SAFARI: A differential approach to probe the cosmological sky-averaged 21-cm signal

30th Anniversary of the Recontres du Vietnam
Windows on the Universe
Astro/Cosmo Plenary Session #1
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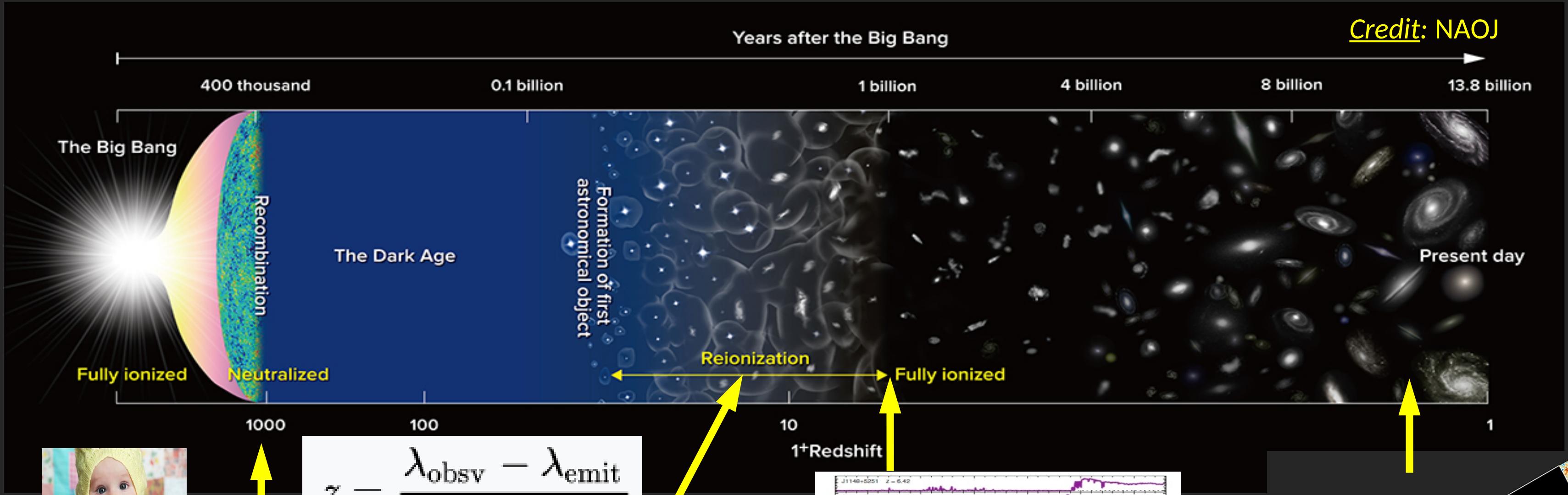
Outline

I. Background
    i. High-redshift universe
    ii. Global 21-cm Experiments
        - Conventional Total-power Experiments
        - EDGES & SARAS Results
    iii. Experimental Challenges

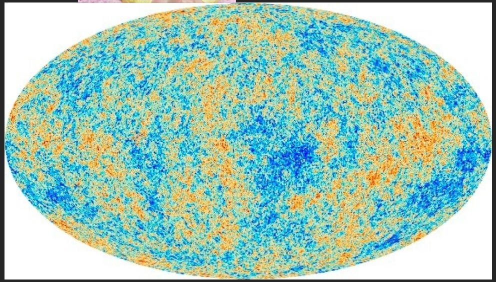
II. SAFARI – Scaled Antennas & Differential Measurement Approach
    i. General Concept & Formalism
    ii. Experiment design and Observation strategy

Early Universe (~400,000 years after the Big Bang)



Credit: NAOJ

$$z = \frac{\lambda_{\rm obsv} - \lambda_{\rm emit}}{\lambda_{\rm emit}}$$

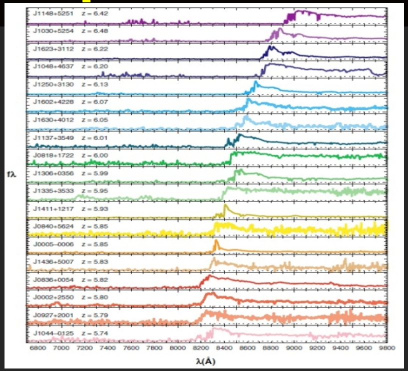


Credit: Planck Collaboration (2016)

CMB (z ~ 1,100)

Credit: Naidu et al. (2022)

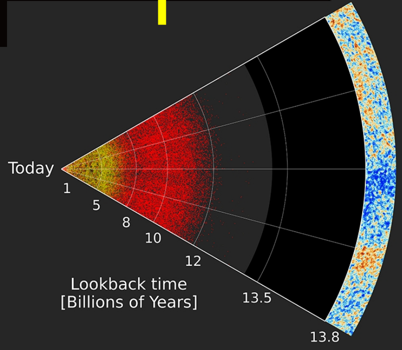
JWST (z ~ 12)



Credit: Fan et al. (2006)

Gunn-Petterson Troughs

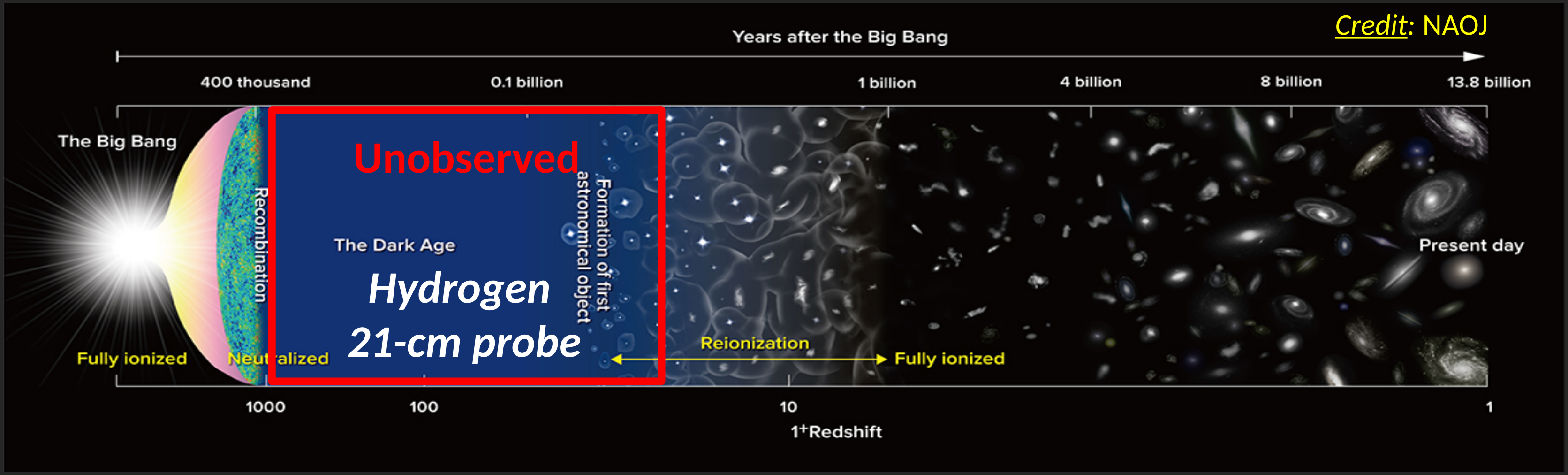
EoR ends (z ~ 6-10)



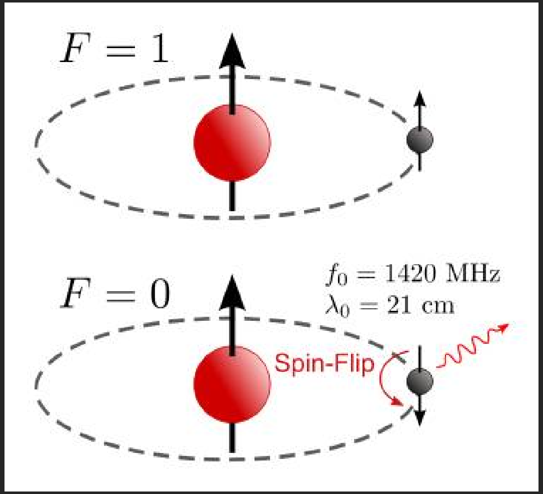
Credit: *Anand Raichoor*

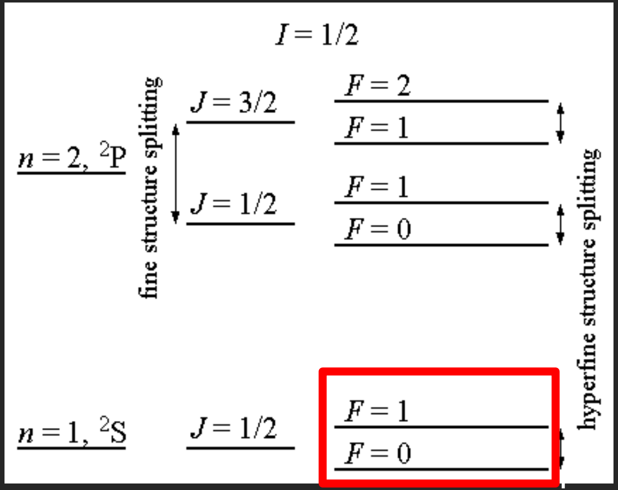
SDSS (Red = quasars, yellow = galaxies)

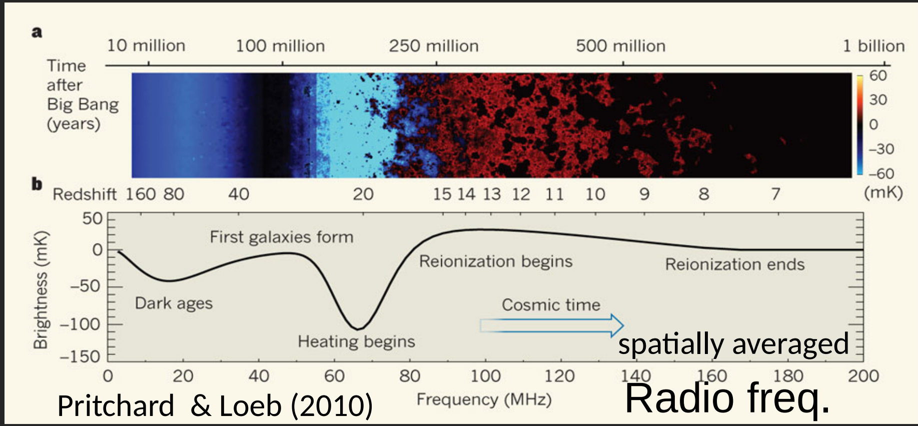
Neutral Hydrogen Spin-flip 21-cm Probe

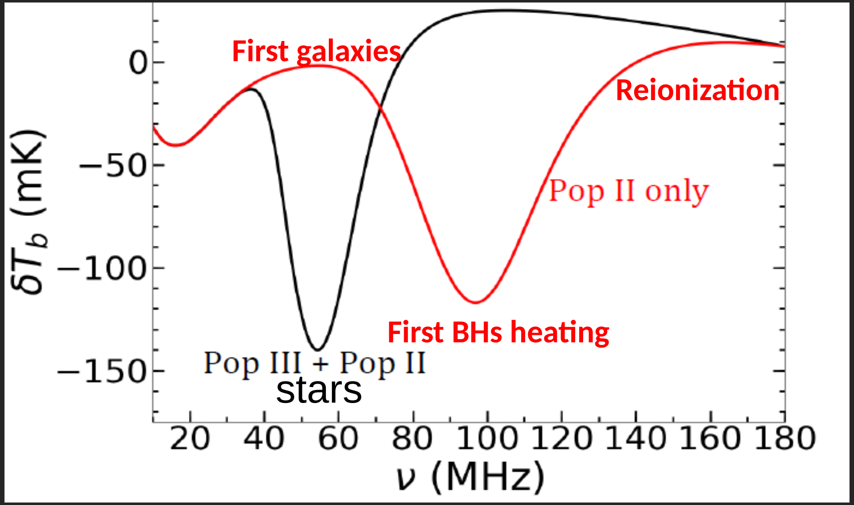


- No observable bright sources
- Abundance of neutral hydrogen in the early time

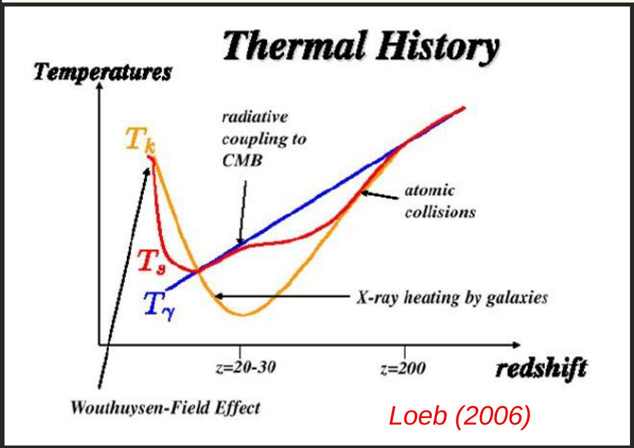








Credit: Burns et al. (2018), *ASR 49:433-450*



$$T_S^{-1} \approx \frac{T_\gamma^{-1} + x_c T_K^{-1} + x_\alpha T_\alpha^{-1}}{1 + x_c + x_\alpha}$$

Wouthuysen-Field Effect

Couple 21-cm photons to Ly-alpha

Ionization history (Neutral Hydrogen density)

CMB

$$\delta T_{\mathrm{b,21cm}}(z) \approx 27\bar{x}_{\mathrm{HI}} \left(\frac{\Omega_{b,0}h^2}{0.023}\right)\left(\frac{0.15}{\Omega_{m,0}h^2}\frac{1+z}{10}\right)^{1/2}\left(1 - \frac{T_\gamma}{T_S}\right)\ \mathrm{mK},$$

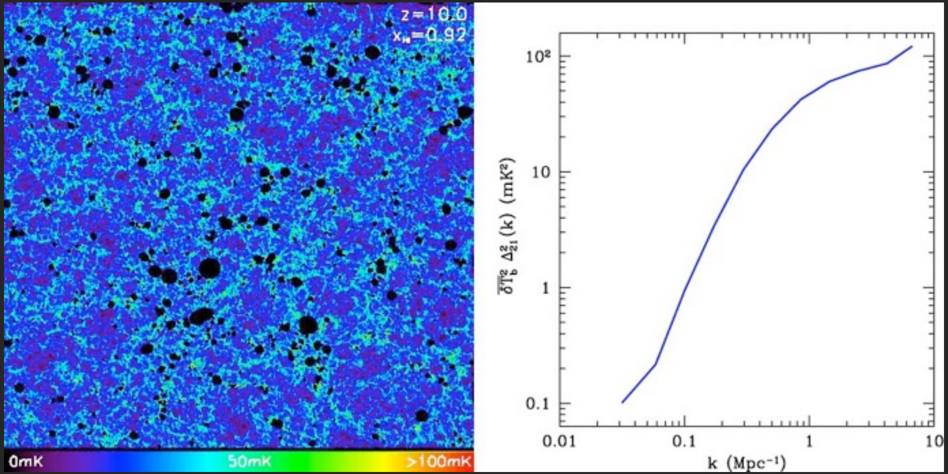
Both are function of redshift z

Thermal history (Spin temperature)

Approach 1: Interferometric EoR 21-cm Experiments

21cmFAST simulation

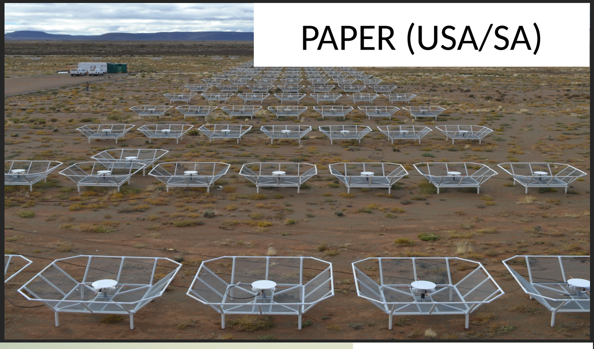
Credit: Mesinger et al. (2011)



Spatial fluctuations of 21-cm emission

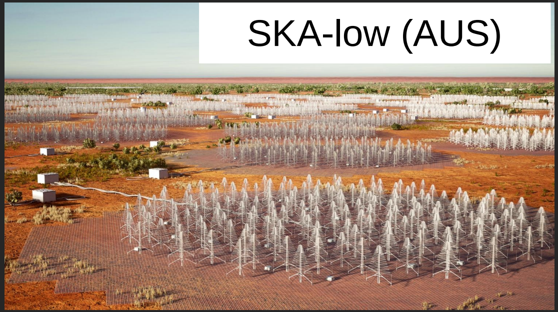
Power spectrum of spatial fluctuations

HERA (USA/SA)



PAPER (USA/SA)

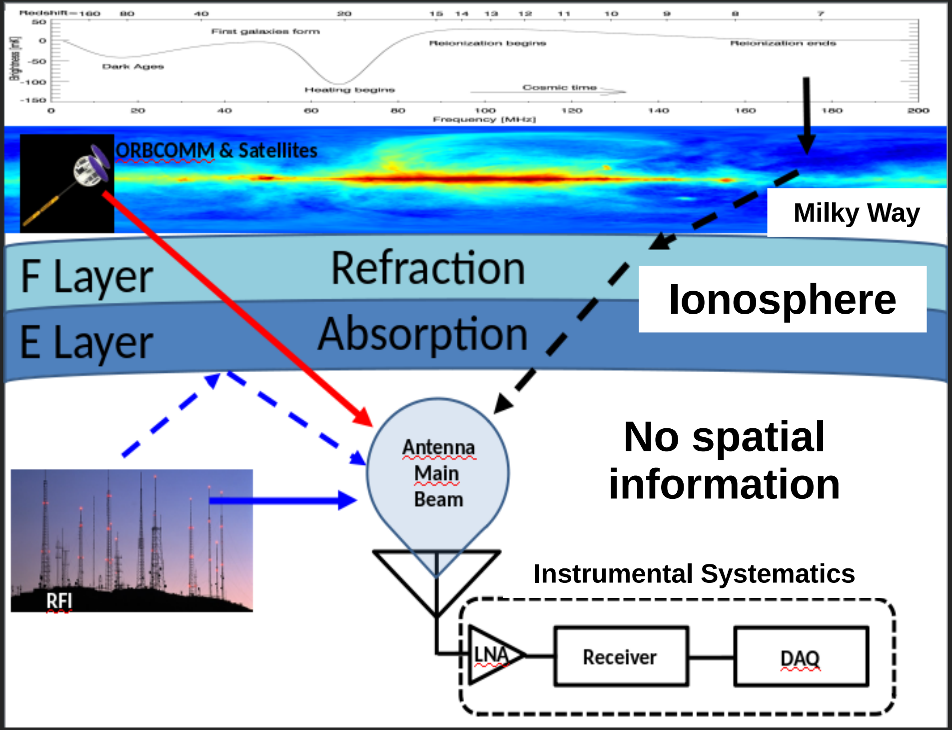
LOFAR (NL)

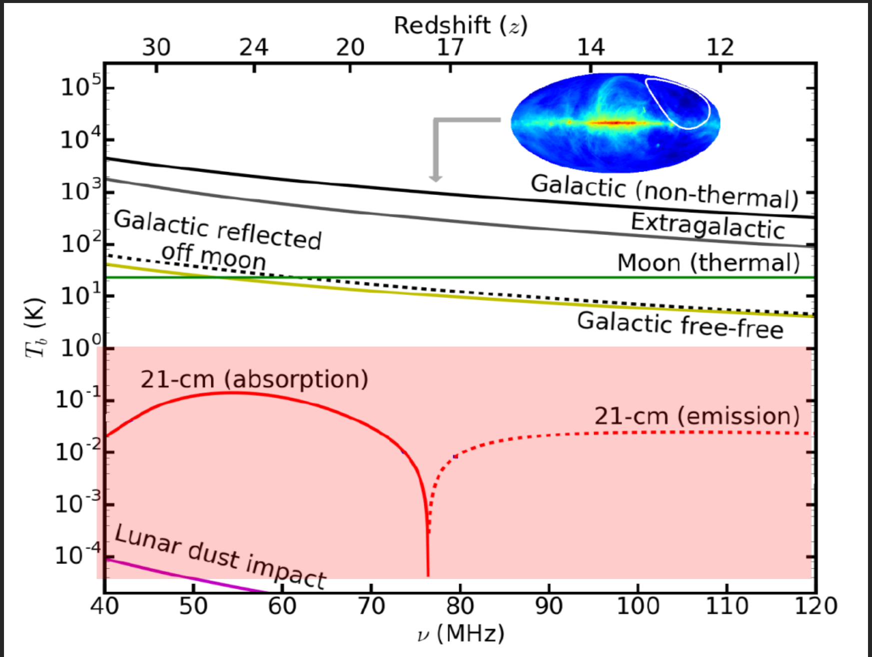


SKA-low (AUS)

MWA (AUS)

Approach 2: Spatially Averaged (Global) 21-cm Measurement (This talk)





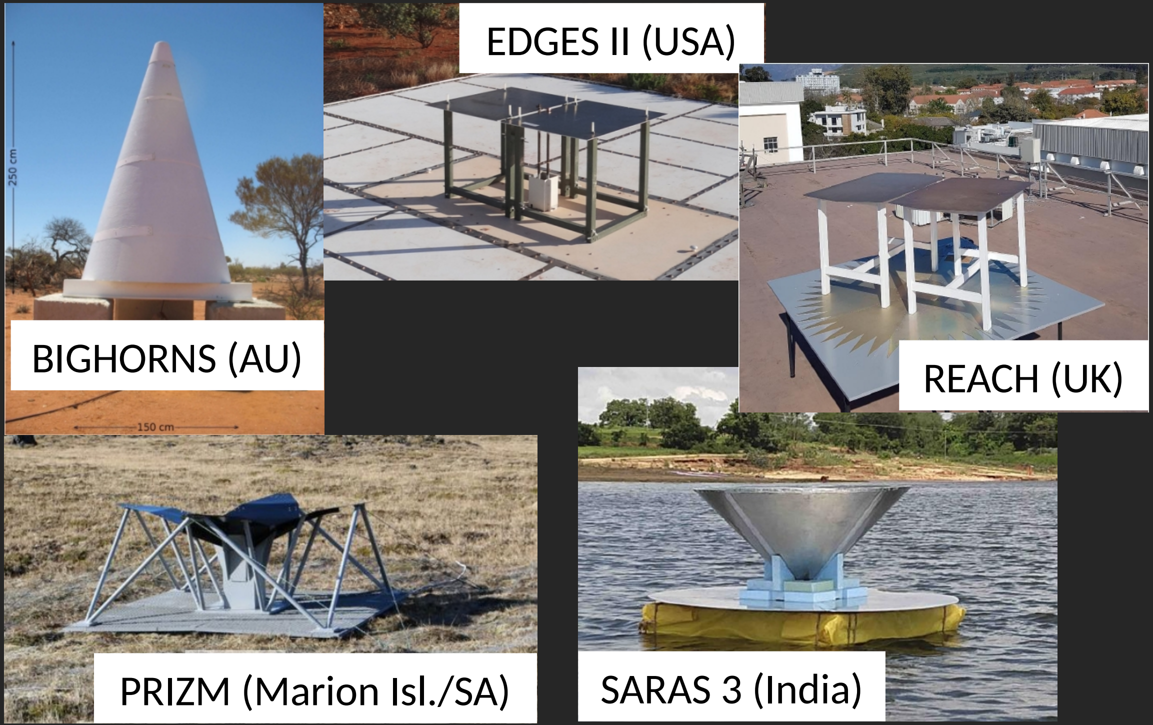
Credit: Burns et al. (2017), *ApJ*

Rationale

- Foreground: spectrally smooth (~ power law with spectral index -β)
  → Get global 21-cm background by subtracting power law

Conventional Global 21-cm Experiment Examples

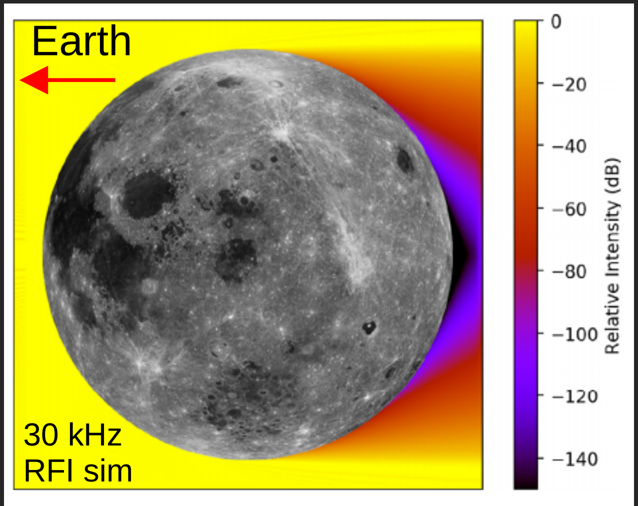
Single element



Compact Array

Try to achieve spectrally smooth antenna response
over a broad range range (somewhere within 40-200MHz)
"Spectral = frequency-dependent"

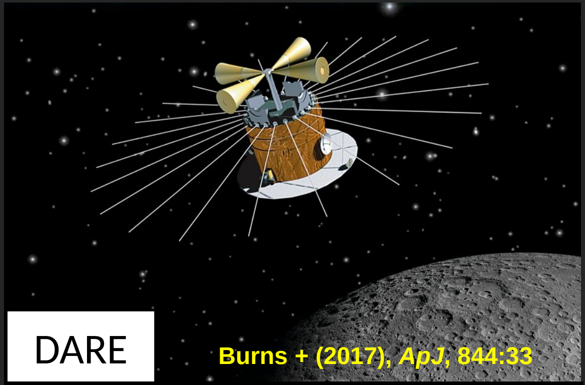
Space & Lunar-based Global 21-cm Experiments

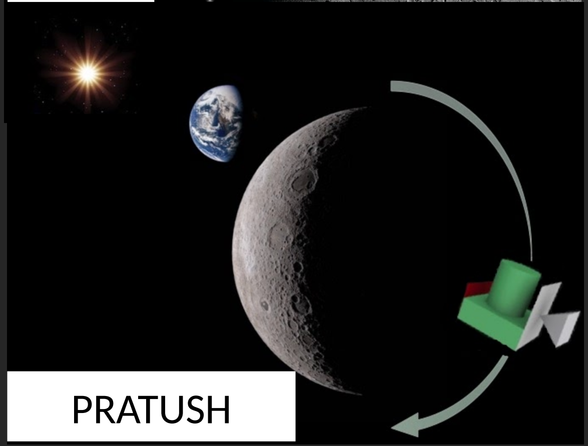


Bassett + (2020), ASR 66

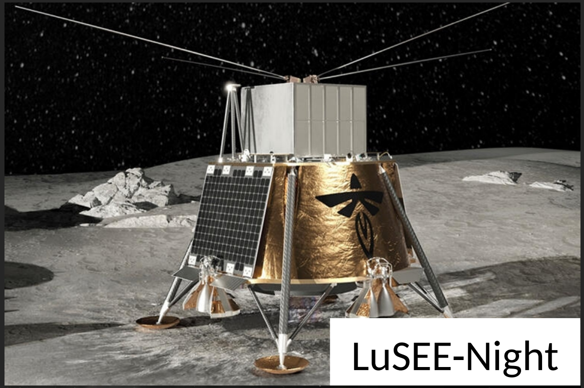
- Radio quiet on lunar farside
- Free from ionosphere
- Logistically challenged

Lunar orbit (farside)

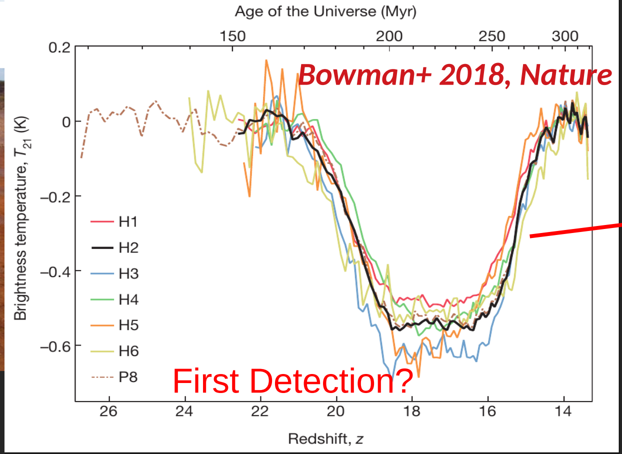


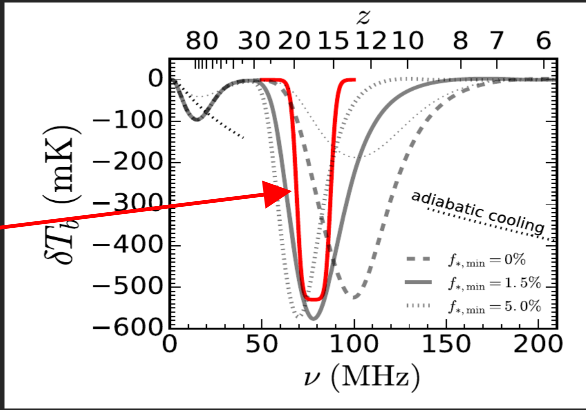


Lunar surface (farside)



EDGES low band (Western Australia)





(Mirocha+ 2019, MNRAS 483)

Observation does not match theory
(Amplitude & Shape)

Possible explanations:

- Instrument systematics
- Foreground fitting error
- Exotic dark matter physics
- Potential excess radio synchrotron background

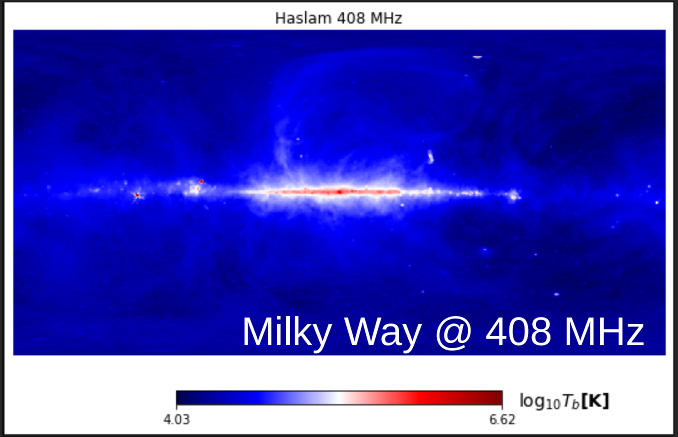
nature astronomy ARTICLES
https://doi.org/10.1038/s41550-022-01610-5
Check for updates

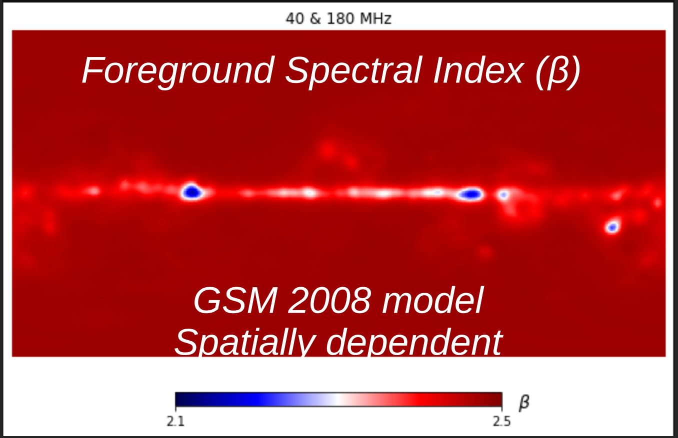
On the detection of a cosmic dawn signal in the radio background *(2021)*

Saurabh Singh[1,2,3], Jishnu Nambissan T.[1,4], Ravi Subrahmanyan[1,5], N. Udaya Shankar[1], B. S. Girish[1], A. Raghunathan[1], R. Somashekar[1], K. S. Srivani[1] and Mayuri Sathyanarayana Rao[1]

hyperfine spin levels in neutral hydrogen atoms. We report a radiometer measurement of the spectrum of the radio sky in the 55–85 MHz band, which shows that the profile found by Bowman et al. in data taken with the Experiment to Detect the Global Epoch of Reionization Signature (EDGES) low-band instrument is not of astrophysical origin; their best-fitting profile is rejected with 95.3% confidence. The profile was interpreted to be a signature of the cosmic dawn; however, its amplitude was substantially higher than that predicted by standard cosmological models. Our non-detection bears out earlier concerns and suggests

Challenge #1 Foreground Removal

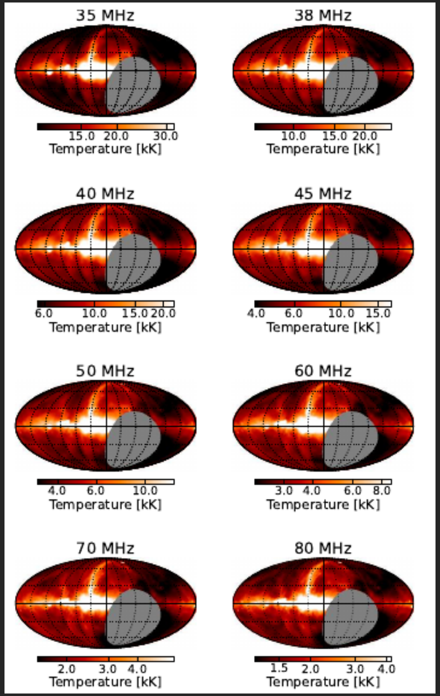




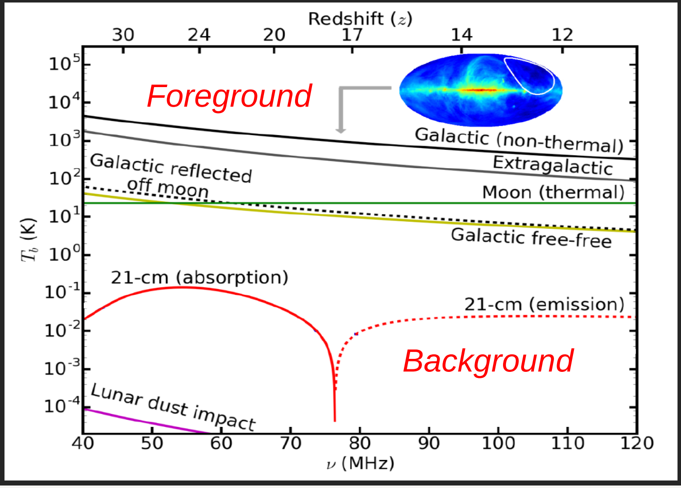
$$\beta(\nu) = -\frac{\log\left[T_b(\nu)/T_b(\nu_{\rm ref})\right]}{\log(\nu/\nu_{\rm ref})}$$

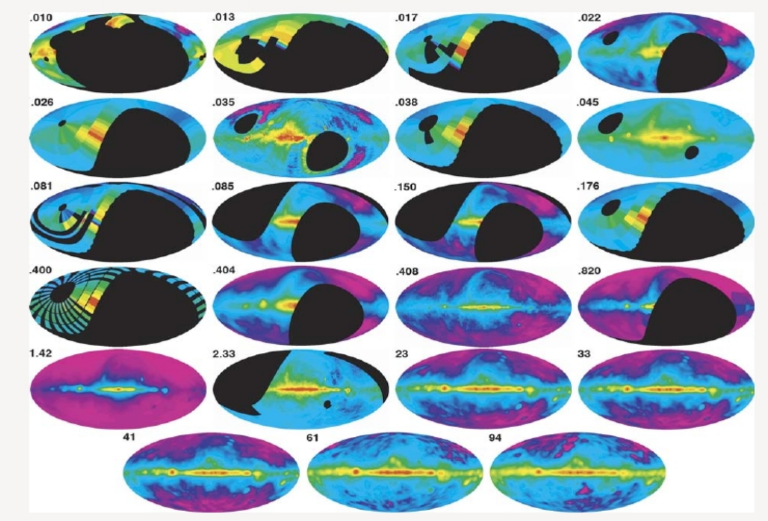
- Incomplete absolute maps

*- High dynamic range (**4-6 orders** of 21-cm signal)*



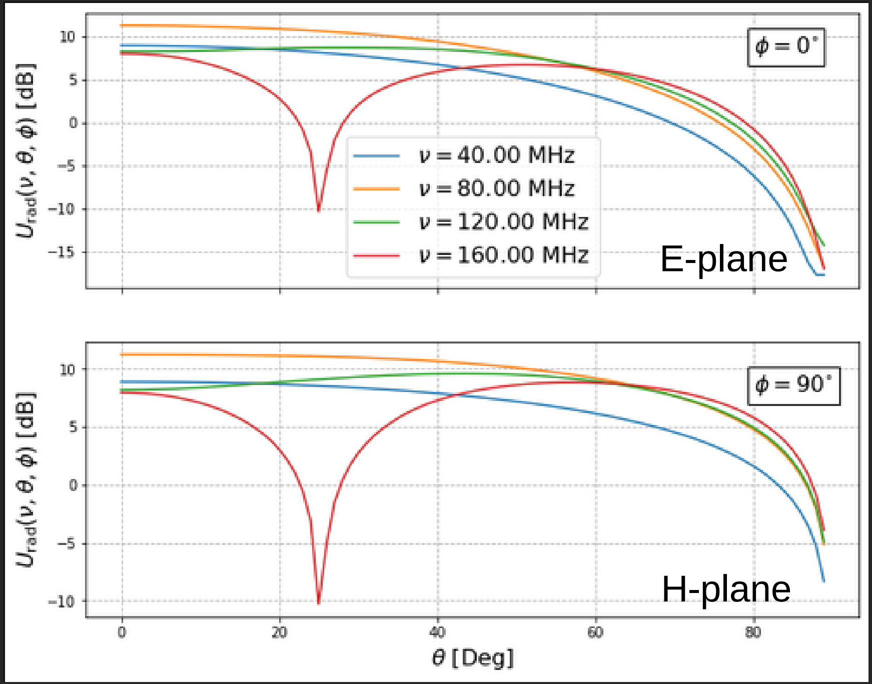
Dowell+ 2017, MNRAS 469



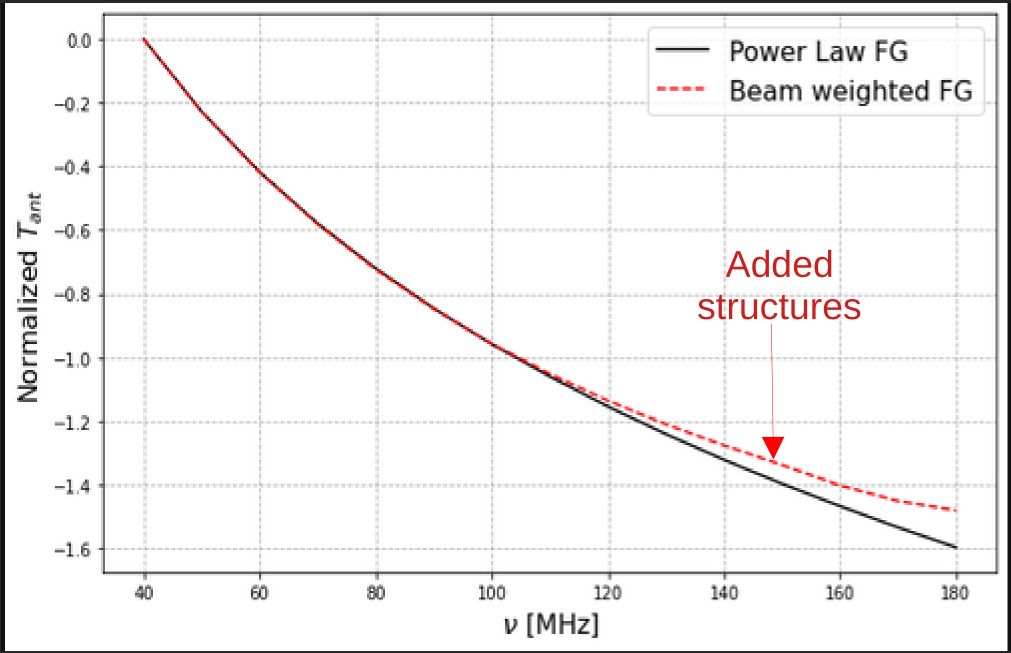


de Oliveira-Costa+ 2008, MNRAS 388

Challenge #2 Chromatic Antenna Response



Typical broadband dipole antenna beam



Observed foreground spectrum being distorted

Our approach: SAFARI
Scaled Antennas For Ascertaining the Radio Index

1) *Uncertain absolute foreground* → Differential measurement

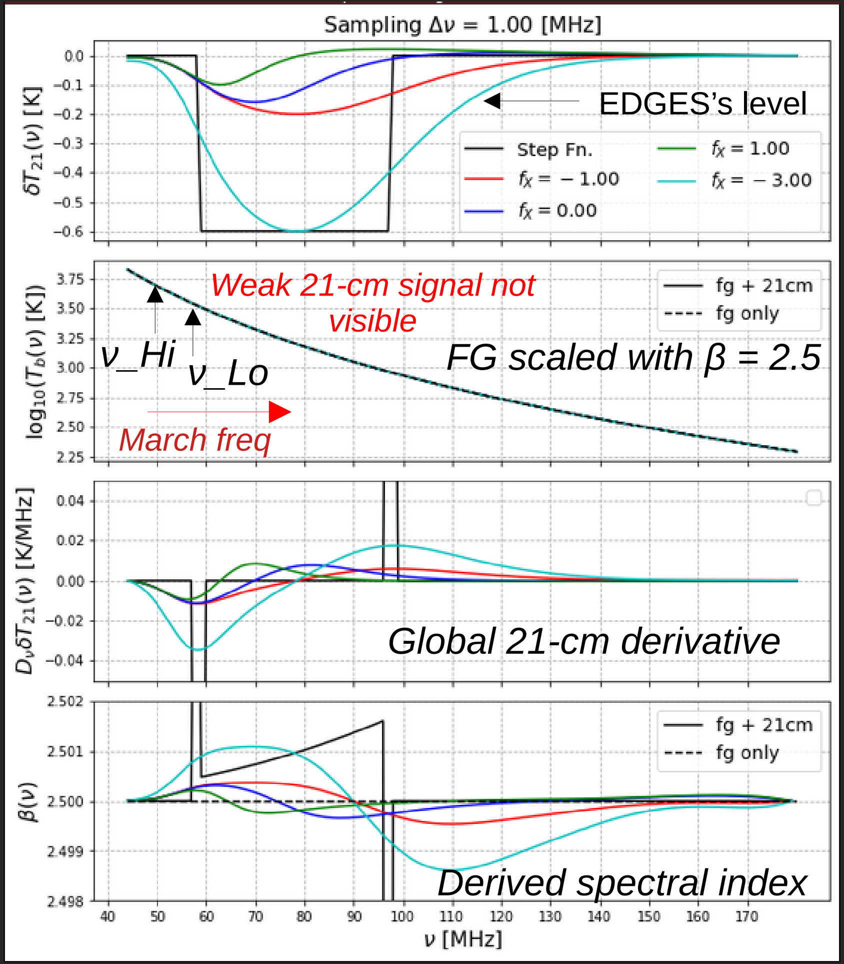
→ Can the FG's spectral index be constrained differentially?

→ How does that help to constrain potential cosmological 21-cm signal?

2) *Chromatic broadband antenna beam* → Scaled antennas

→ Can identical performance be achieved between two frequencies?

Spectral index β as proxy



Simulation settings:

- Scaled Haslam sky map (408 MHz) with a power law (spectral index = -2.5)

- Add different underlying background signal

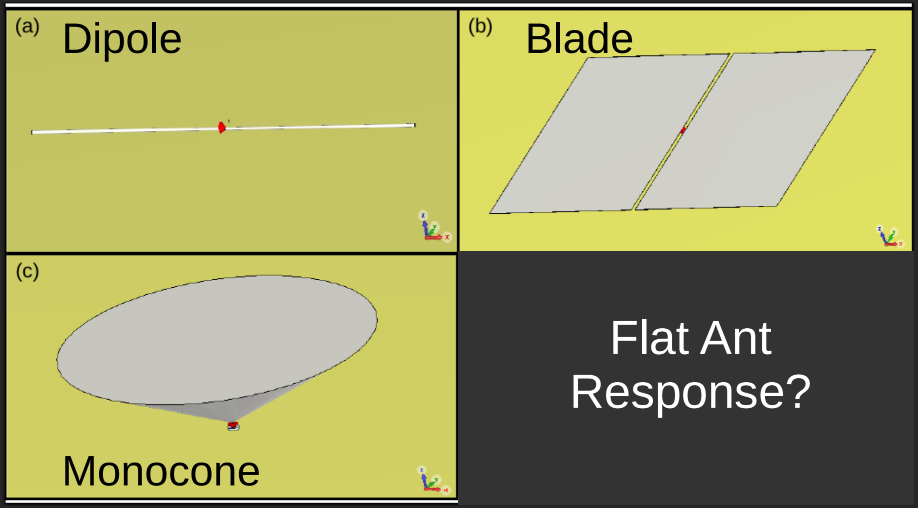
Derived Spectral Index

(differential measuring the *i*-th adjacent freq pair):

$$\beta^i_{obs} = -\frac{\log[T(\nu_{Hi})/T(\nu_{Lo})]_i}{\log(\nu_{Hi}/\nu_{Lo})_i}$$

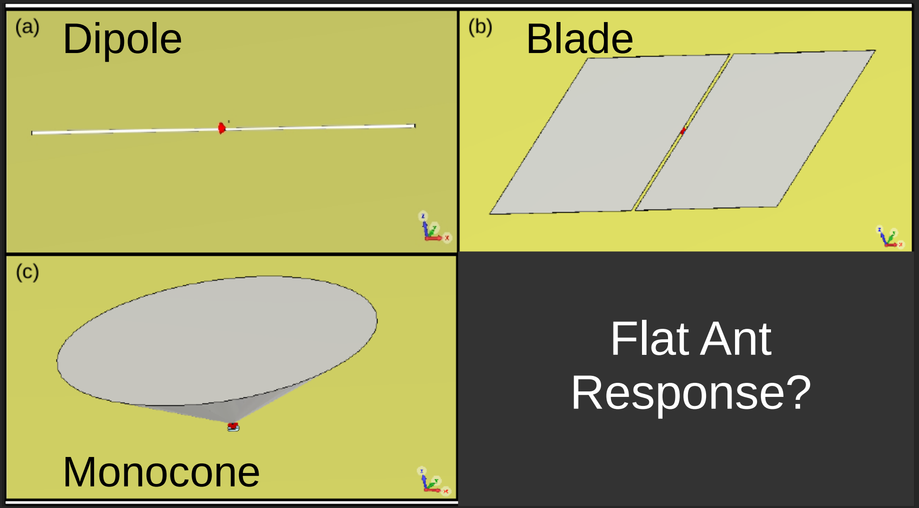
- *If no background signal, β = flat (dashed)*
- *Change in β = deviation from power law FG → **Proxy** for background 21-cm signal*

Broadband vs scaled narrow band (Beam)



- Dipole, blade *(Mozden+ 2016)*, & monocone *(Raghunathan+ 2021)* with infinite ground plane simulation boundary condition

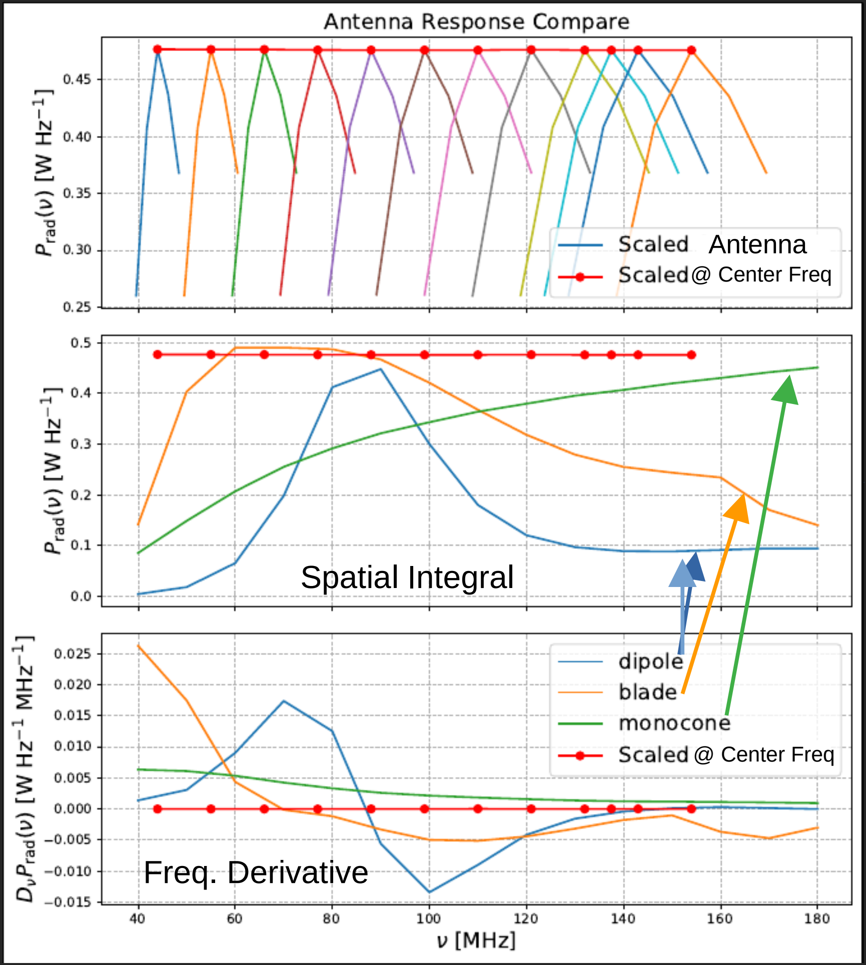
Broadband vs scaled narrow band (Beam)



- Dipole, blade *(Mozden+ 2016)*, & monocone *(Raghunathan+ 2021)* with <u>infinite ground plane</u> simulation boundary condition

Radiated power: $P_{\rm rad}(\nu) = \iint_{\Omega} U(\nu,\theta,\phi)\,{\rm d}\Omega.$

Radiation intensity ~ Farfield beam



Nhan & Bradley (In Prep)

Scaled antennas – Antenna design selection

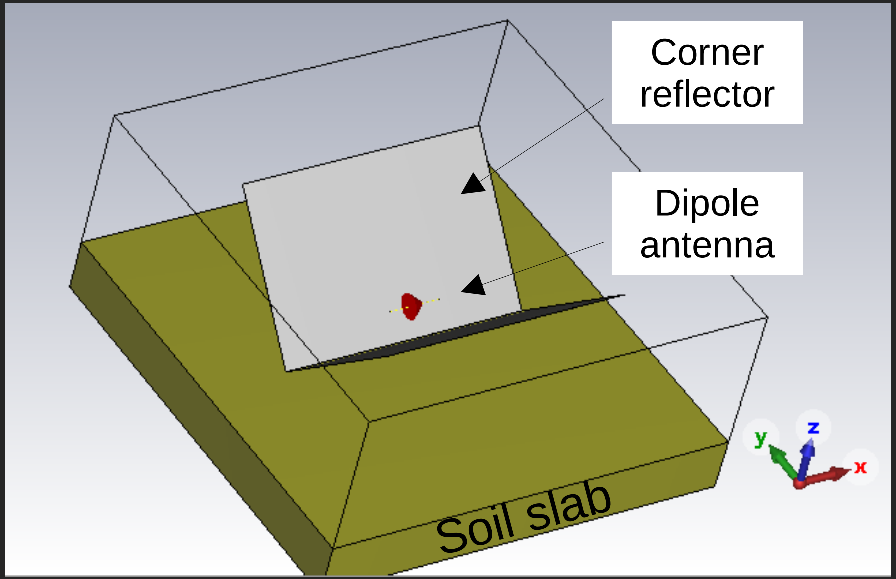
Criteria:

- High gain → narrow beam
- Narrow band
- Simple for scaling
- Low interaction with surrounding

Scaled every components respect to wavelength λ (practicality challenge):

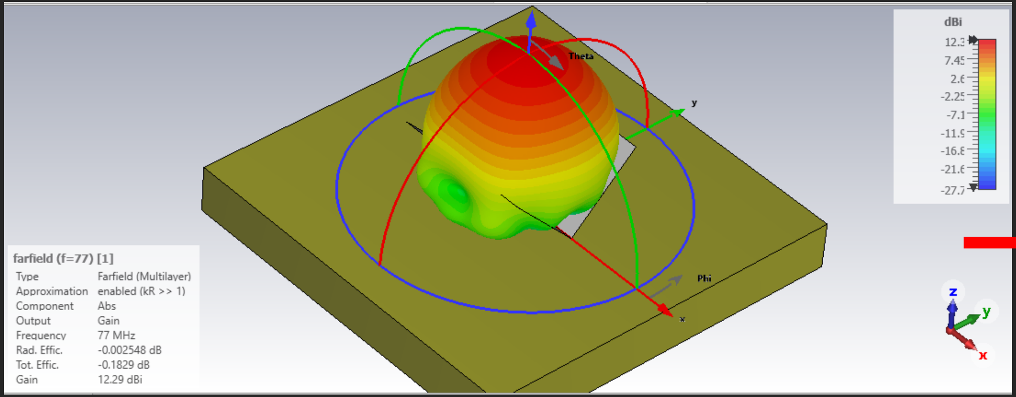
- Dipole arm length & diameter
- Dipole height
- Reflector panel size
- Etc.

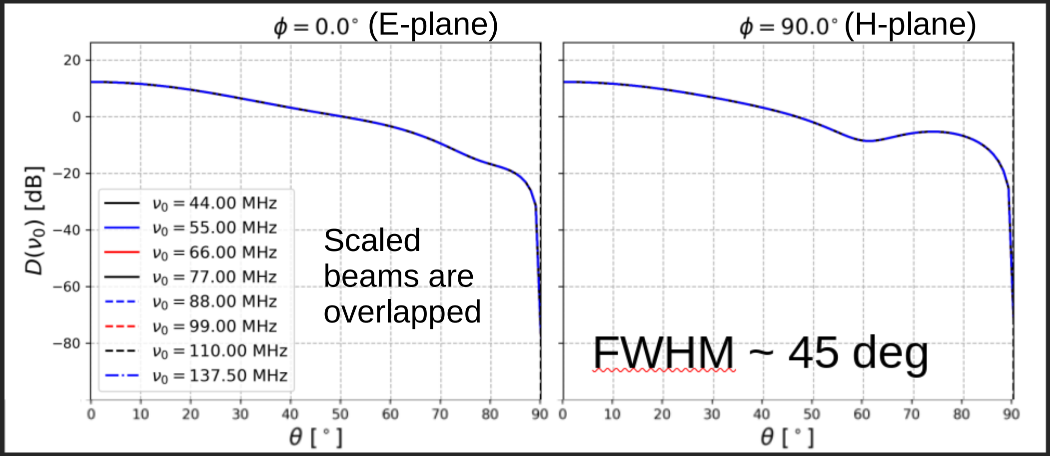
Other studied designs: simple dipole & Yagi
Not meeting the requirements



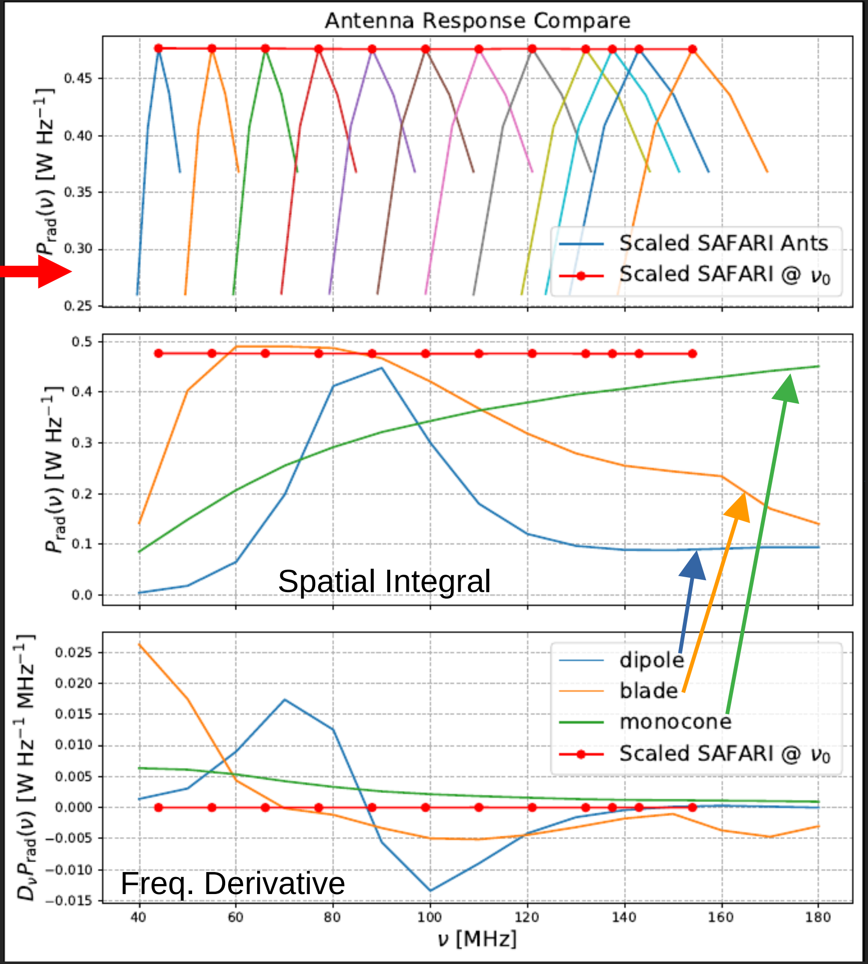
@ 110 MHz: reflector ~ 11.4 m x 7.6 m

Chosen Antenna Design – Dipole with corner reflector



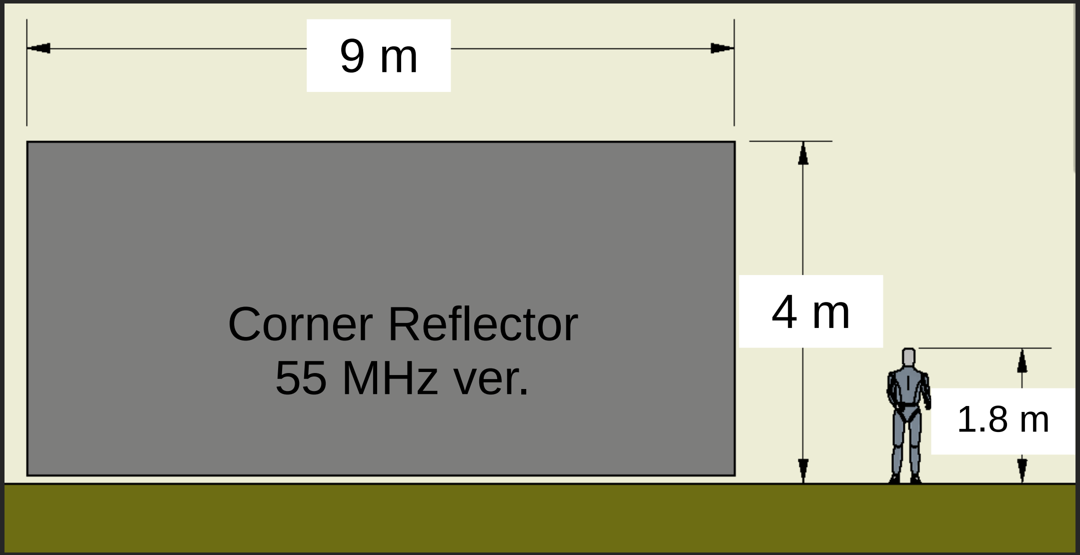


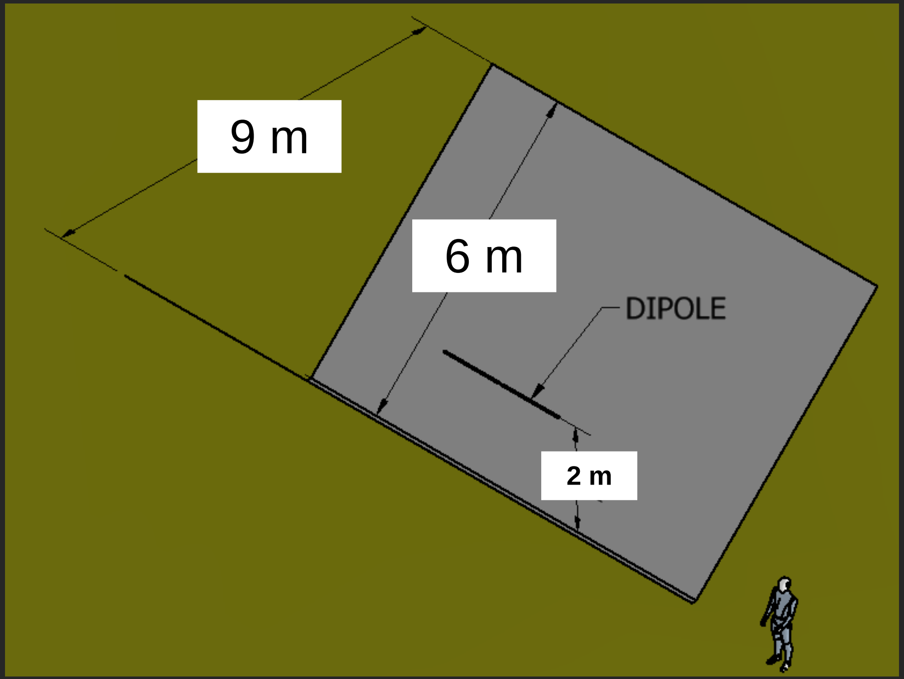
Constant antenna quality (Q-) factor



Nhan & Bradley (In Prep)

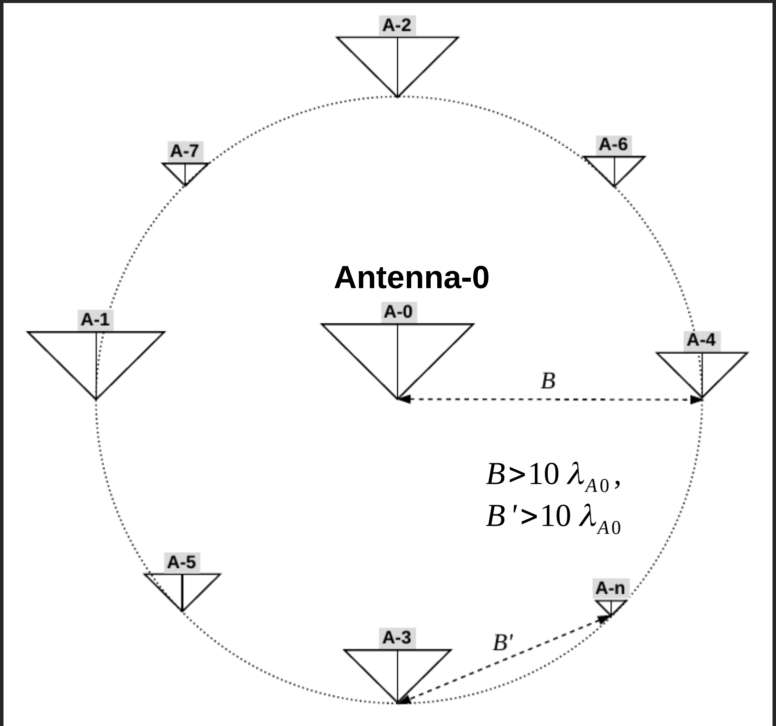
Scaled corner reflector

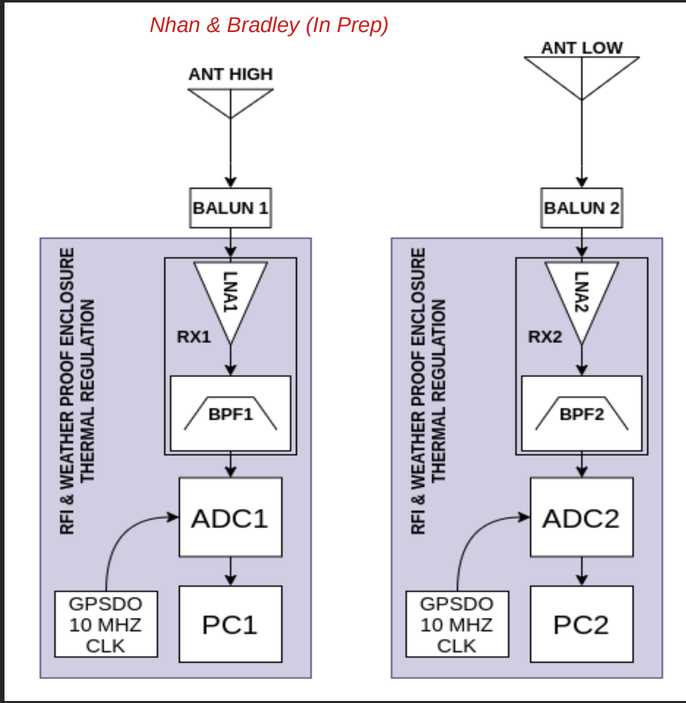




Antenna deployment configuration

Randomized layout to minimize systematics





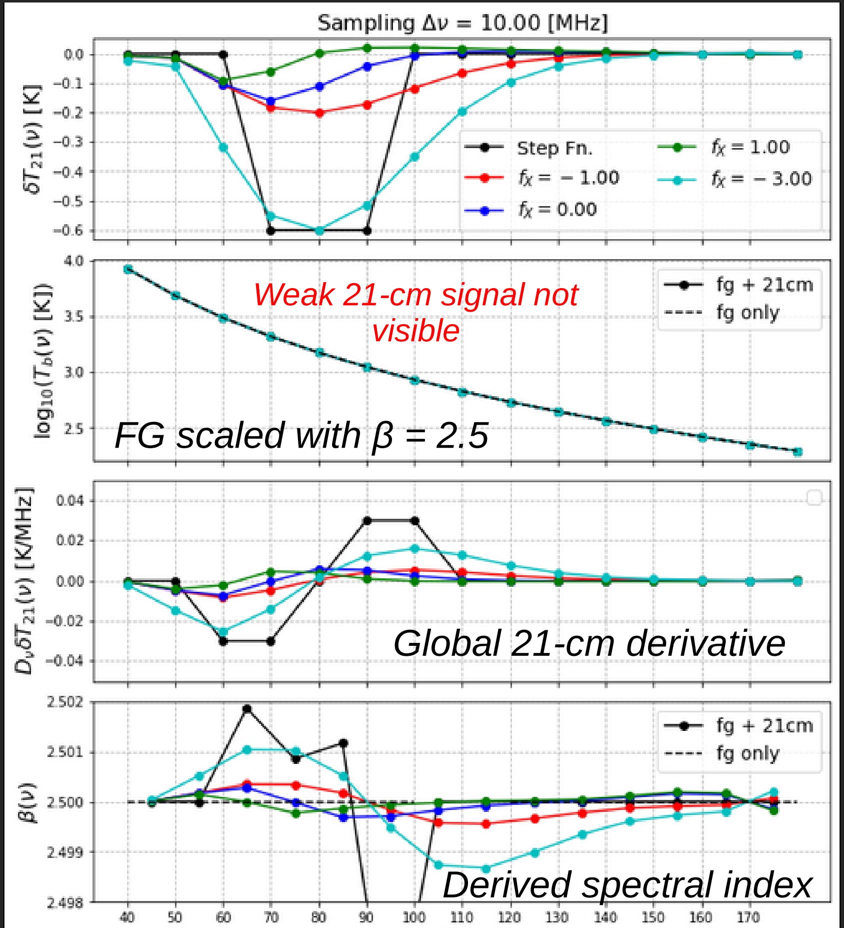
Low-noise amplifier

Bandpass filter

Analog-to-Digital

Independent & self-contained systems

Practical Antenna Scaling



Nhan & Bradley (In Prep)

Scaling the antennas components (e.g., dipole diameter, reflector panel sizes)

Derived Spectral Index (for *i*-th adjacent freq pair):

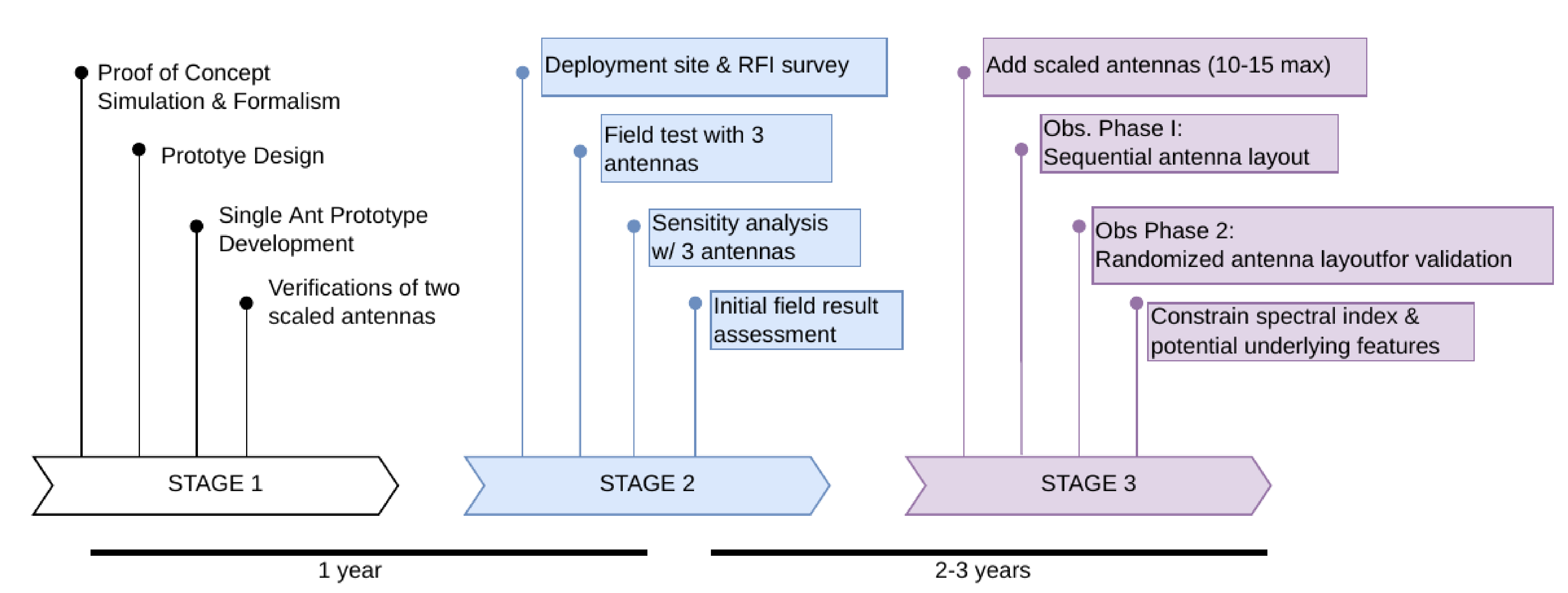
$$\beta^i_{obs} = -\frac{\log[T(\nu_{Hi})/T(\nu_{Lo})]_i}{\log(\nu_{Hi}/\nu_{Lo})_i}$$

Scaling the antennas ~ every **10 MHz**
→ Enough resolution for the change in spectral index

***Goals:* Detection & isolation**
(not characterization yet)

Adaptive antenna design allows us to scale up & down the band with the same beam
(Since we don't know where the signal actually is)

Prototype and Deployment Phases



Conclusion

- Observation of the Dark Age and Cosmic Dawn using 21-cm neutral hydrogen signal is challenging due to:
  - Uncertain bright foreground synchrotron emission
  - Need to characterize high precision antenna response
  - Any instrumental systematic can distort the weak 21-cm signal of interest
- EDGES, SARAS, and other ground-based global 21-cm experiments are working on verifying the report 78-MHz absorption feature
  - A new measurement approach is imperative to isolate different types of systematics
- SAFARI will provide:
  - **Differential measurement** of the **foreground spectral index** as a sensitive **proxy** for the weak global 21-cm background signal <u>without the need of complete knowledge of the foreground emission</u>
  - A pathway to achieve **spectrally flat antenna response** by **scaling narrow-band antennas** electromagnetically
    - An **adaptive** scheme that can scale the antennas up and down the frequency range to search for the unknown global 21-cm signal