APSERa: Towards developing a ground-based CMB spectral distortion detection experiment

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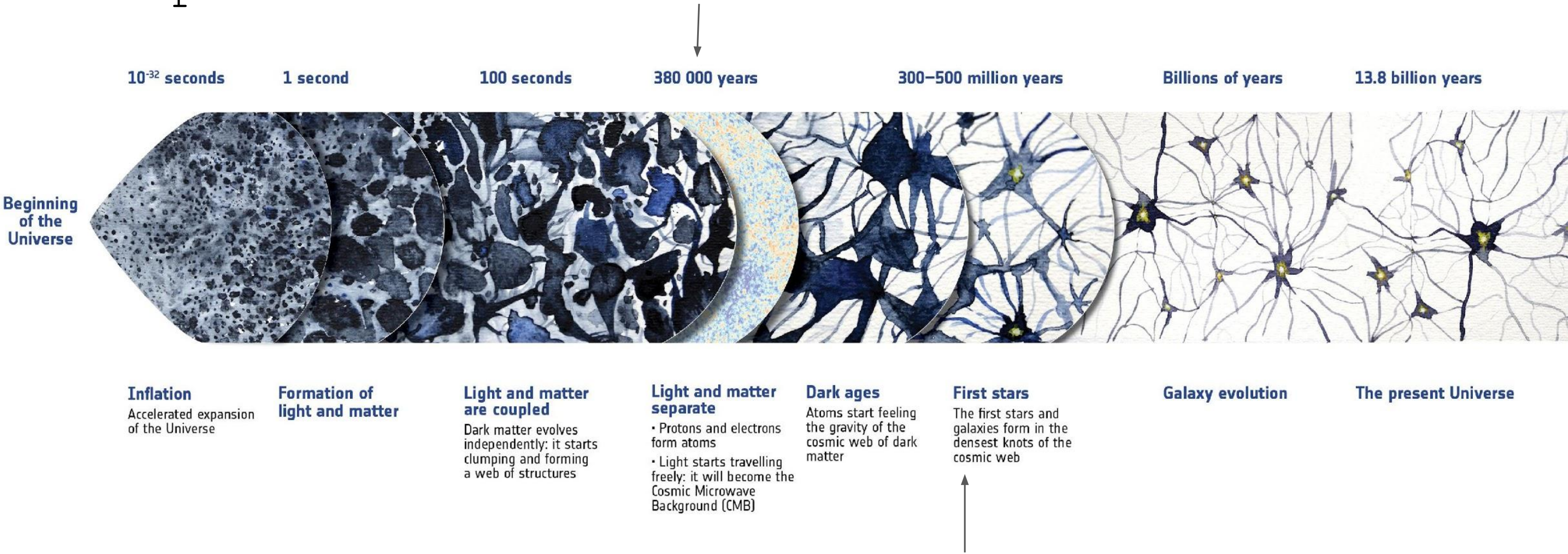
On behalf of the RRI CMB DISTORTION LAB

http://www.rri.res.in/DISTORTION/

1. Raman Research Institute
2. Lawrence Berkeley National Lab

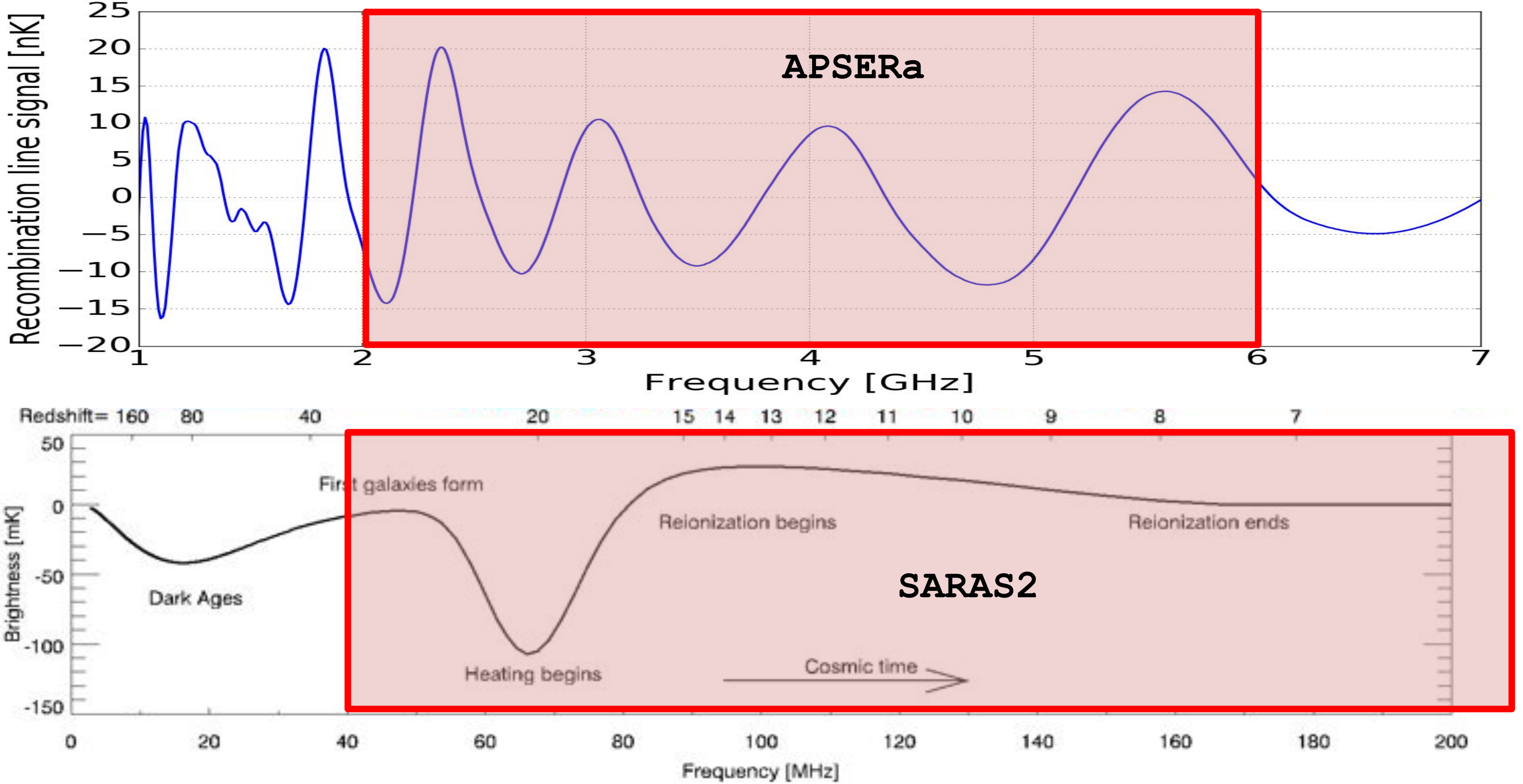
RRI

APSERa : Array of Precision Spectrometers for the Epoch of Recombination

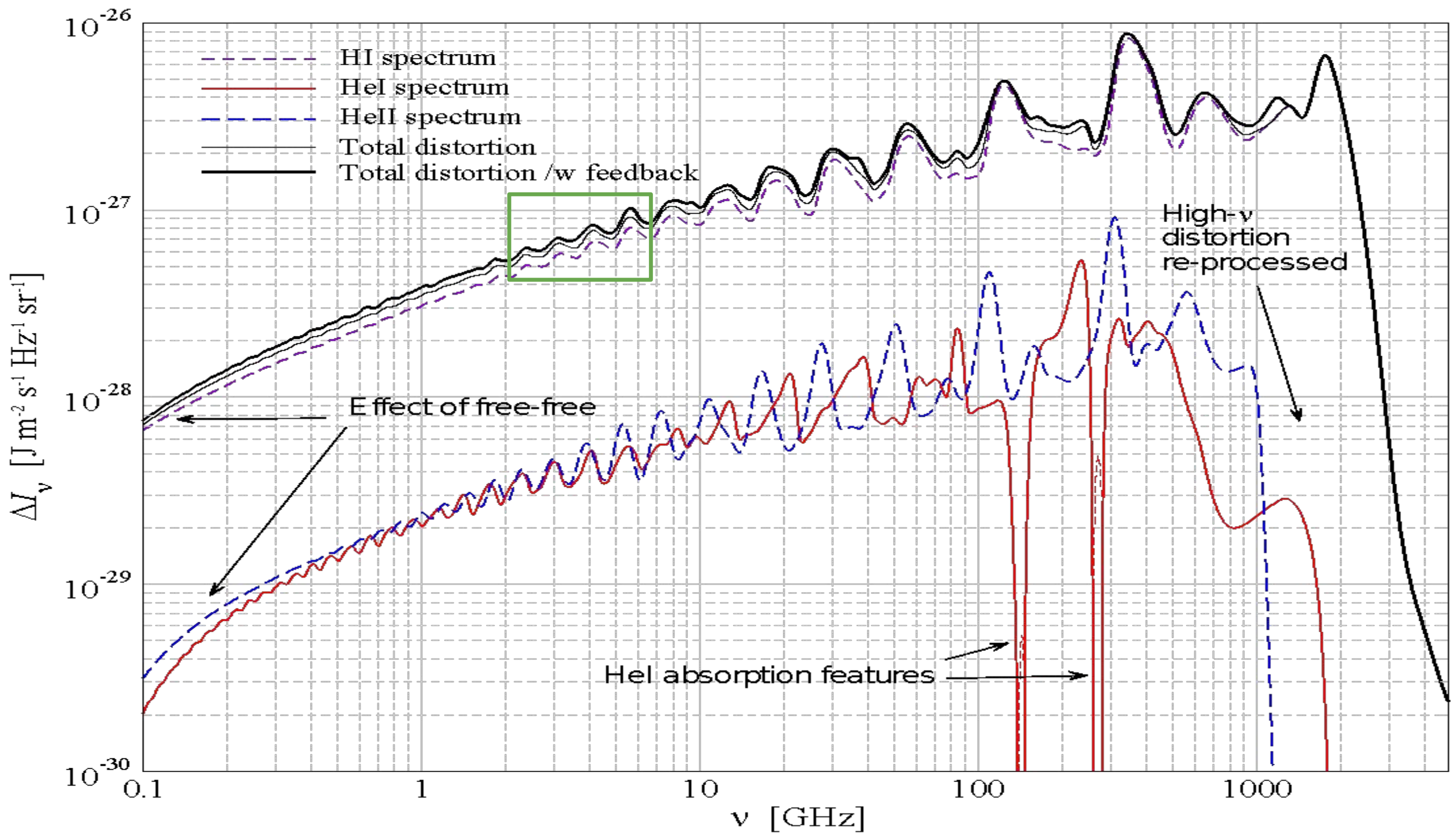


SARAS : Shaped Antenna measurement of the background RAdio Spectrum

CMB DISTORTION LAB FOCUS

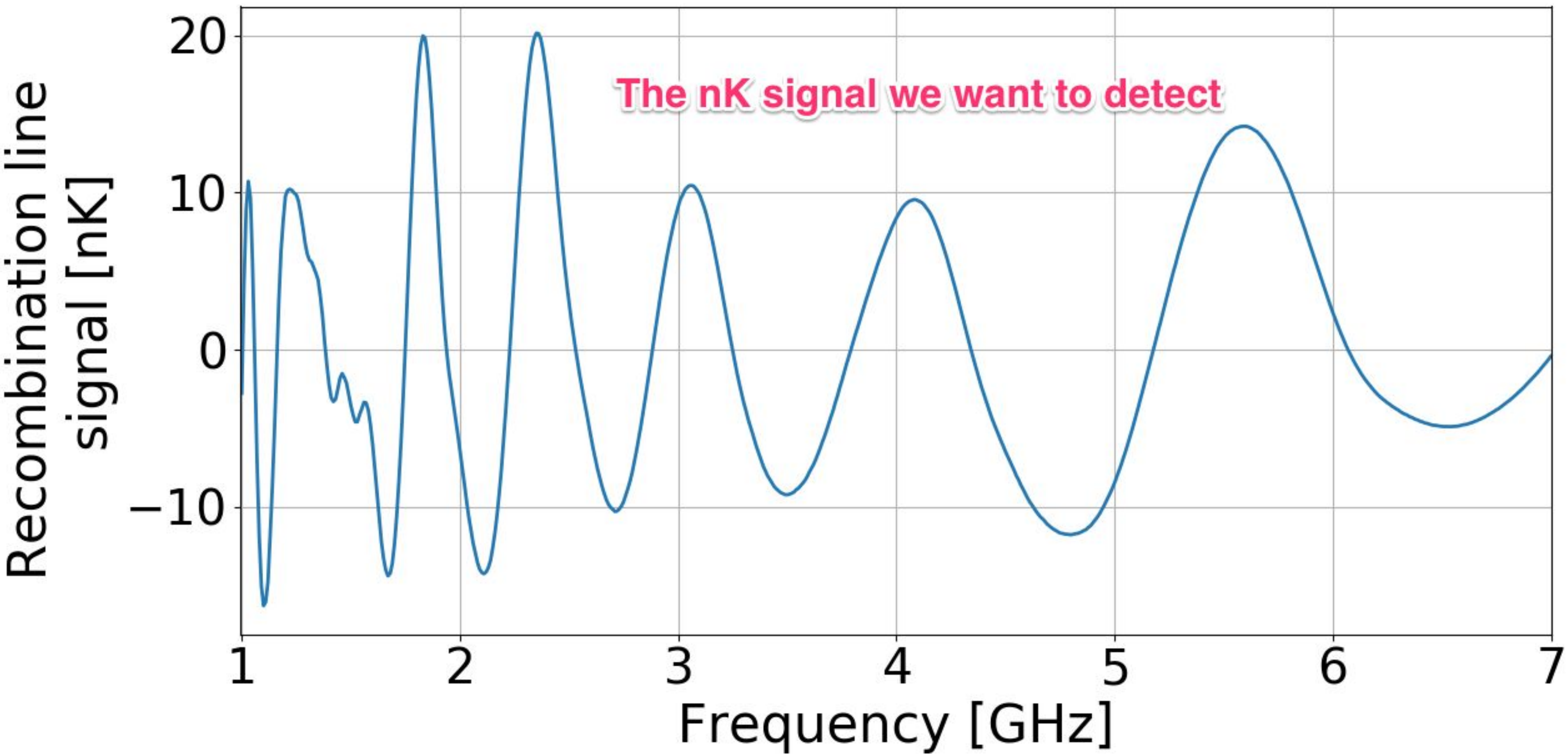


APSERa: What's the signal?



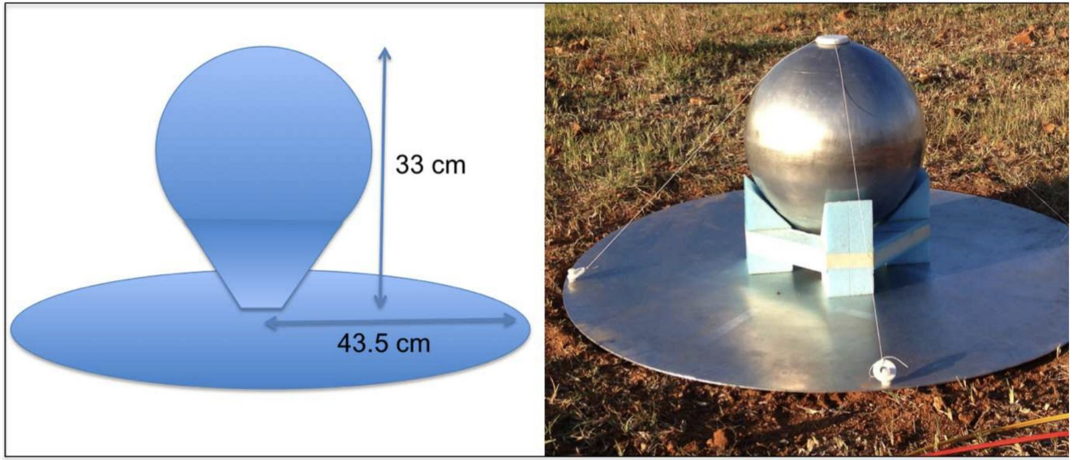
Adapted from: Chluba, J., & Ali-Haimoud, Y.,2016, MNRAS, 456, 3494

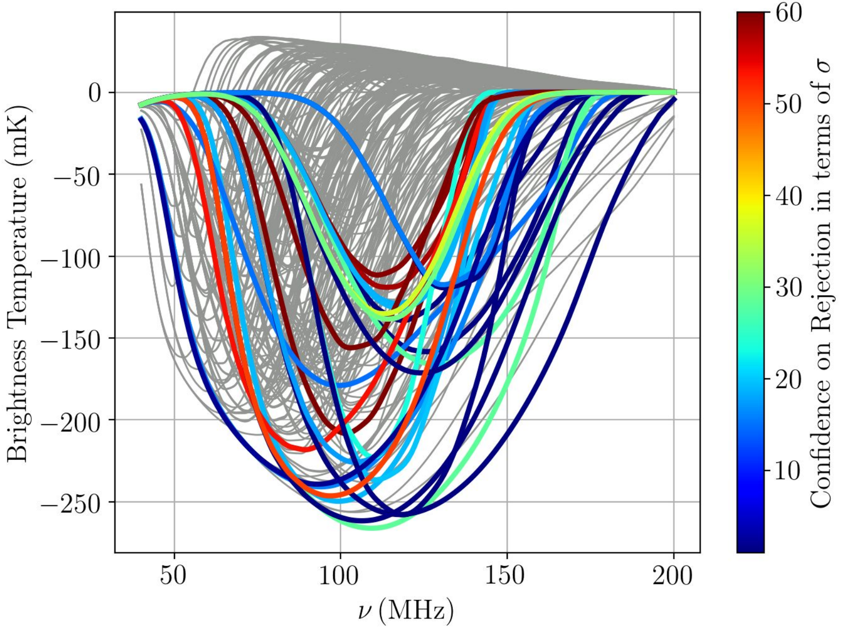
What APSERa will be looking for



Adapted from: Chluba, J., & Ali-Haimoud, Y.,2016, MNRAS, 456, 3494

SARAS2 : Shaped Antenna measurement of the background RAdio Spectrum 2





Singh et. al 2017
1710.01101

Singh et. al 2017
1711.11281

Basic scheme - Spectral **Radiometer**

****Not bolometer(s)**

Voltage Sampling Spectrometer

Antenna

Signal-processing

Analog receiver

+ Calibration

Digital receiver

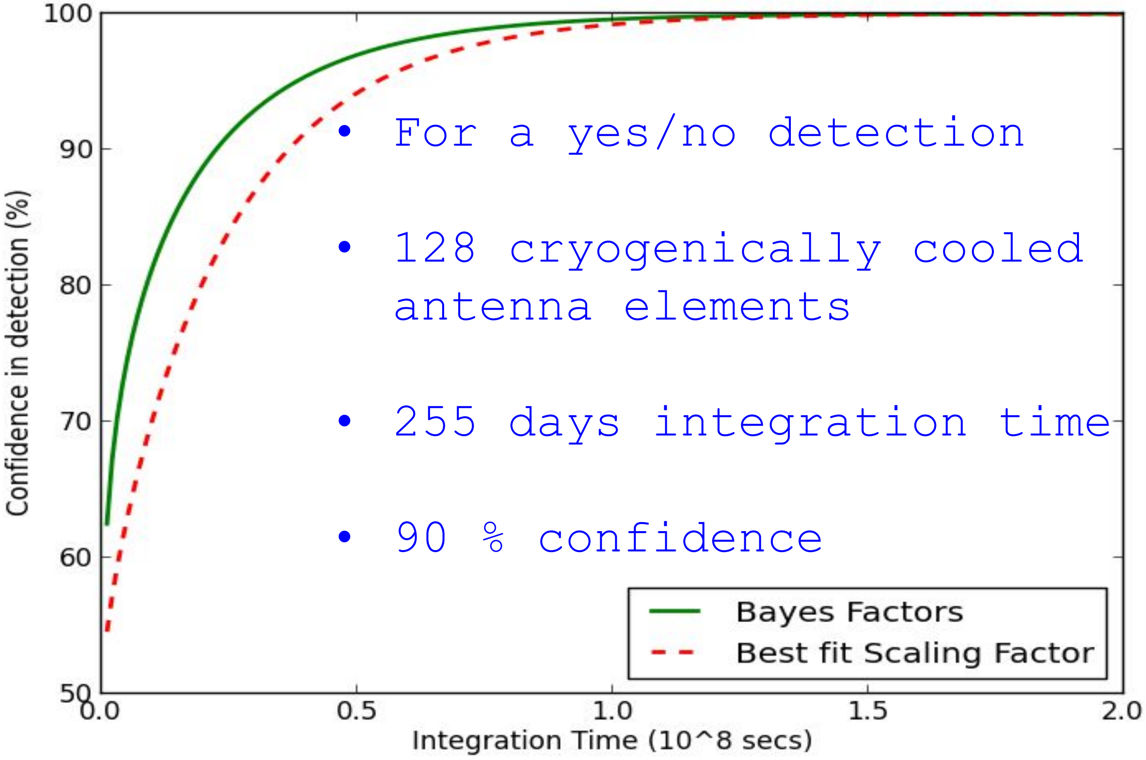
Record data

Data-Processing

Some *notes*

- Low-frequencies - RJ regime
- Don't worry about angular resolution: wide beam, more sky-power
- Global / average sky-spectrum (\ell = 0)
- High frequency resolution (~1000 channels): observing all channels all the time
- Rich spectral structure in signal
- Sky-drift shows up as increase in mean temp, and spectral index change
- APSERa: Single octave (avoids self-generated radio frequency interference from harmonics of system clocks and local oscillator frequencies)

Optimistic prediction: white noise limit



- For a yes/no detection
- 128 cryogenically cooled antenna elements
- 255 days integration time
- 90 % confidence

1. Ground based
   a. In-lab expertise
   b. Complement space-based efforts
2. Smooth foregrounds
   a. Simulation demonstrated
   b. Non-smoothness is science
3. ‘Clean’ site
   a. Pole good candidate
4. Smooth bandpass

** post COSMOSPEC: Now even better!

1501.07191

What’s the challenge

- Foregrounds
  - Dynamic Range
  - Separation
- Systematics
  - Noise
  - Shapes
- RFI

Design principles

- Design instrument to have ‘Smooth’ bandpass
- We use **Maximally Smooth functions** to parameterize smoothness
- Each component is custom designed to have MS transfer function
- Check at each stage of integration that MS criteria is satisfied

MS functions:

- Do not allow zero crossings in higher order derivatives
- Polynomial in log(ν) and log(T) space

$$10^{\Sigma p[i]*\log(\nu/\nu 0)i}$$

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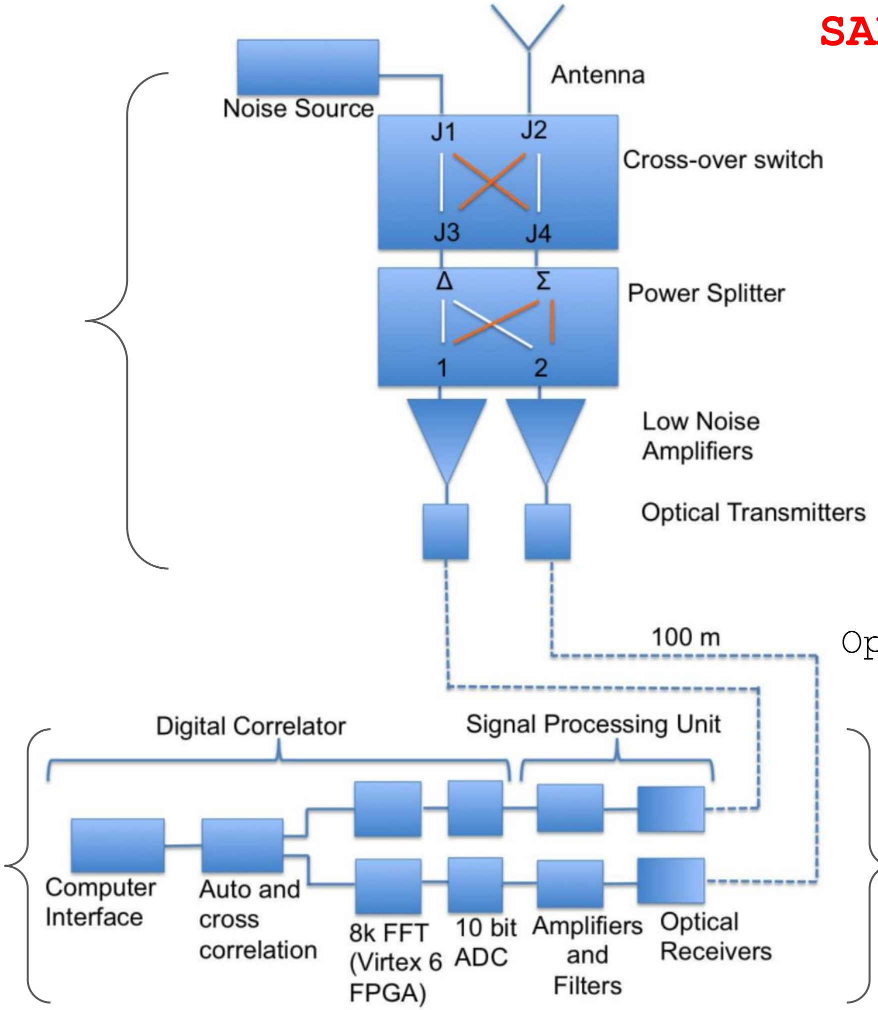
SARAS2 receiver schematic



Toggle path

Splits power

Sits beneath antenna ground in a faraday cage

Optical isolation

Signal conditioning, digitization, correlation

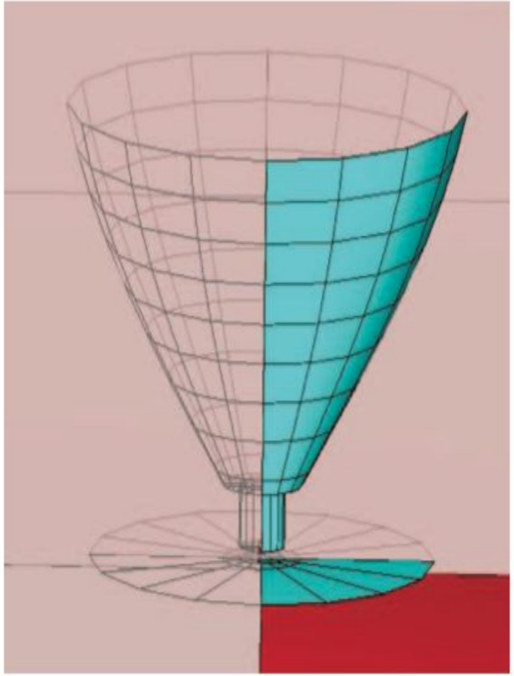
SARAS2 results have rejected 10% of reionization models (Cohen et al. 2017 atlas of templates) all with inefficient heating of gas by primordial X-ray sources and rapid reionizaion

Singh et.al, 2017
arXiv: 1703.06647
arXiv: 1711.11281
arXiv: 1710.01101

Antenna requirements

- Frequency independent
  - Else couples spatial to freq structure
- Smooth return loss
  - Else introduces ‘shapes’ in measured spectrum
- Efficient
  - Else deteriorates SNR

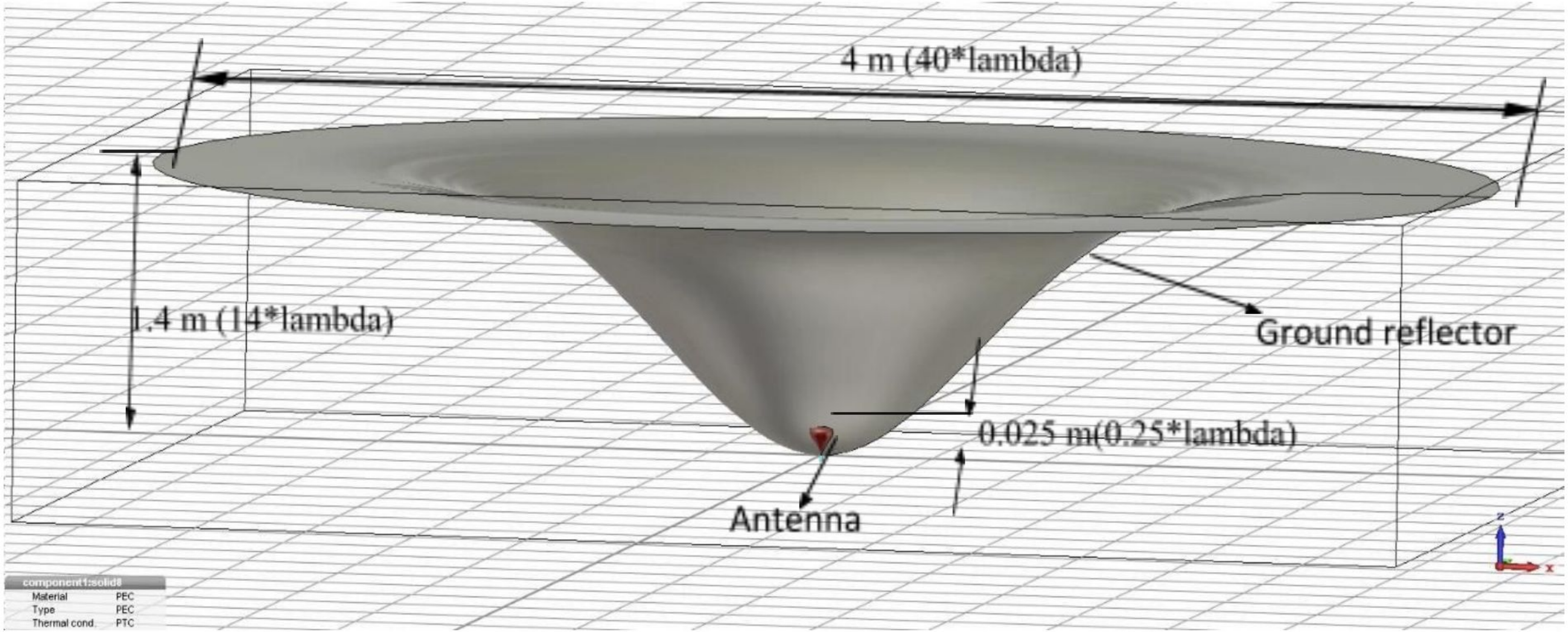
Antenna



Raghunathan et.al 2015 IEEE-APS (APWC)

Courtesy: A Raghunathan

Antenna



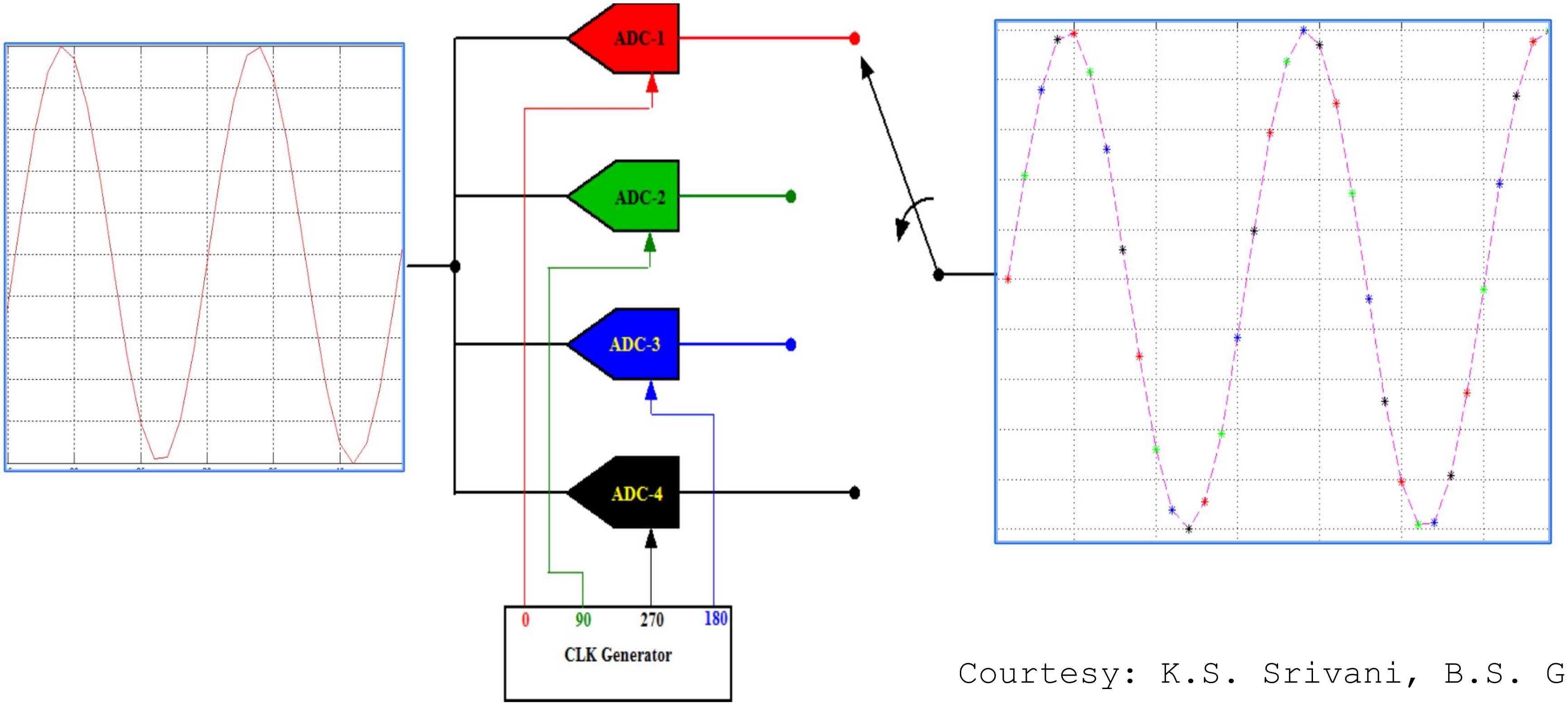
Design frequency 3 GHz, lambda = 0.1 m

Courtesy: Kavitha K

Analog system

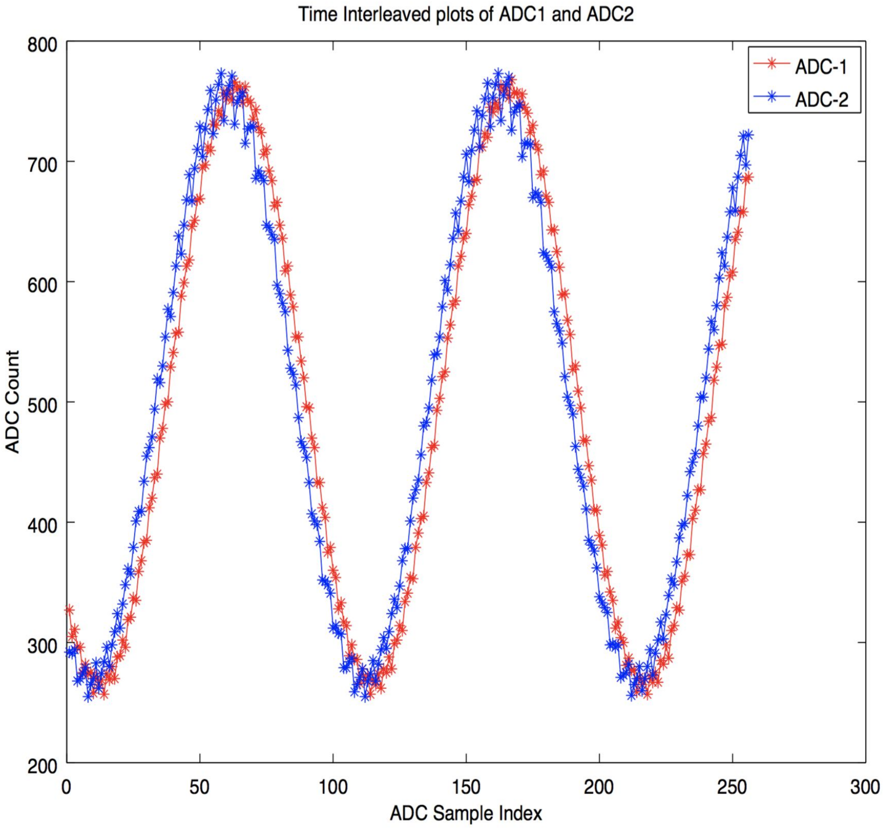
- Short cable lengths
- Move to optical early
- To operate in receiver noise dominated mode reaching to reach thermal noise dominated
- Batteries (no SMPS / AC-DC)
- Prototype v1 will have room-temperature amplifier

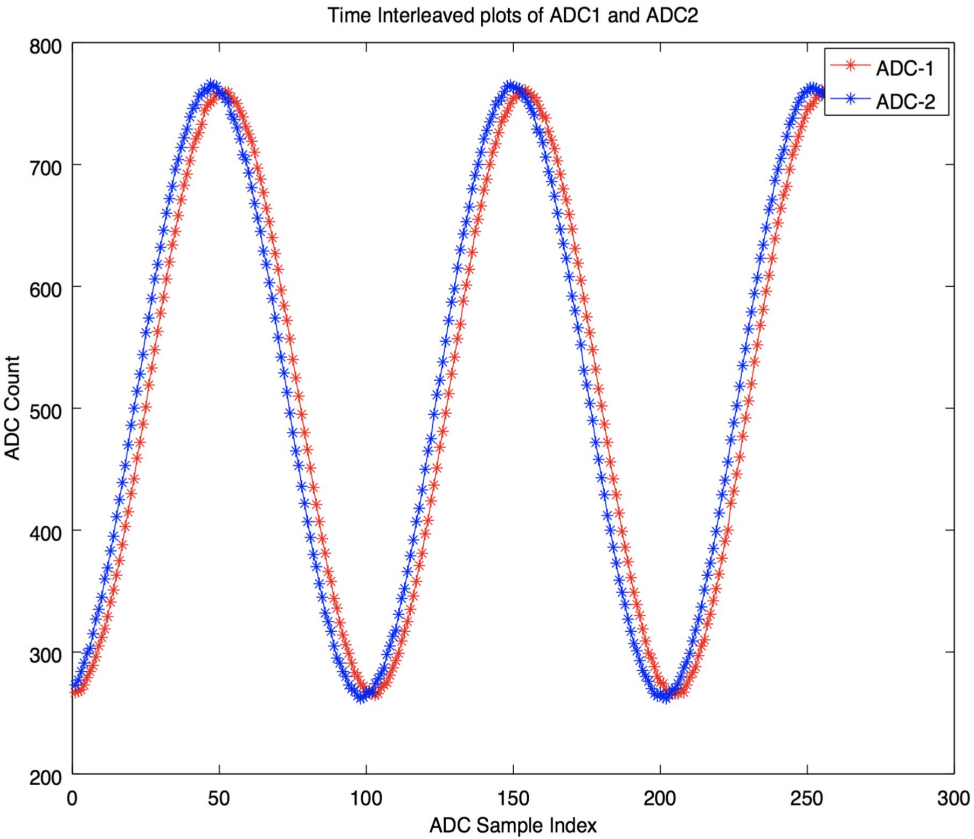
Digital system



Courtesy: K.S. Srivani, B.S. Girish

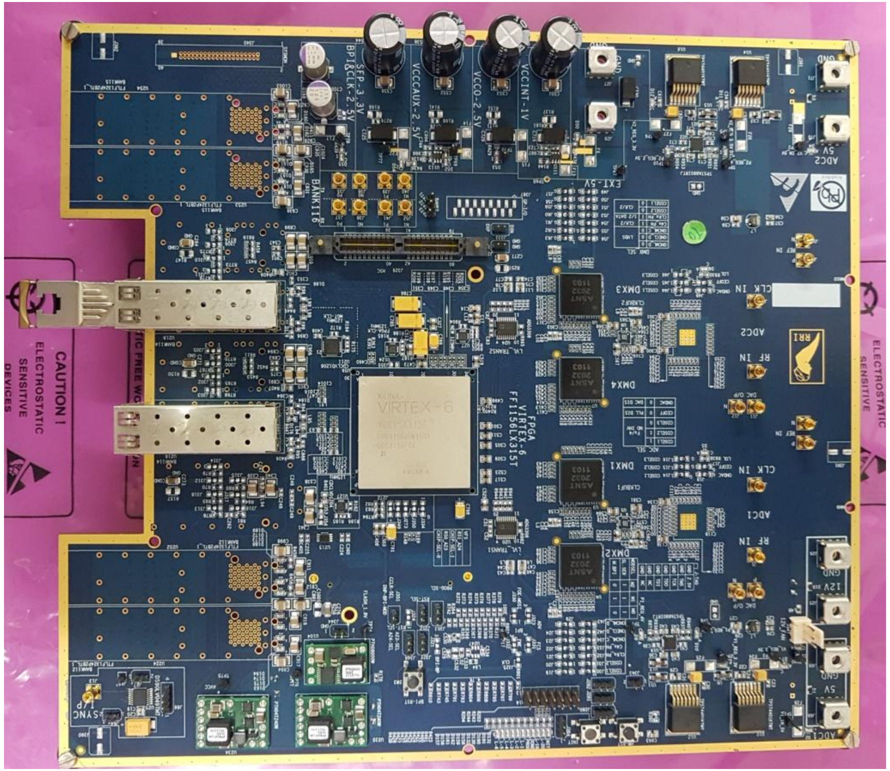
ADC calibration : critical for interleaved sampling





Move towards direct samping

- **SPARC -Spectrometer for Precision meAsurement of signals from the Recombination epoCh**
- Demonstrated operation of the two ADSANTEC ADCs on SPARC at 4Gsps using optimised VHDL firmware to grab high-speed data from ADCs.
- Currently, evaluation of the optimised VHDL firmware to configure the SPARC in correlation spectrometer mode is in progress. In this mode 1024-point autocorrelation spectra(from the two ADCs) and the cross-correlation spectrum are computed in real-time.



Courtesy: K.S. Srivani, B.S. Girish

**** Long laundry list, keep checking off as we go**

Prototype steps

- Demonstrate integrability of custom designed antenna, analog, and digital receiver
- Lab characterization of system characteristics - in particular bandpass calibration

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- Field readiness

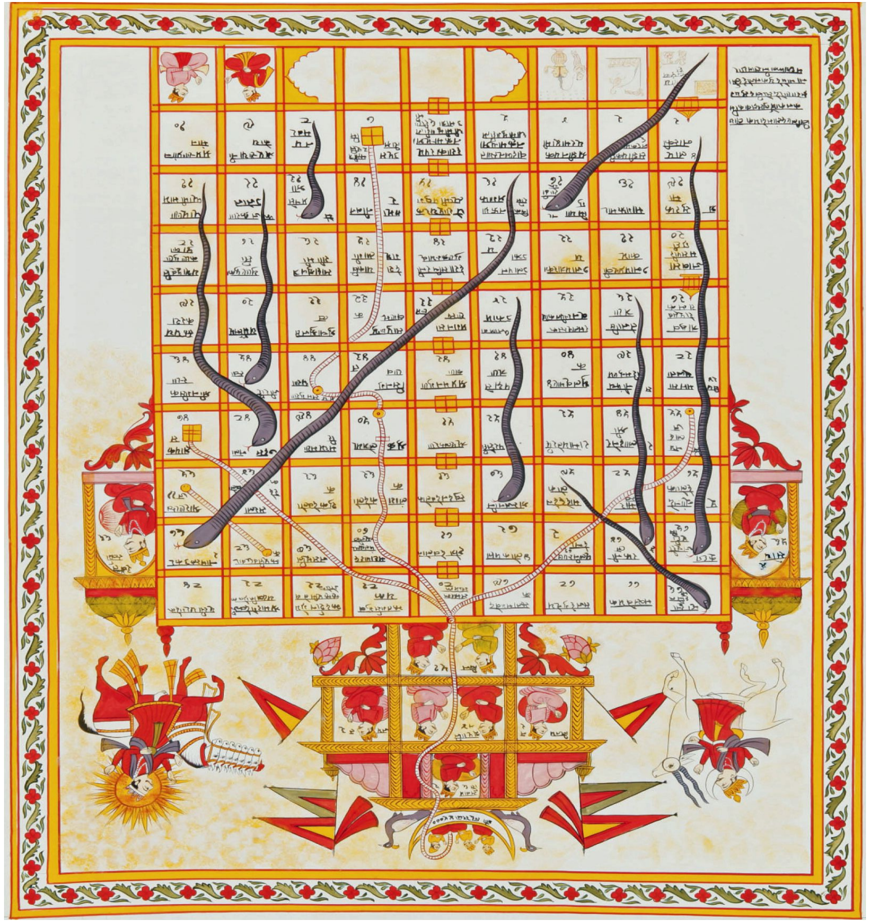
- Optimize for scalability

What’s keeping us up at night

- **Additives**
  - 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!)
  - With SARAS2 we have been able to achieve smooth receiver transfer function at 1 part in 10000 level including reflections!
  - Getting to 1 part in 1e9 -- ?????

Rungs on the ladder/snake

- Atmosphere ?
- Galactic recombination lines?
- Polarization to temperature leakage ?
- Intrinsic foreground spectral structure ?



People

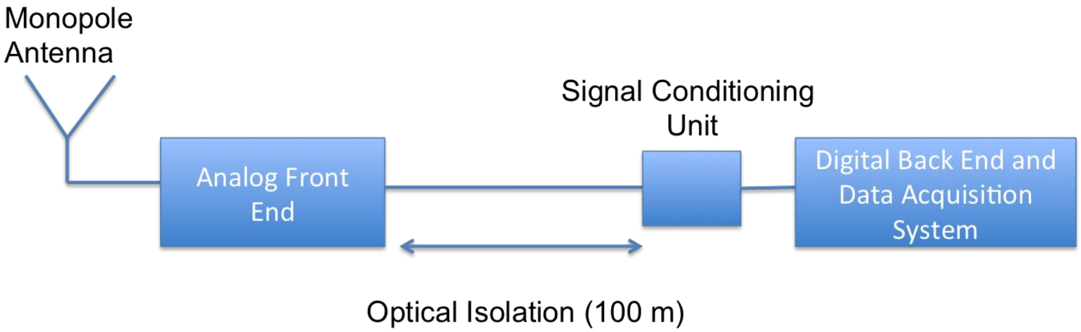
- Ravi Subrahmanyan (RRI)
- N Udaya Shankar (RRI)
- Jens Chluba (U.Manchester)
- Jishnu Nambissan T (RRI)
- Saurabh Singh (RRI)
- Srivani K S (RRI)
- Girish B S (RRI)
- Somashekar R (RRI)
- Raghunathan A (RRI)
- Kavitha K (RRI)
- Shruti B (RRI)
- Magendran S (RRI)

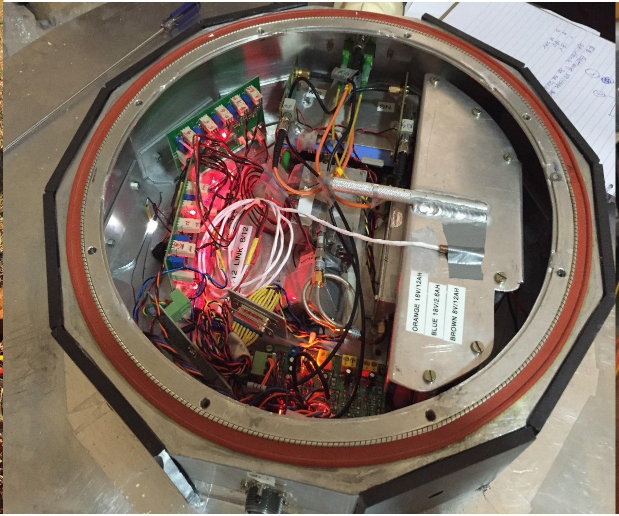
THANK YOU

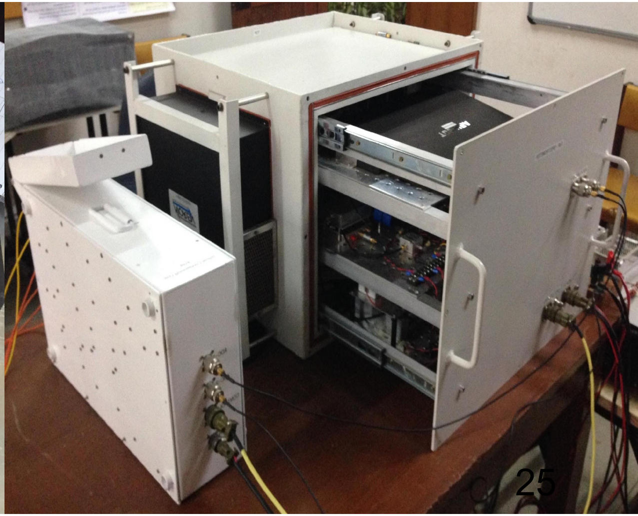
BACKUP SLIDES

SARAS2 system

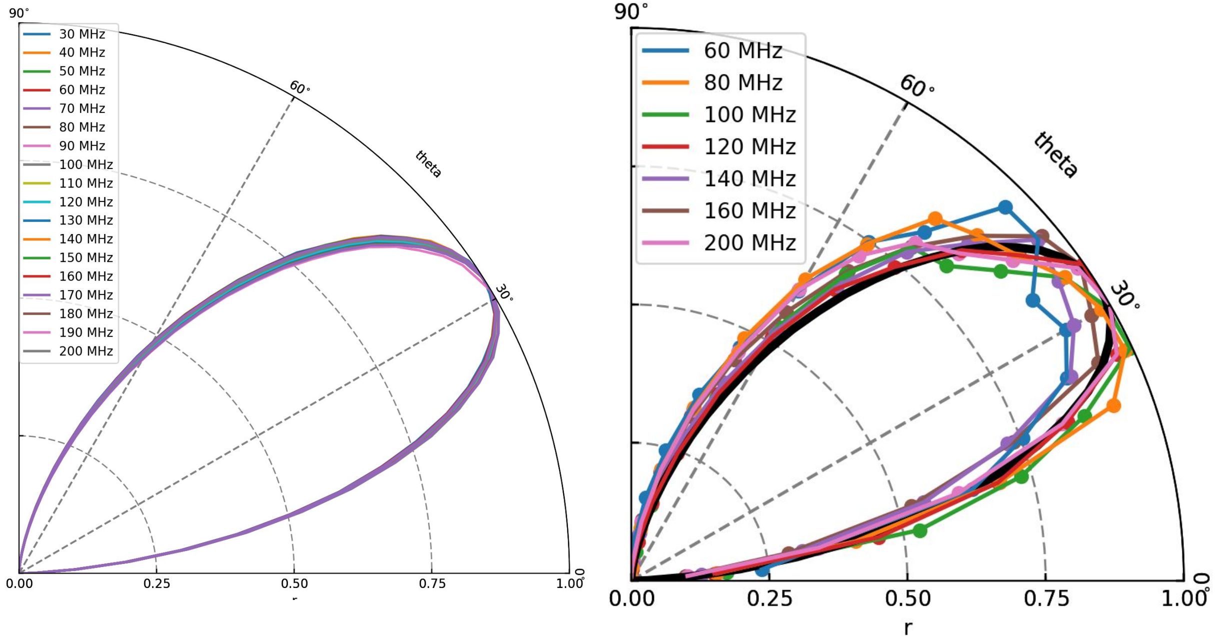
Singh et. al 2017
1710.01101





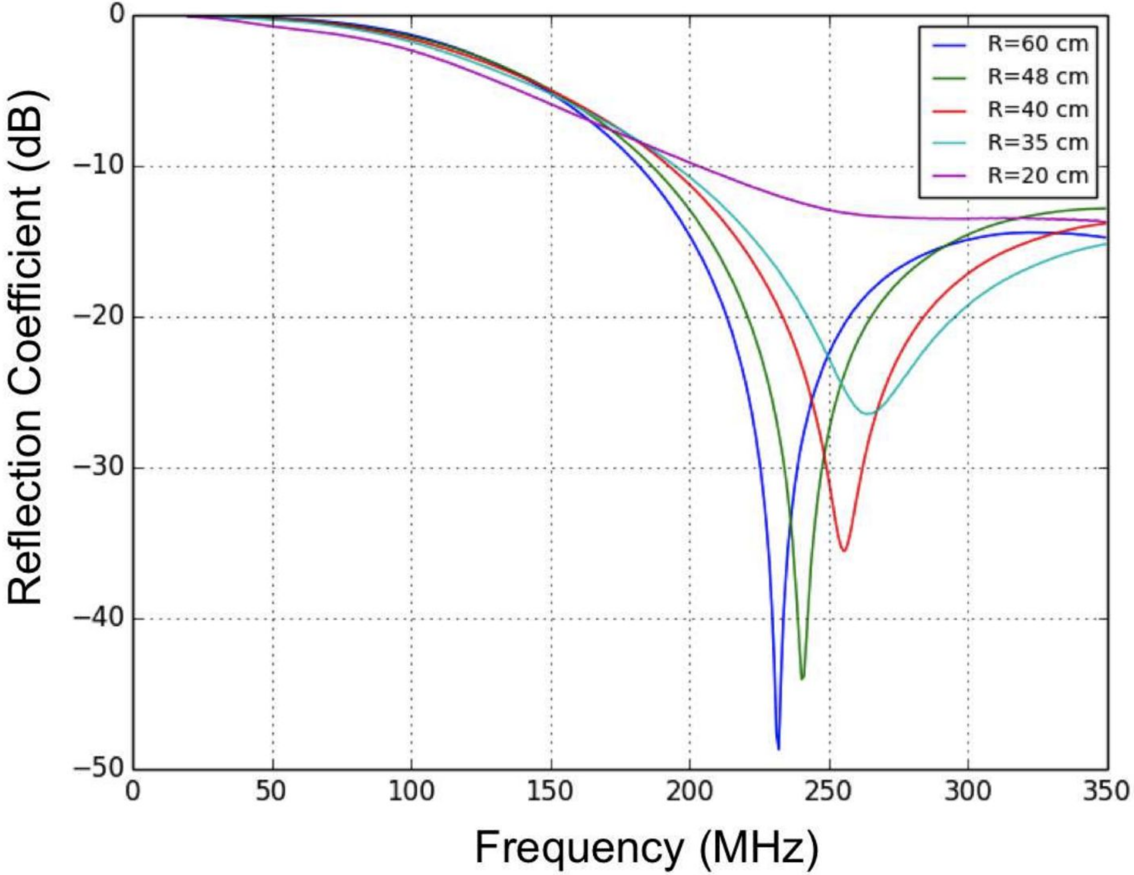


SARAS2 beam



Singh et. al 2017
1710.01101

SARAS2 reflection coefficient



Singh et. al 2017
1710.01101

Adopting an inadequate model would result in systematic residuals to the fit to foregrounds+systematics. The least squares fit would attempt to maximize the correlation (or anti-correlation) of these residuals to the 21-cm template under consideration so that including a scale factor times the 21-cm template, the overall residuals would be a minimum. Consequently, the unmodeled foreground+systematics might partially or wholly mimic the 21-cm signal—thus yielding a false positive—or partially or wholly cancel a true 21-cm signal in the data, thus yielding a false negative. In these circumstances small fit residuals might suggest excellent fits with low formal statistical errors in the fitted scale factor a; however, the errors are obviously underestimates since the unmodeled systematics are not considered in the error computation.

1711.11281v1

Experiment	Frequency Range	Antenna	Presence of Balun	Calibration Scheme	Type of Spectrometer
SARAS 2	40 – 200 MHz	Spherical Monopole antenna	No	Noise source coupled into system via power combiner without Dicke switch	Cross-correlation
EDGES	100 – 200 MHz (High-Band) 50 – 100 MHz (Low-Band)	Blade Antenna	Yes	Switching between antenna and noise source	Auto-correlation
BIGHORNS	70 – 200 MHz	Conical log-spiral antenna	Yes	Switching between antenna and reference load	Auto-correlation
SCI-HI	40 – 130 MHz	HIbiscus antenna	Yes	Switching between antenna, 50 Ω, 100 Ω and short termination	Auto-correlation
LEDA	40 – 85 MHz	Dual-polarized dipole antenna	Yes	Switching between antenna and noise source combined with cross-correlation from other antennas for antenna gain and beam estimation	Auto-correlation

Singh et. al 2017
1710.01101

$$T_a - T_{ref0} = \frac{P_{off}}{(P_{cal} - P_{off})} \times T_{cal}.$$

Patra. al 2013
1211.3800