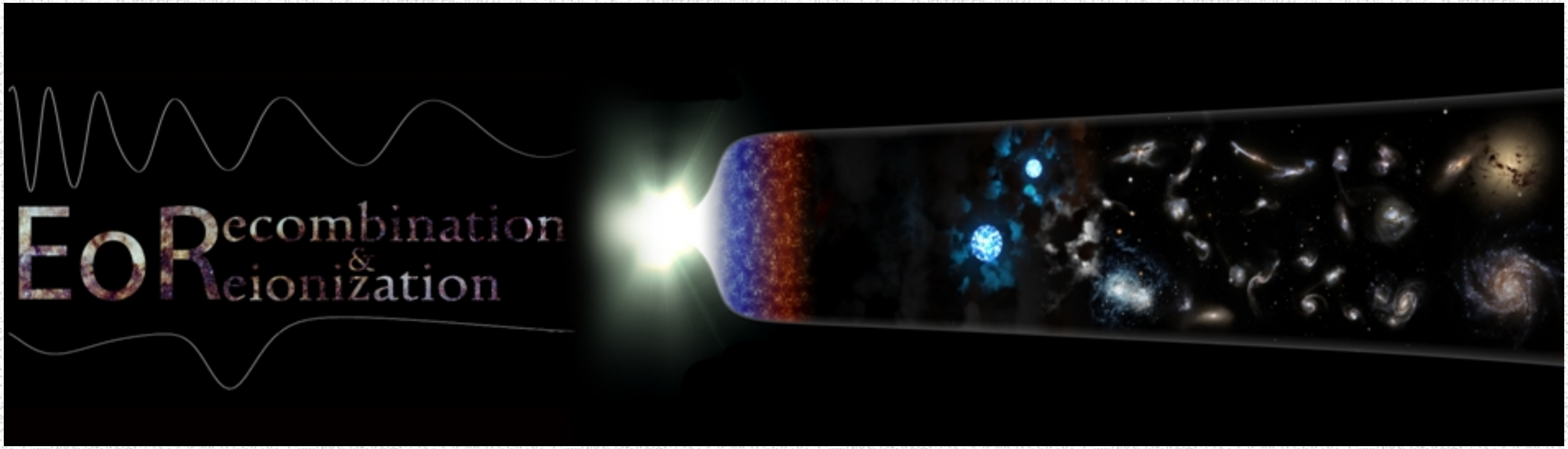
(PLUS UDAYA SHANKAR & JENS CHLUBA;
AND BASED ON ASTRO-PH/1501.07191)



Spectral distortions group at the Raman Research Institute, Bangalore

All-sky or global CMB distortions from reionization & recombination

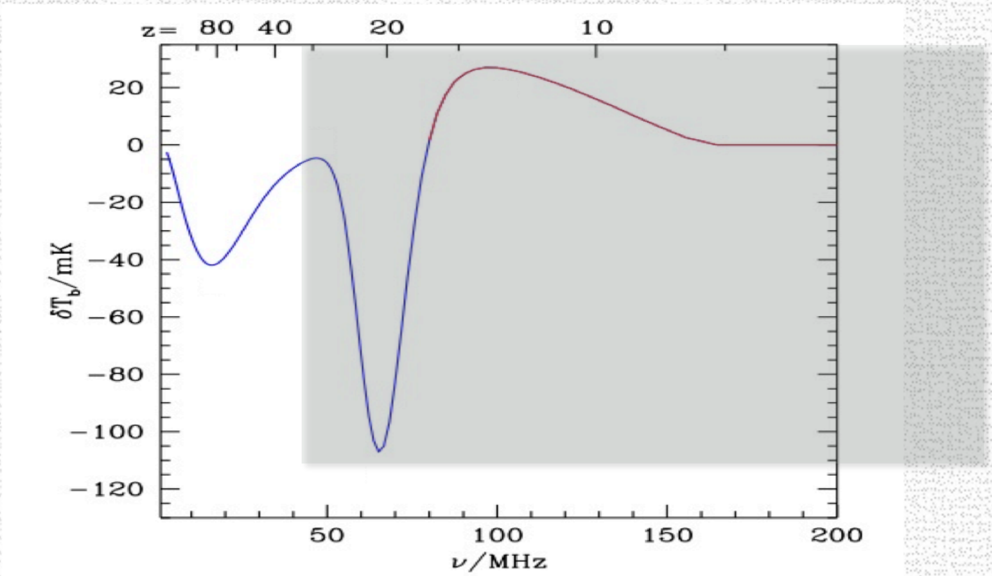
At cm and longer wavelengths

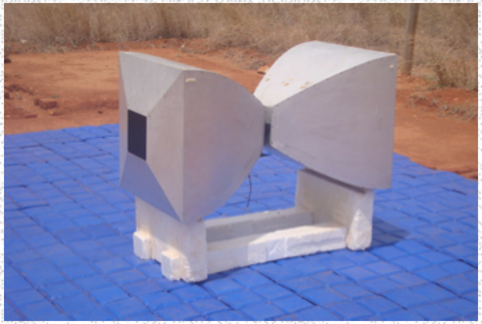
Ground based. Although we could propose a space mission to the Indian Space Research Organization if we have a case for that.

- SARAS: Shaped antenna measurement of the background radio spectrum. 40-250 MHz band.
- ZEBRA: Zero-spacing interferometer measurements of the background radio spectrum. 40-250 MHz band.
- APSERA: Array of precision spectrometers for the Epoch of Recombination. Octave band in the 2-6 GHz window.

www.rri.res.in/DISTORTION

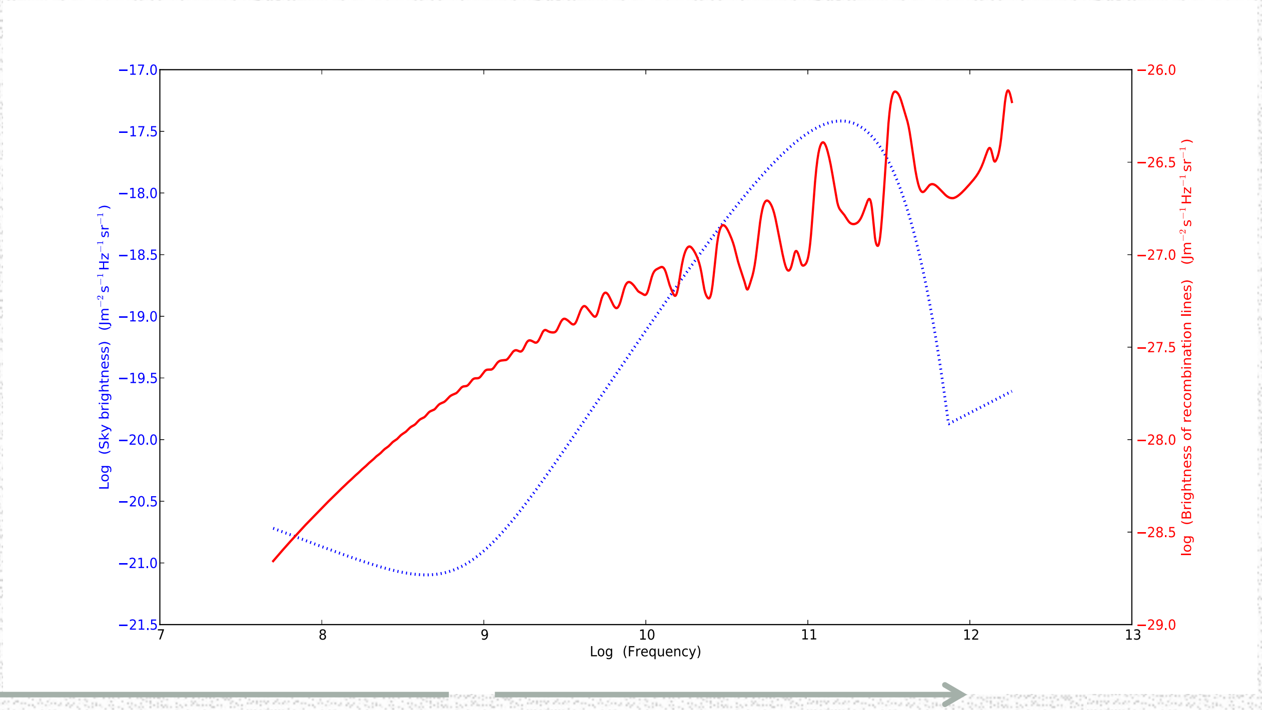
Reionization: SARAS & ZEBRA





- These cover the frequency range 40-250 MHz.
- These are in advanced stages of systems development, field testing.
- The experience feeds into the design of APSERa prototype spectral radiometer.

Additive Spectral structure from Cosmological Recombination



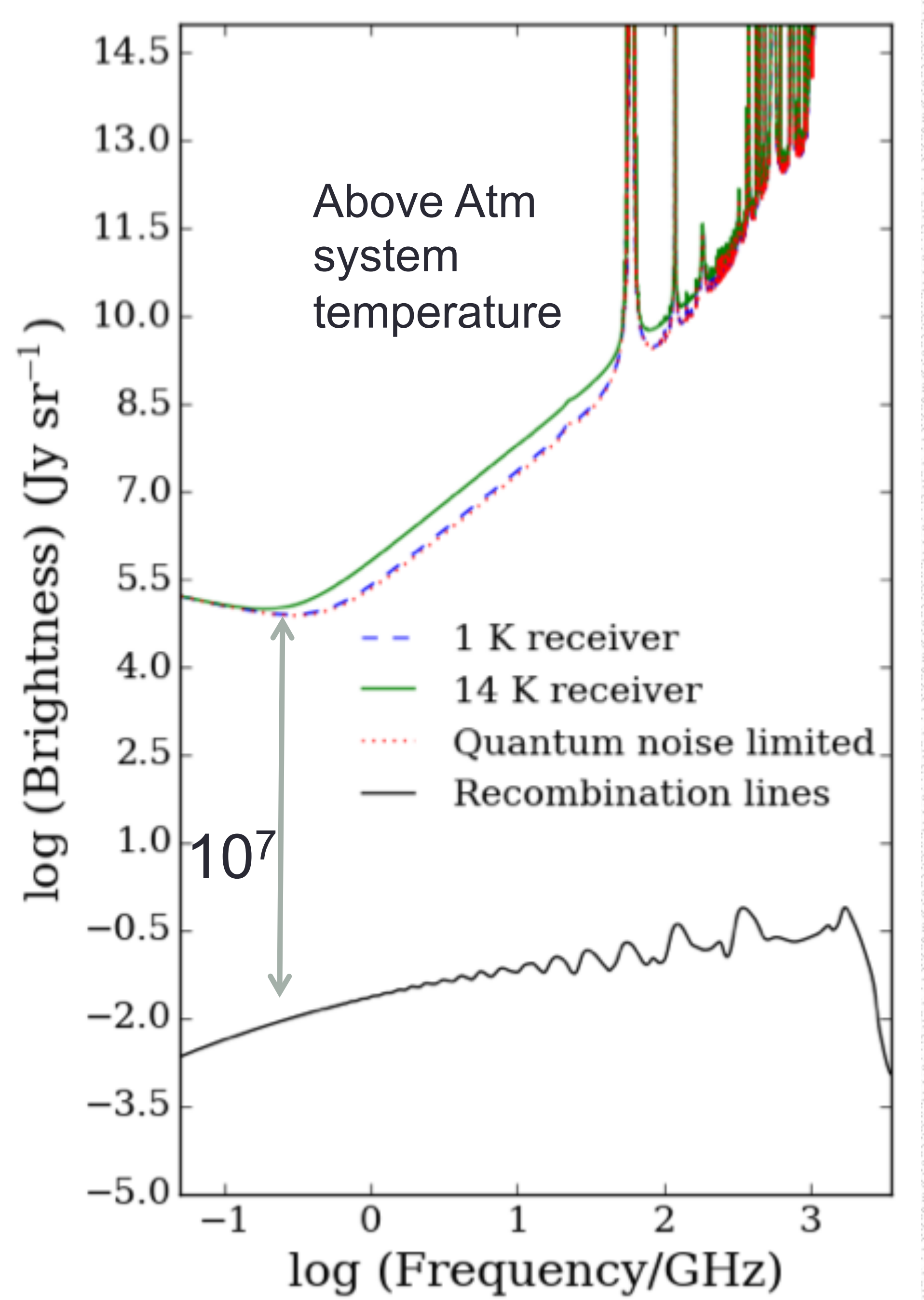
Galactic +Extragalactic Sources dominate the foreground

CMB dominates

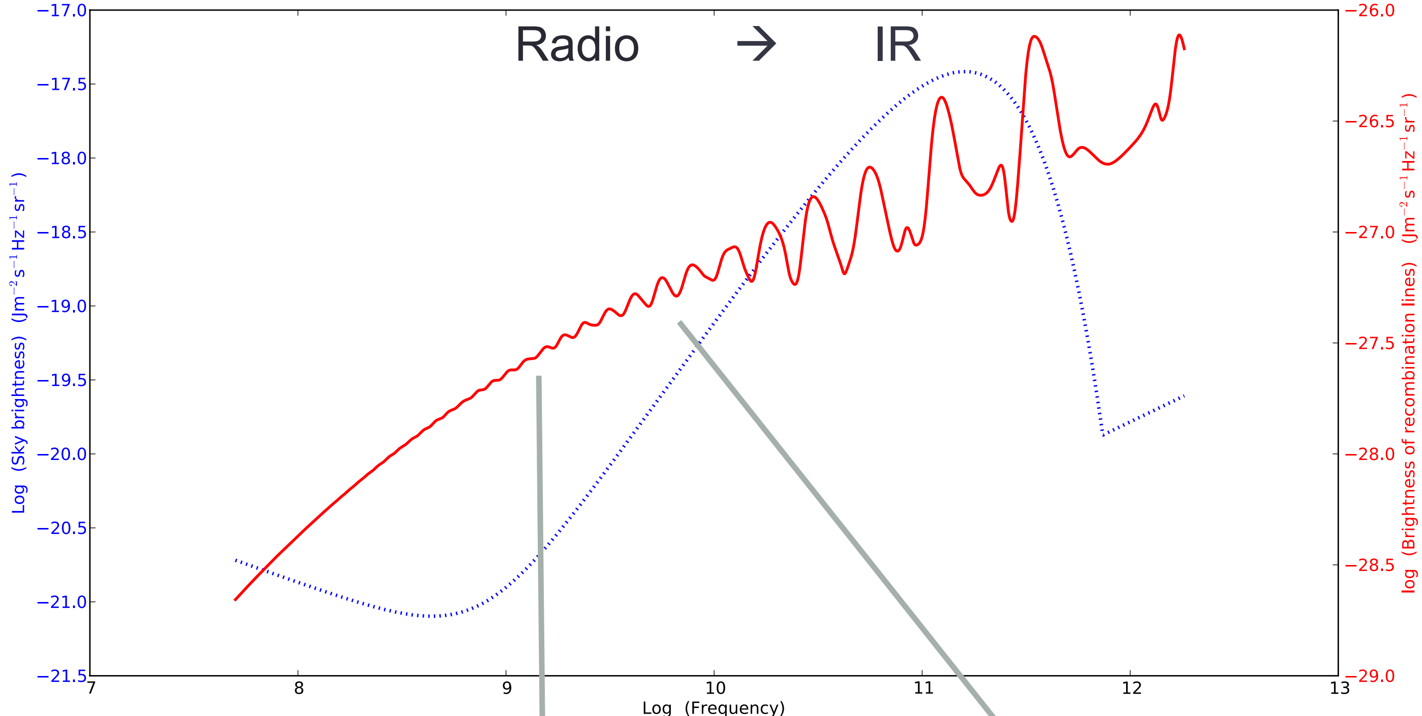
a) Additive smooth continuum in the Radio, microwave and IR

b) Ripple structure that gets more complex in details towards IR

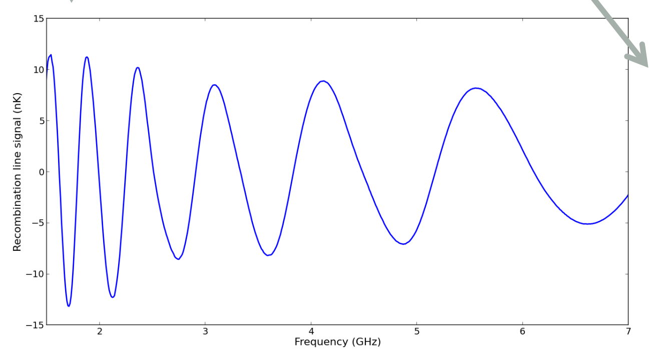
Ground based detectors: signal power vs system noise



Could we model the system noise to greater than 1:10^7 so that the recombination spectrum may be detected?



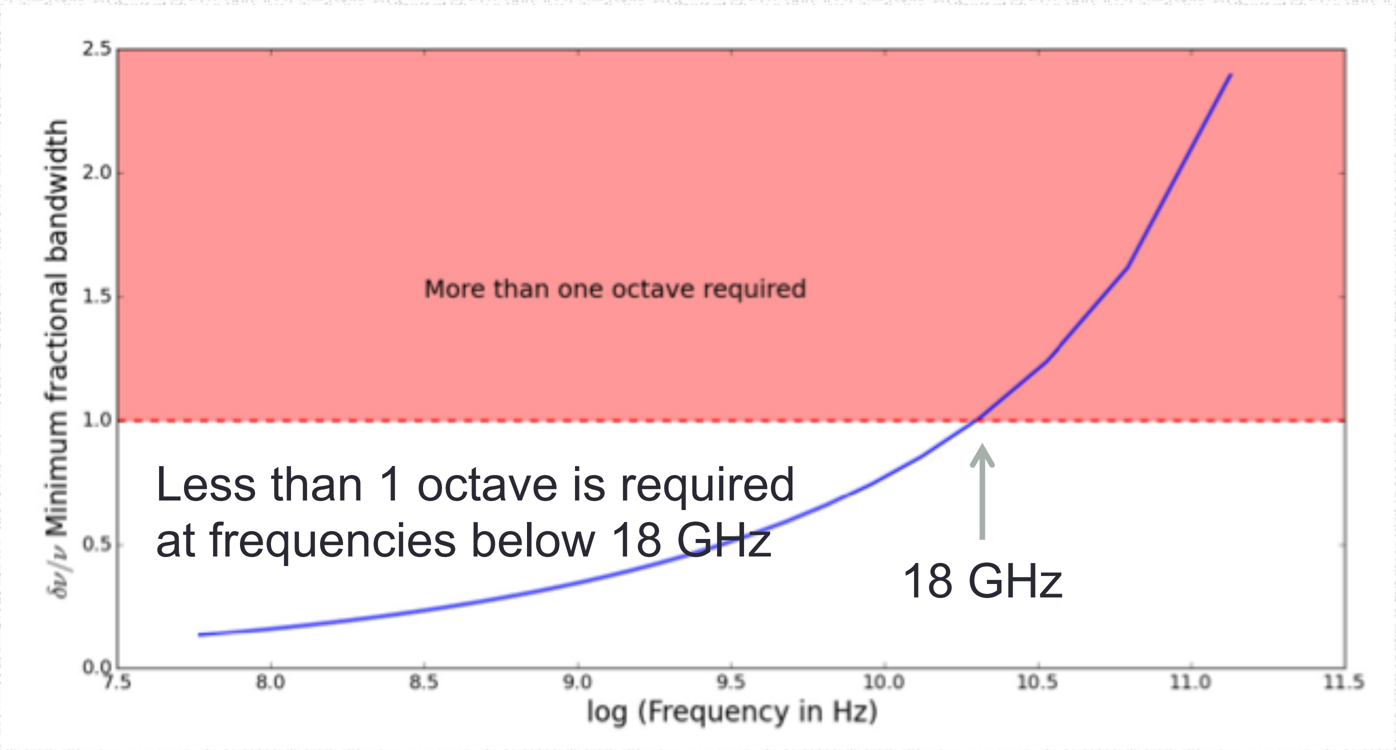
2 GHz → 9 GHz



Fine spectral structure as a residue of a fit of a smooth component to the total recombination spectrum

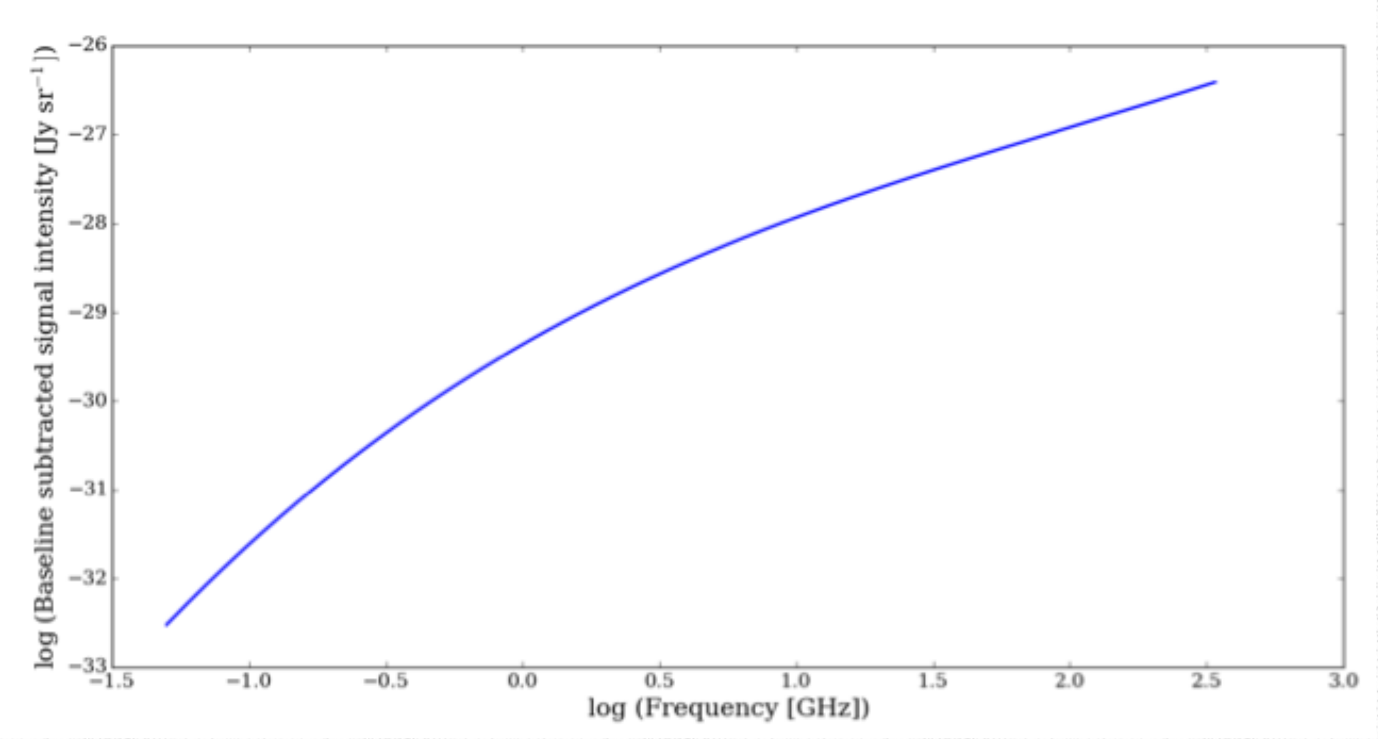
Aim to detect just the ripple component from Recombination as a spectral distortion?

Bandwidth that includes a sufficiently complex signal structure



- Include at least two adjacent n ➔ (n-1) α transitions in the spectral segment
- So that the recombination line structure would be distinctive
- We prefer not to have receiver bandwidths exceeding an octave to prevent self-interference.

Signal amplitude in the ripple structure

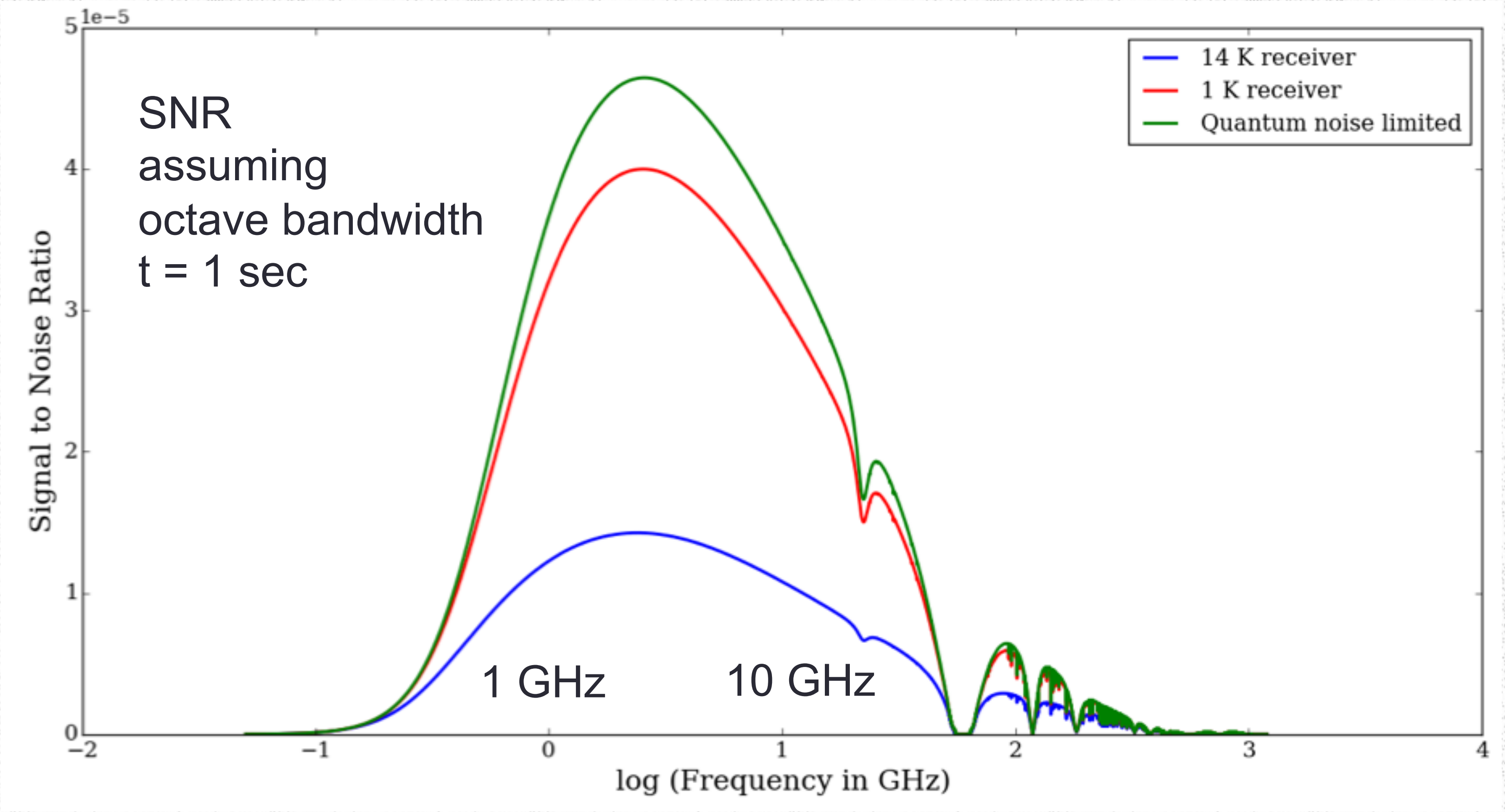


- Half the peak-to-peak amplitude of the residual after subtracting a spline fit through points at the locations of the recombination line peaks.

System noise, Estimator of Signal, Signal-to-noise ratio

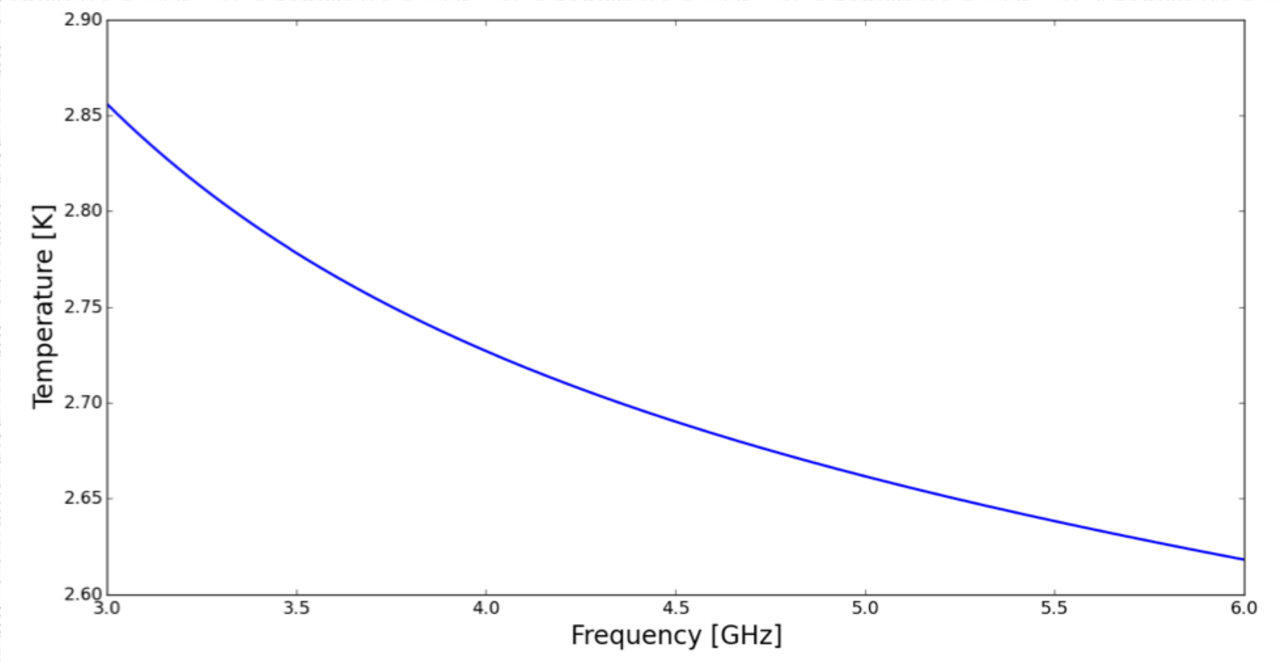
- System noise T : Rec + Ant + Gnd + Atm + Gal + ExGal + CMB (referred to above atmosphere Tsys)
- Signal estimator: $S = \sum_{k=0}^{N} a_k w_k$ weighted sum of the measurements, which ideally yields the amp A_o of the ripple
- SNR $= \frac{A_0}{T}\sqrt{\frac{B \cdot t}{2}}$

Optimum observing band



APSERa will operate in an octave window in the 2-6 GHz band

Mock Observation



Interpolate between all-sky maps at 0.408, 1.420 & 23 GHz (without CMB)

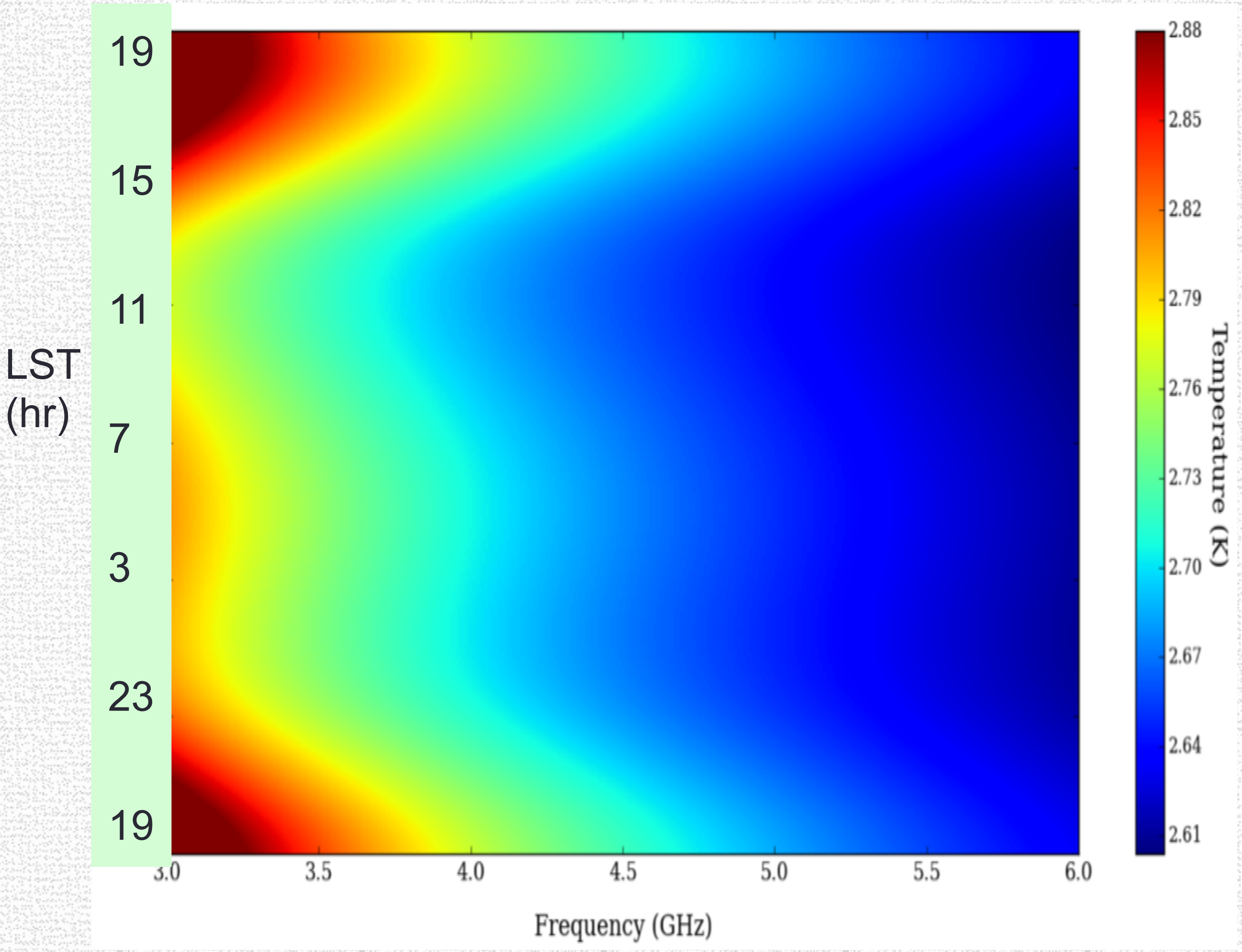
Then add CMB + recombination lines

Average sky pixel intensities weighted by a $\cos^2$(ZA) beam

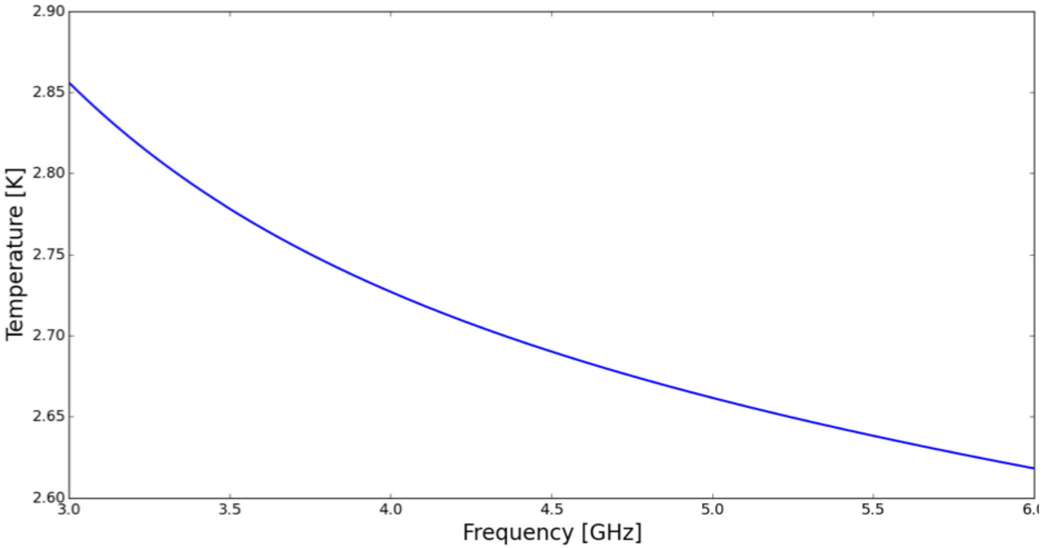
Beam assumed to be frequency independent

Calibration with hot/cold loads

Recorded spectrum is a temperature calibrated sum of power laws, of unknown form.

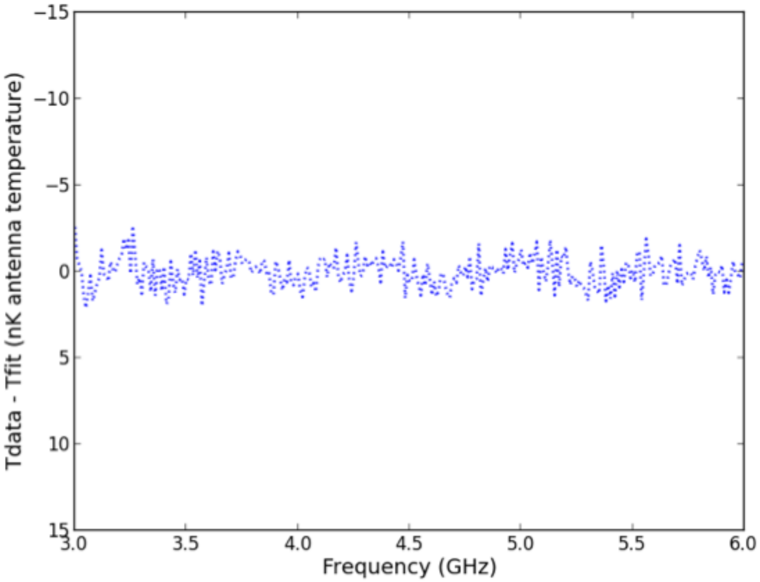

19
15
11
LST
(hr)
7
3
23
19
3.0
3.5
4.0
4.5
5.0
5.5
6.0
Frequency (GHz)
2.88
2.85
2.82
2.79
2.76
2.73
2.70
2.67
2.64
2.61
Temperature (K)

Simply polynomial fits would not separate the recombination lines



Residual on removing a 9th order polynomial fit to the mock data

A 10 nK amplitude ripple signal is expected



The function modeling the foreground + CMB must not also fit to the recombination line ripple.

Complete Monotone functions

- f(x) is complete monotone in $a \le x \le b$, where $a \ge 0$ and $b \ge 0$,
  if $(-1)^n \, d^n f(x)/dx^n \ge 0$ in the domain for every integer $n \ge 0$
- Function f(x) is positive and derivatives are alternately negative and positive
- Sum of complete monotones is also a complete monotone
- $f(x) = 1/(a + bx)^c$ is a complete monotone
- A power law with negative index, and a sum of such power laws, are complete monotones.

Maximally Smooth Function

- A *smooth* function that fits to log-T vs log-freq space
- n^{th} order polynomial in which all derivatives of order 2 and above have no zero crossings in the domain.
- This may be a parabolic function, but without any embedded ripples.
- Polynomial is written as a Taylor expansion about the lowest frequency in the band – so that the coefficients may be solved for sequentially and the function approximated to greater accuracy
- Till the residuals saturate and are the ripple component of recombination spectrum.

Analytic fitting function for a joint fit to foreground + CMB + recombination line ripple

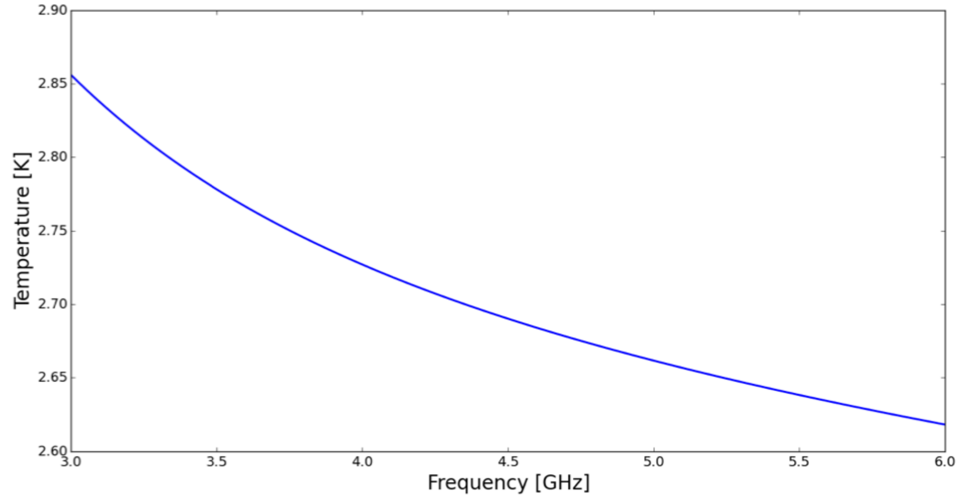
$$T(\nu) = \left(\frac{h\nu}{k}\right) / \left(e^{\frac{h\nu}{kp_0}} - 1\right) + p_1 T_{\mathrm{rec}}(\nu) + 10^{\sum_{i=0}^{n} [\log_{10}(\nu/\nu_0)]^i \, p_{i+2}}$$

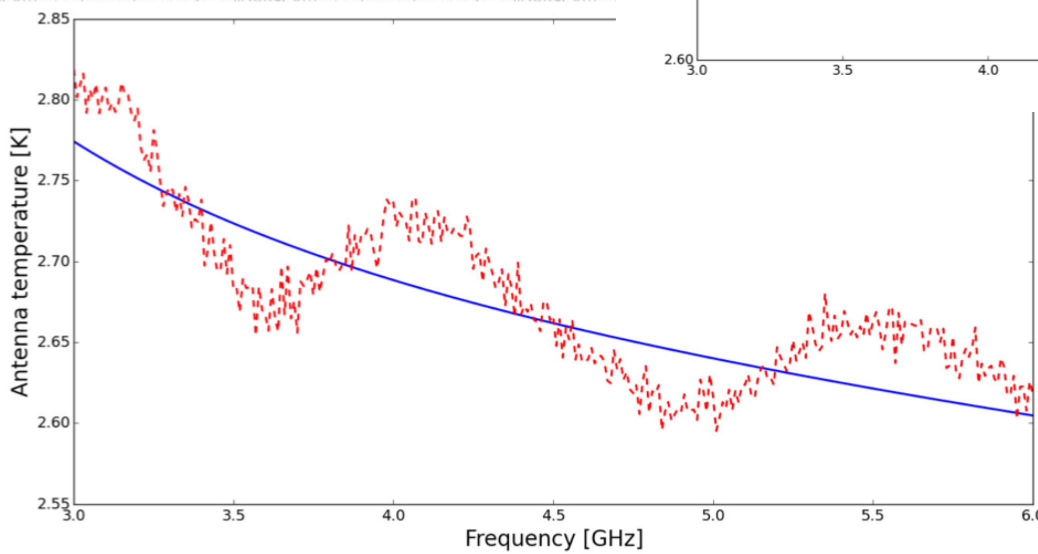
CMB term

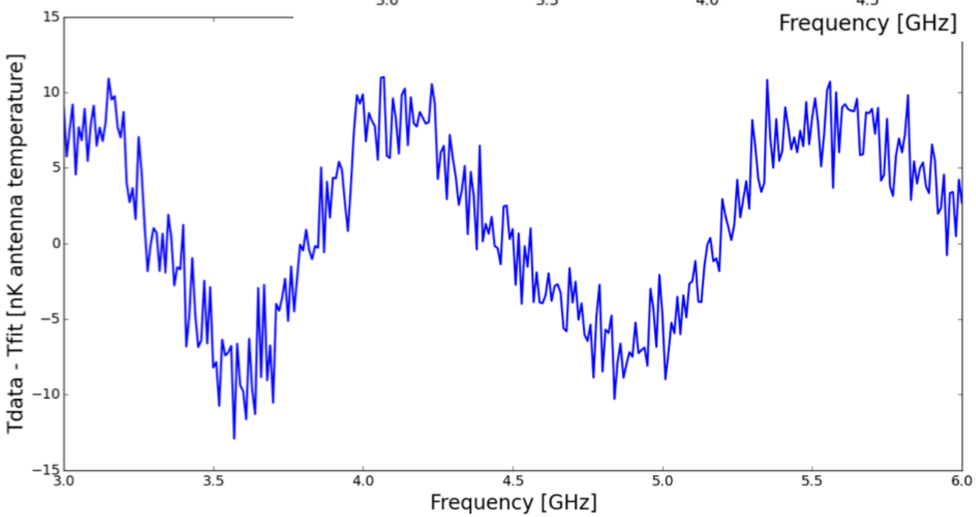
Recombination ripple term

Maximally smooth polynomial in log-T log-ν

Fit to mock spectra using a Maximally Smooth function + CMB





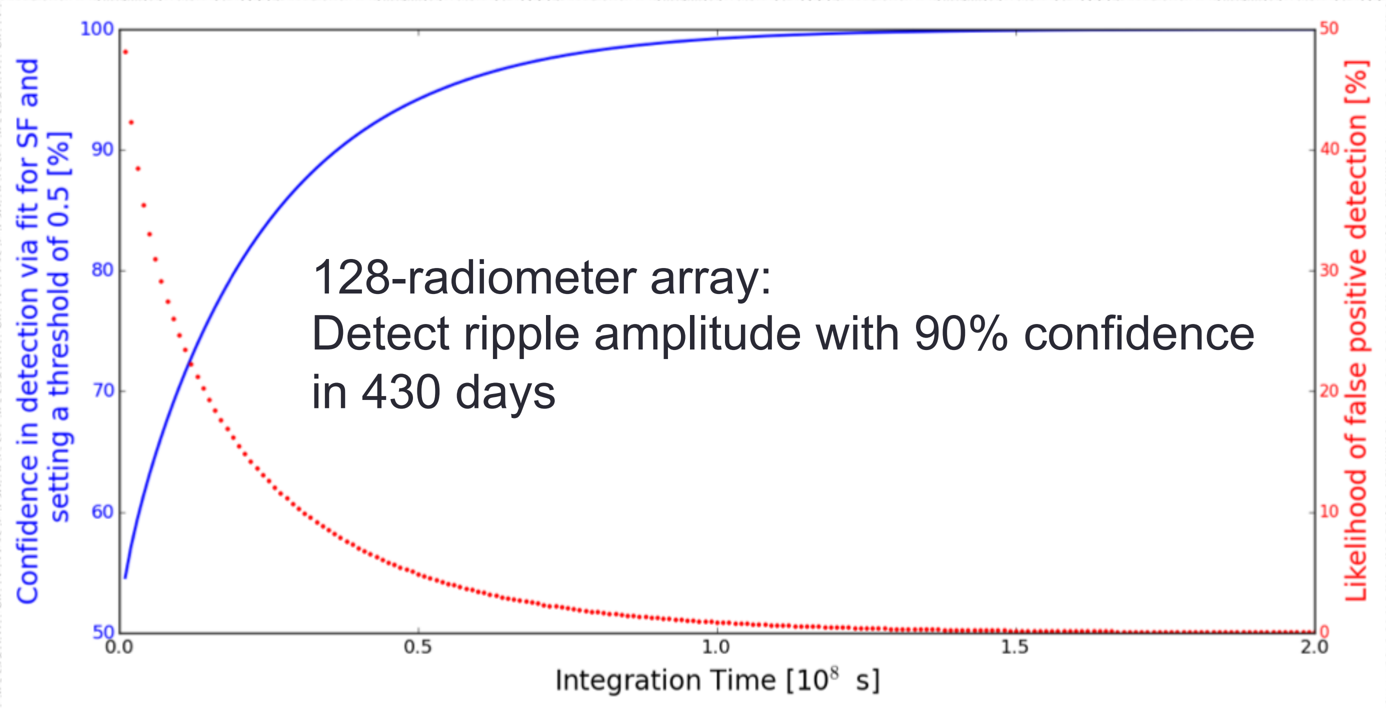


Fitting is robust:

Tested with mock spectra distributed in LST

Tested with spectra in bands 2.0-4.0, 2.5-5.0, 3.0-6.0 GHz

Detection confidence



- Fit to mock spectra generated with and without the recombination lines
- MCMC analysis to derive distributions in amplitude of recombination line ripple
- Derive confidence in detection & confidence in rejection of false positives versus integration time

Maybe first ask the simplest question!

- Does the observed spectrum contain the predicted template exactly?

- Bayes Factor $$BF = \frac{P(D|H_2)}{P(D|H_0)}$$

H_2: Hypothesis that the data has the ripple

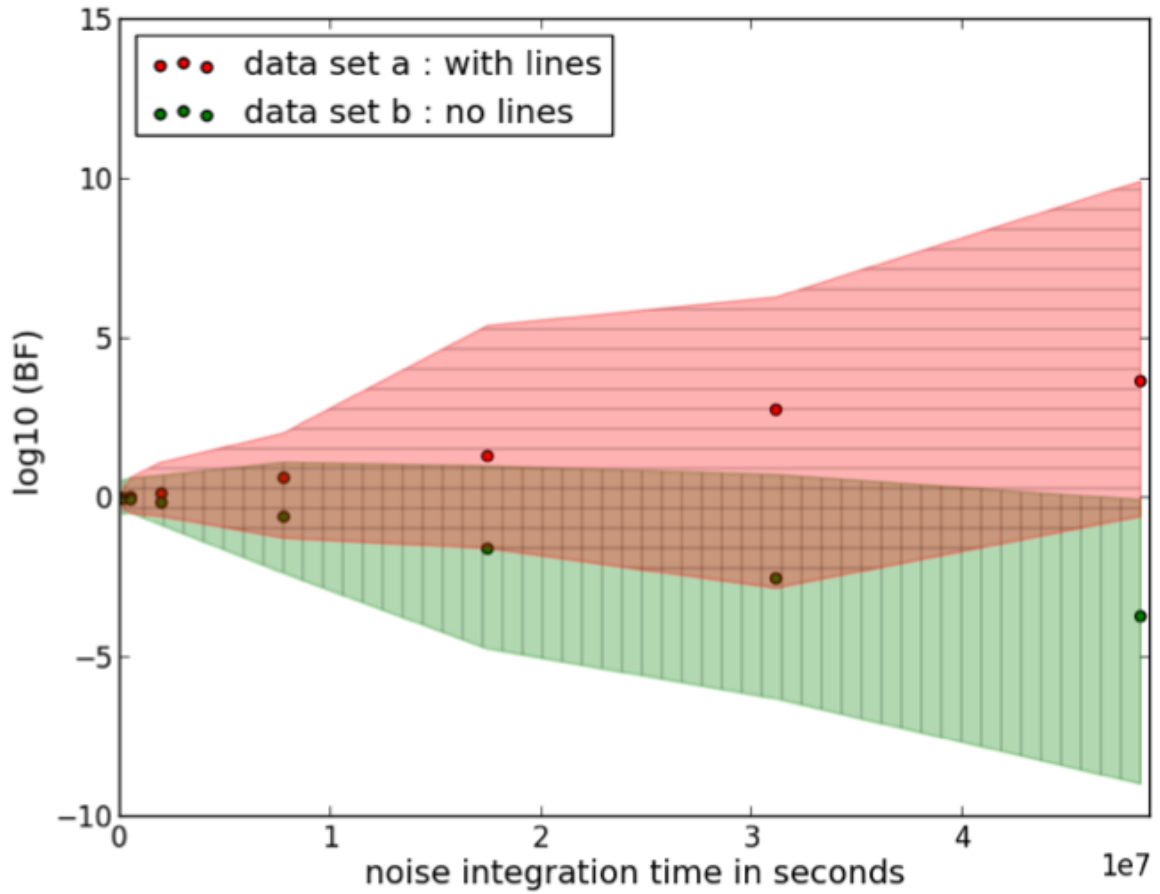
H_o: Hypothesis that the data does not have the ripple

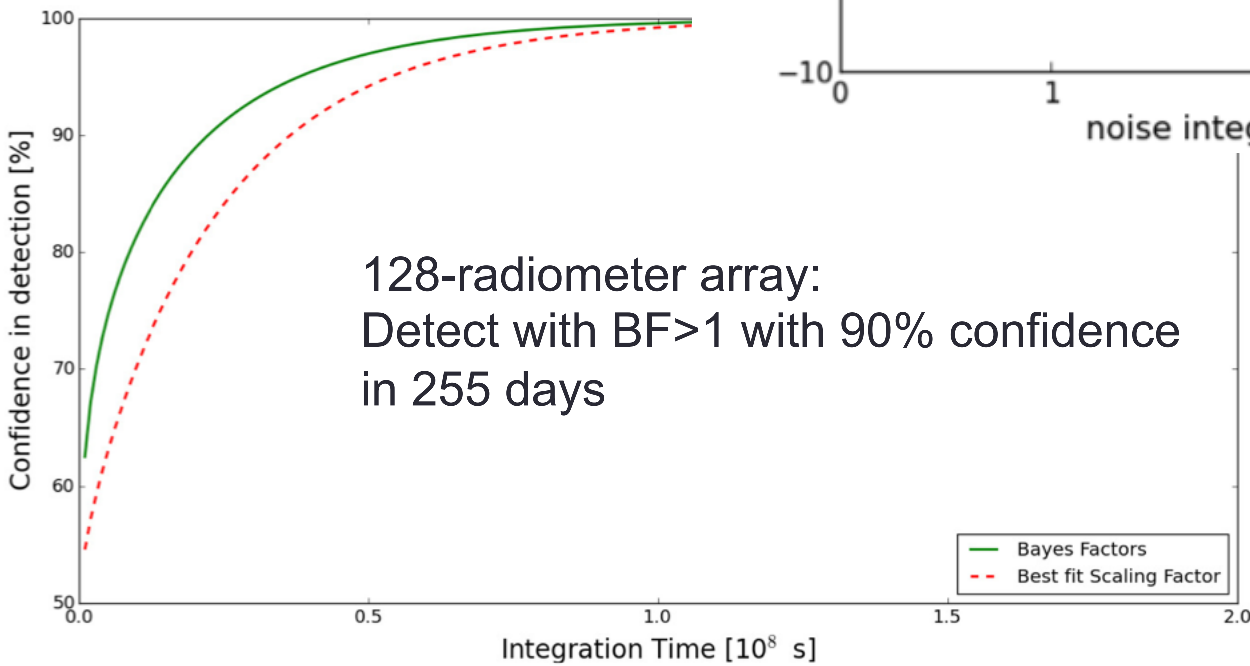
- Likelihood functions:

$$P(D\ |H_0) = \prod_{i=1}^{N} \frac{e^{-\frac{y_{res0}[i]^2}{2\sigma_0^2}}}{\sqrt{2\pi\sigma_0^2}}$$

$$P(D\ |H_2) = \prod_{i=1}^{N} \frac{e^{-\frac{y_{res2}[i]^2}{2\sigma_2^2}}}{\sqrt{2\pi\sigma_2^2}}$$

BF distributions





128-radiometer array:
Detect with BF>1 with 90% confidence
in 255 days

More work needed….

- Multi-path propagation of receiver noise within the signal path – via reflections at impedance mismatches – may cause confusing spectral ripples if the path delays are right (or wrong!)
- Mode coupling of sky structure into spectral structure – via frequency dependence in antenna pattern
- Mode coupling of sky linear polarization into spectral structure – via Faraday Rotation
- RFI: locations at high latitudes to avoid geostationary satellite downlinks
- GPS sources, sources with complex spectra