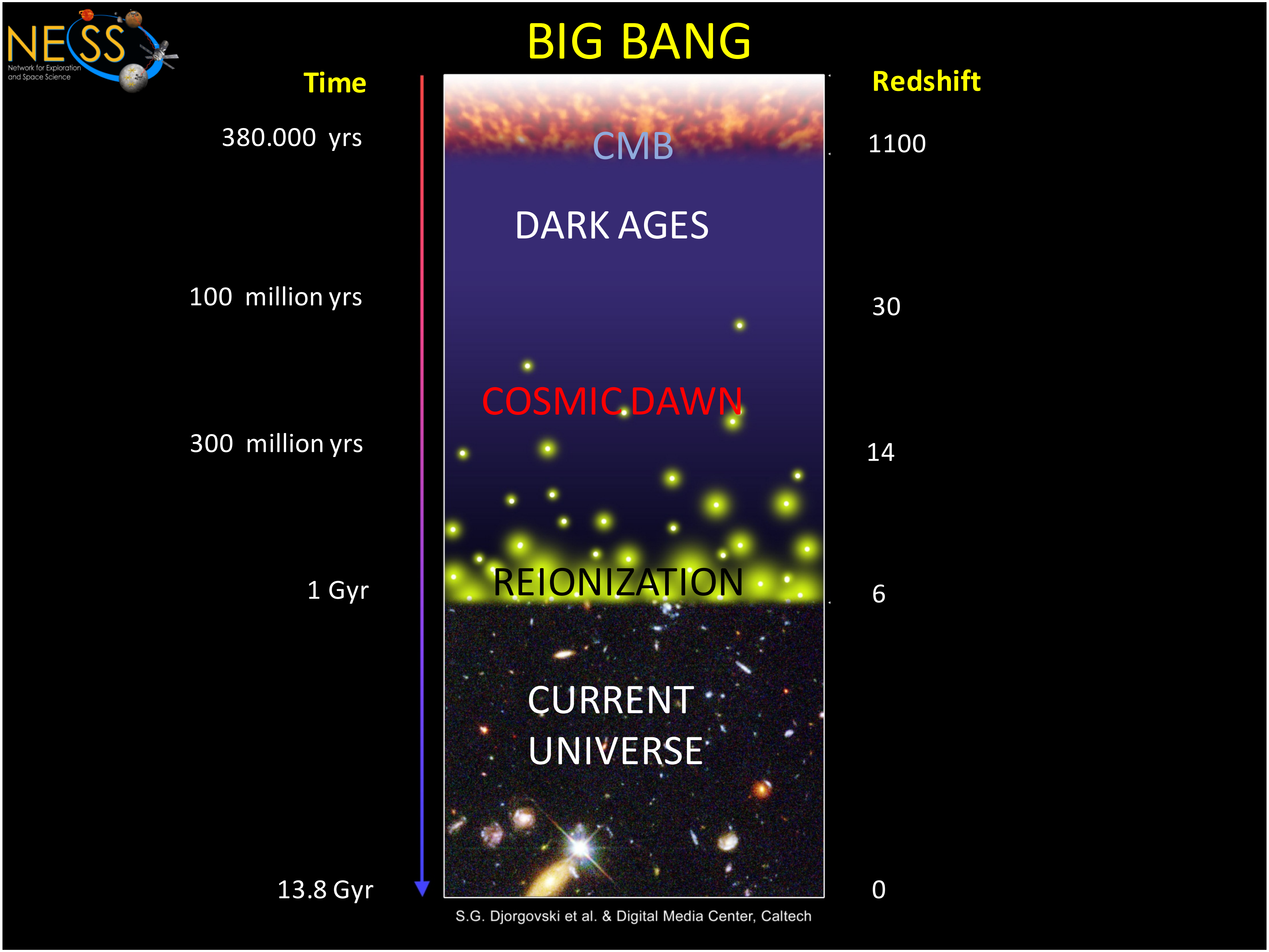
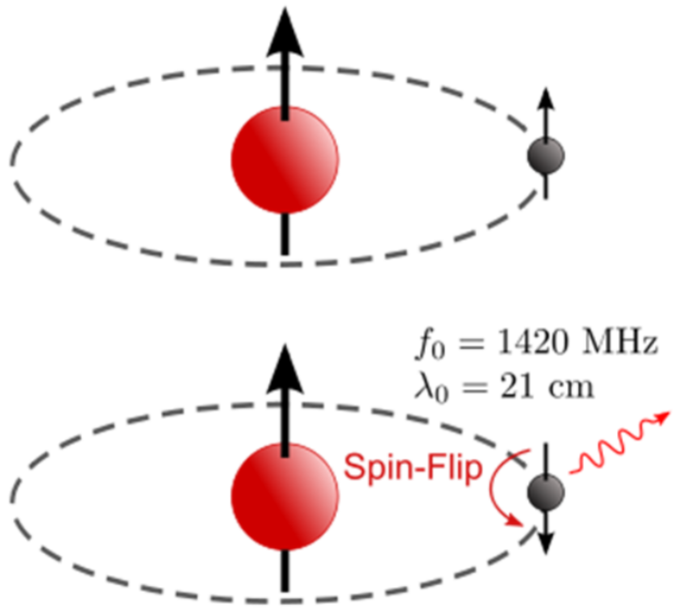
Preparing for the Dark Ages Radio Explorer (DARE) through Ground-Based Observations

Raul Monsalve
University of Colorado Boulder


BIG BANG
Time
Redshift
380.000 yrs
1100
CMB
DARK AGES
100 million yrs
30
COSMIC DAWN
300 million yrs
14
REIONIZATION
1 Gyr
6
CURRENT UNIVERSE
13.8 Gyr
0
S.G. Djorgovski et al. & Digital Media Center, Caltech

Emission at 21-cm from Hydrogen Atom



Parallel spins
Upper ground state

Anti-parallel spins
Lower ground state

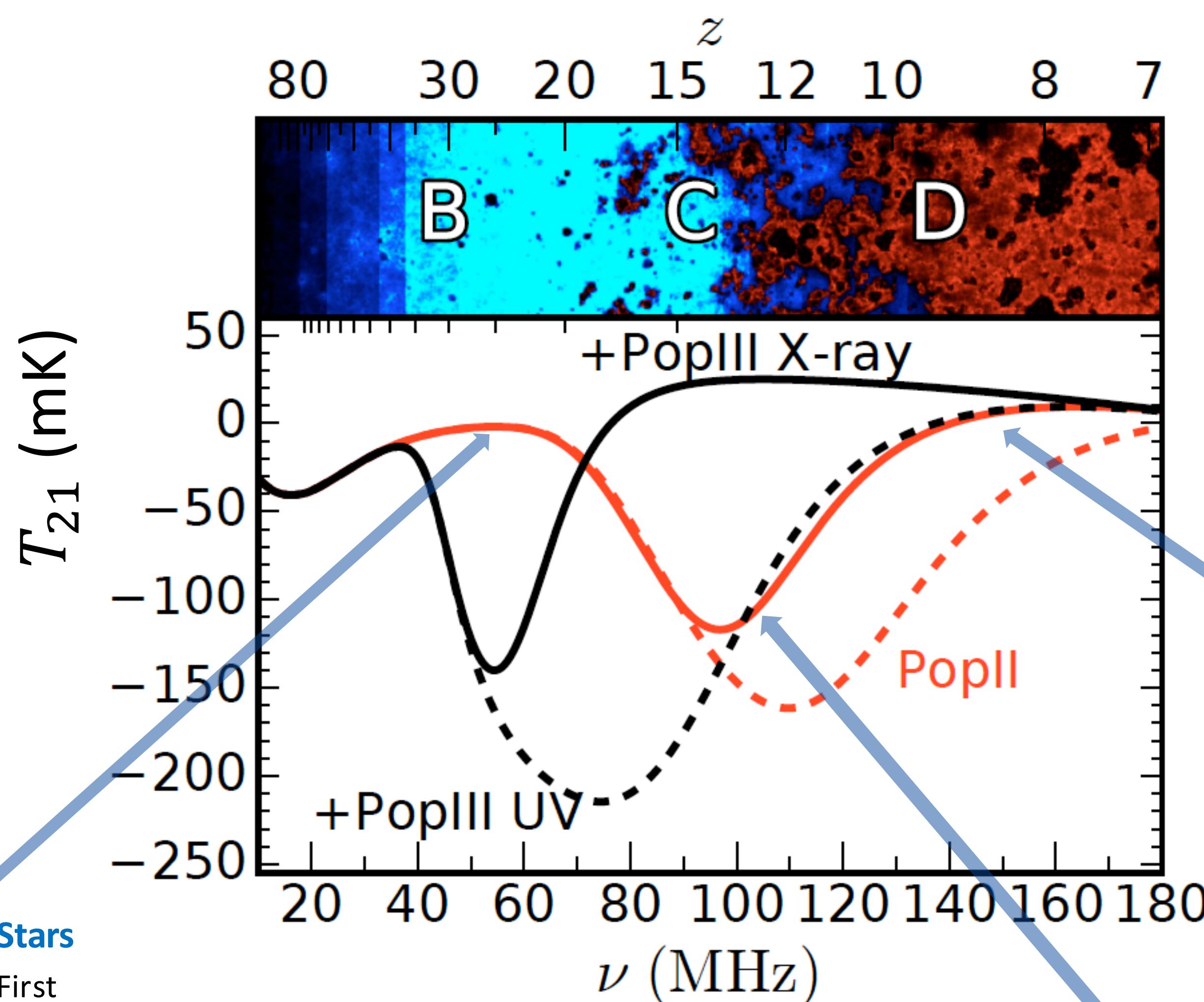
Due to Cosmological Expansion

Redshift	Frequency
0	1420 MHz
6	200 MHz
35	40 MHz

$$\upsilon_{\mathrm{obs}} = \frac{\upsilon_{\mathrm{emit}}}{(1+z)}$$

The Global (sky-average) 21-cm Signal

$$T_{21} = 27 x_{HI} \left(\frac{1+z}{10}\right)^{1/2} \left(1 - \frac{T_{CMB}}{T_S}\right) \text{ mK}$$



Adapted from Pritchard & Loeb (2015)

B: Ignition of First Stars

- When did the First Stars ignite? What were their characteristics?

C: Heating by First Black Holes

- When did the first accreting black holes turn on? What were their characteristics?

D: The Onset of Reionization

- What was the history of Reionization in the early Universe?

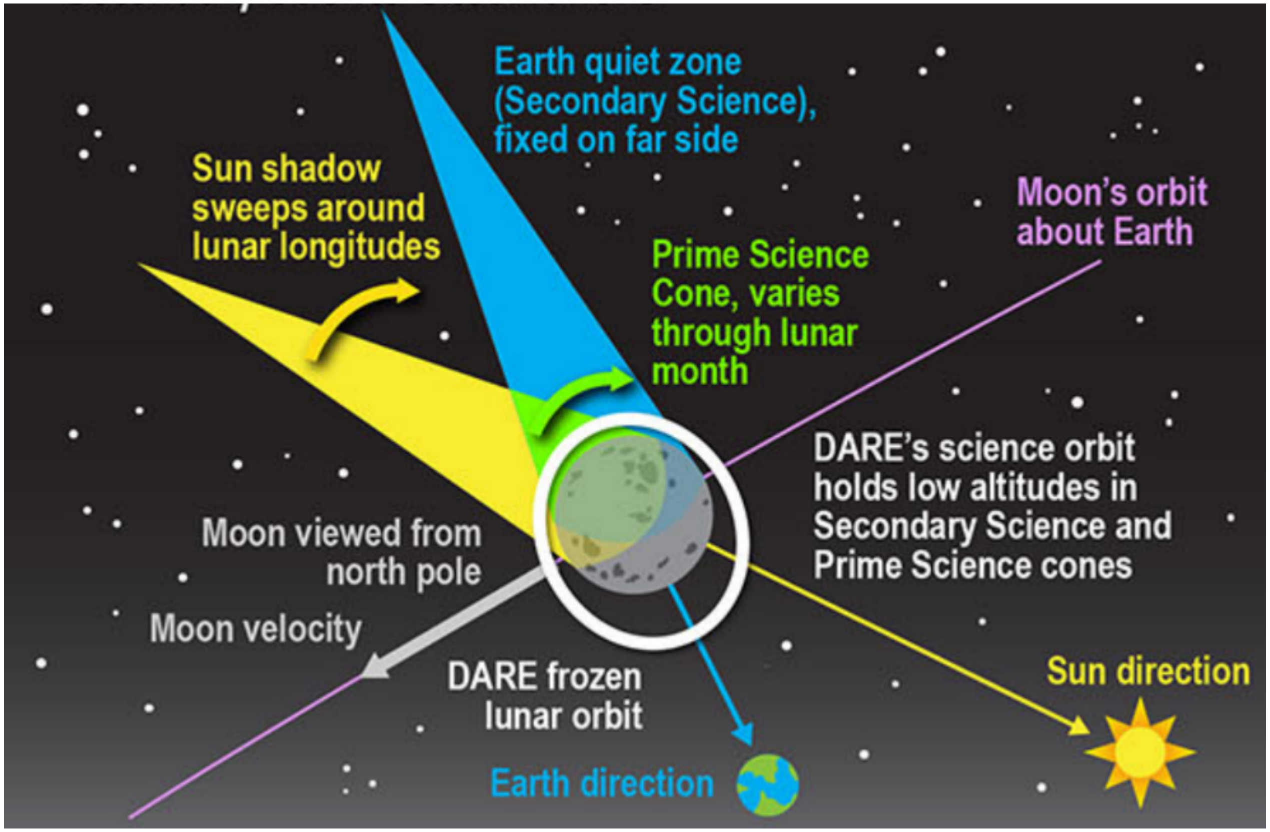
Measurements from the Lunar Farside

1) **Ideal place** to conduct cosmological 21-cm measurement (orbiting, or observing from the surface).

2) Moon **shields** the instrument from **terrestrial Radio Frequency Interference (RFI)** and from the **Sun**.

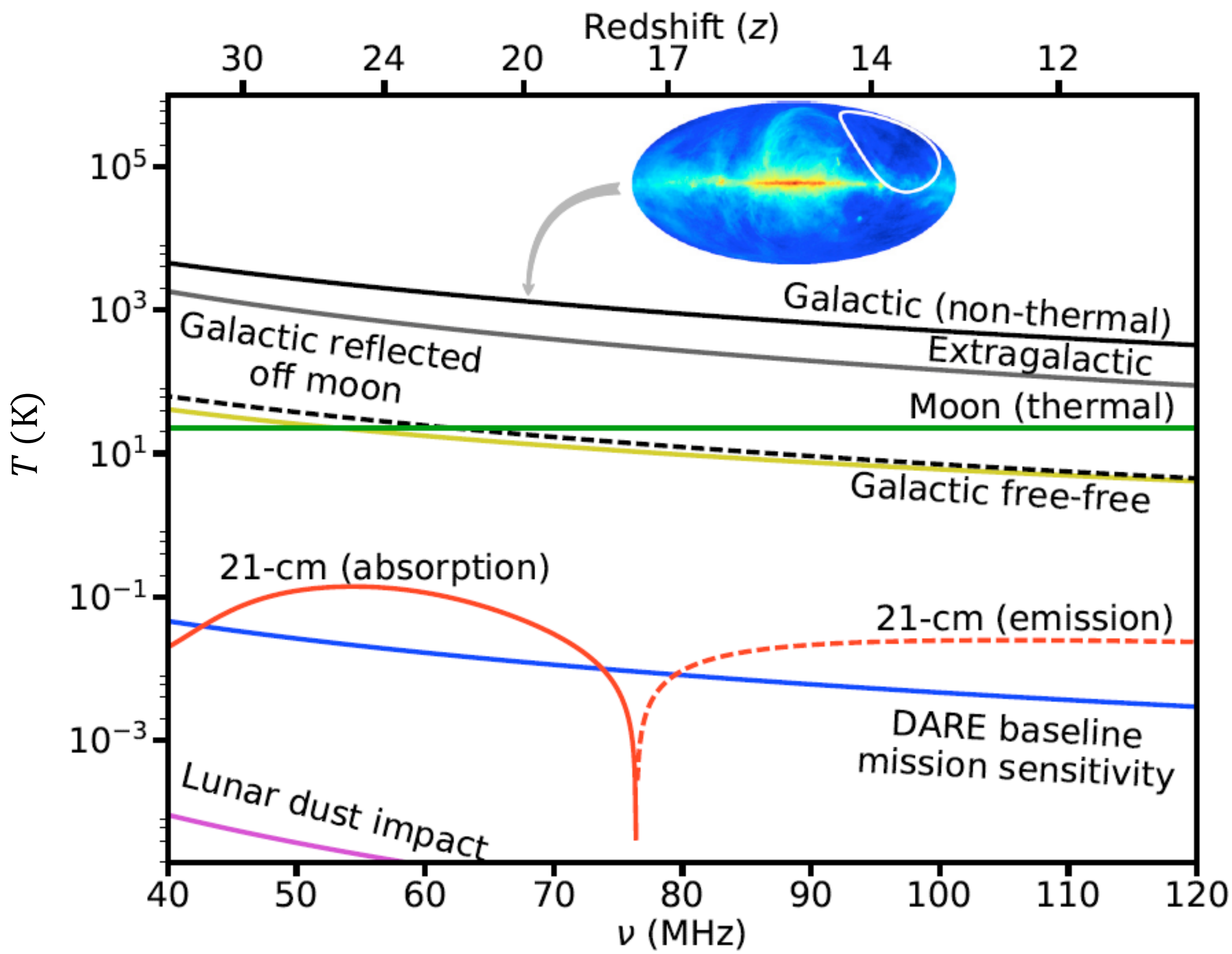
3) **Earth's ionosphere** impacts low-frequencies radio measurements through its own emission, absorption, and refraction.

4) Lunar environment **completely eliminates these effects** and complexities.



Measurement Model

$$T_{\text{ant}} = T_{21} + \int T_{\text{fg}} \cdot Beam \cdot d\Omega$$



Parameter Estimation

University of Colorado Boulder

Linear Measurement Model Based on Singular Value Decomposition (SVD)

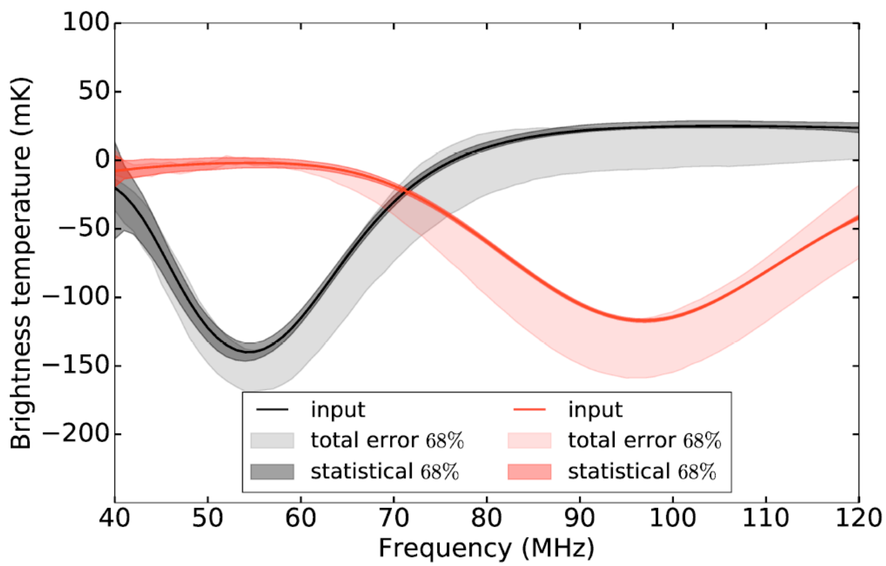
$$T_{A,M}^{(r)}(\nu,\lambda) = \sum_i (\lambda_{21})_i \, f_i(\nu) + \sum_j (\lambda_{sys})_j^{(r)} \, g_j(\nu)$$

21-cm basis functions

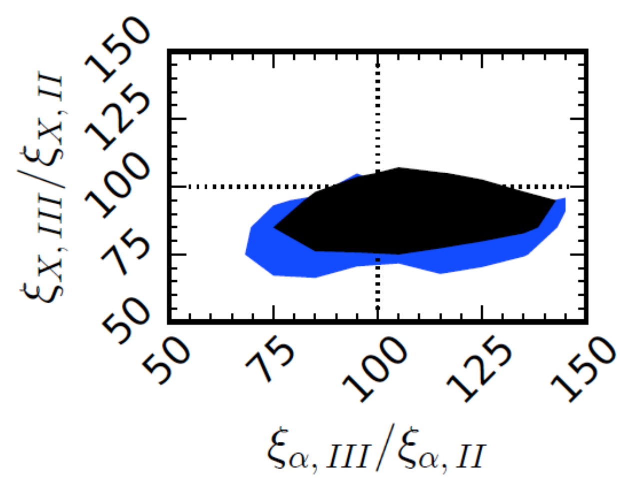
Instrument and foreground basis functions

Markov Chain Monte Carlo (MCMC)

Reconstructed 21-cm Signal (Simulation)

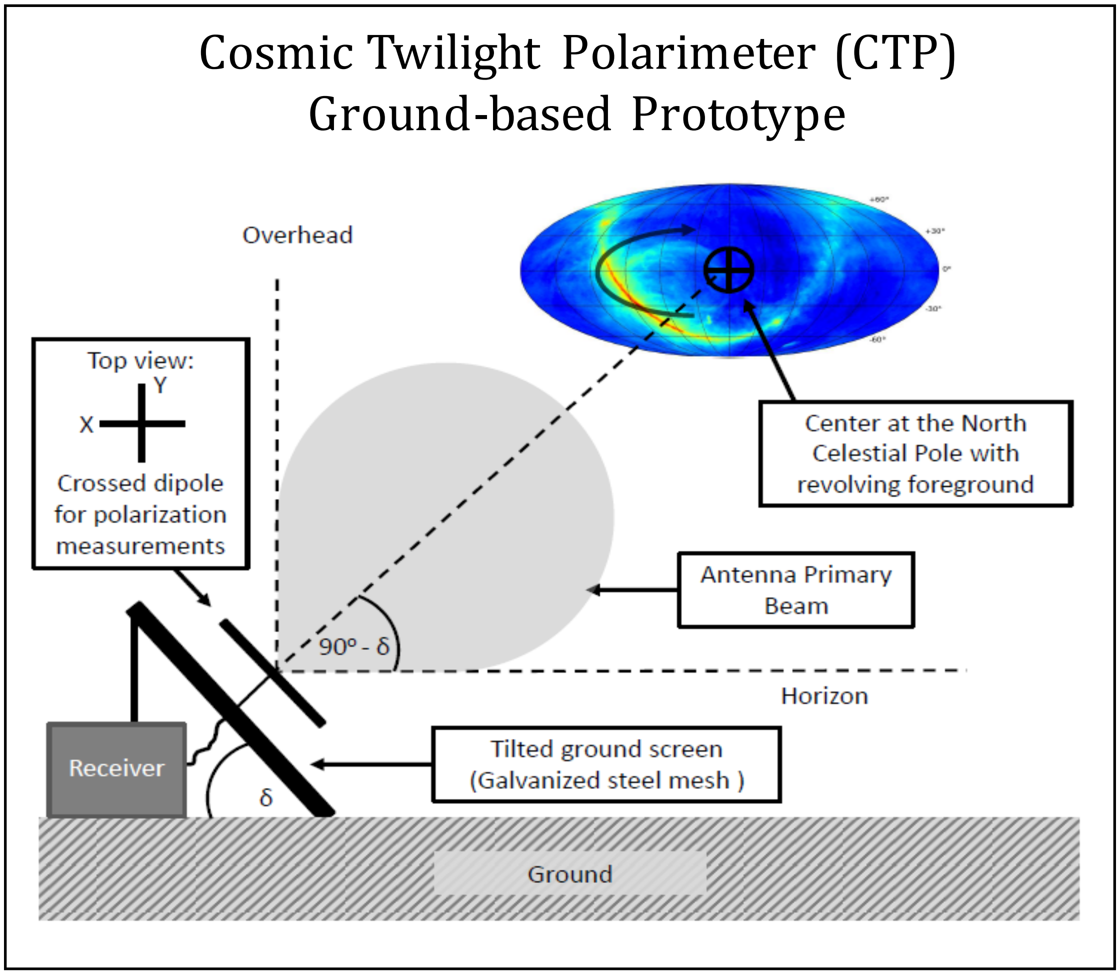


Estimated Parameters (Simulation)



Beam and Foreground Characterization

1) Technique based on the **modulation of foregrounds**.
2) **Foreground** varies spatially but is **spectrally smooth**.
3) **Global 21-cm** signal is spatially uniform but **spectrally complex**.
4) Frequency-dependent modulation amplitude represents **the foreground alone, and is contained in Stokes Q**.
5) **Stokes I contains both**, foreground and 21-cm signal.



University of Colorado Boulder

National Radio Astronomy Observatory

Ground-based Prototype

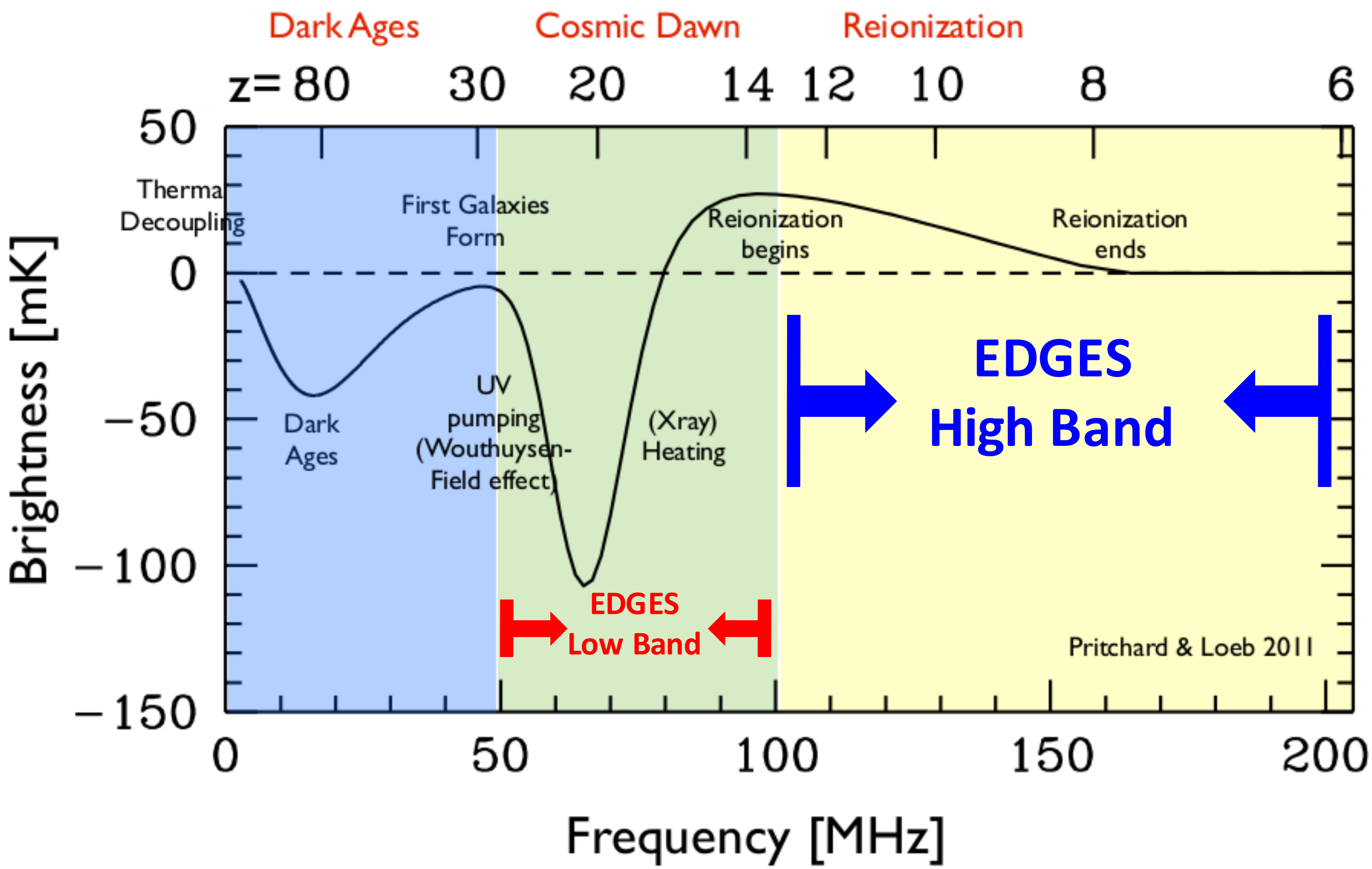
EDGES

Experiment to **D**etect the **G**lobal **E**oR **S**ignature

Dr. Judd Bowman (PI)
Dr. Alan Rogers
Dr. Raul Monsalve
Mr. Thomas Mozdzen
Ms. Nivedita Mahesh

Arizona State University
MIT Haystack Observatory
University of Colorado Boulder

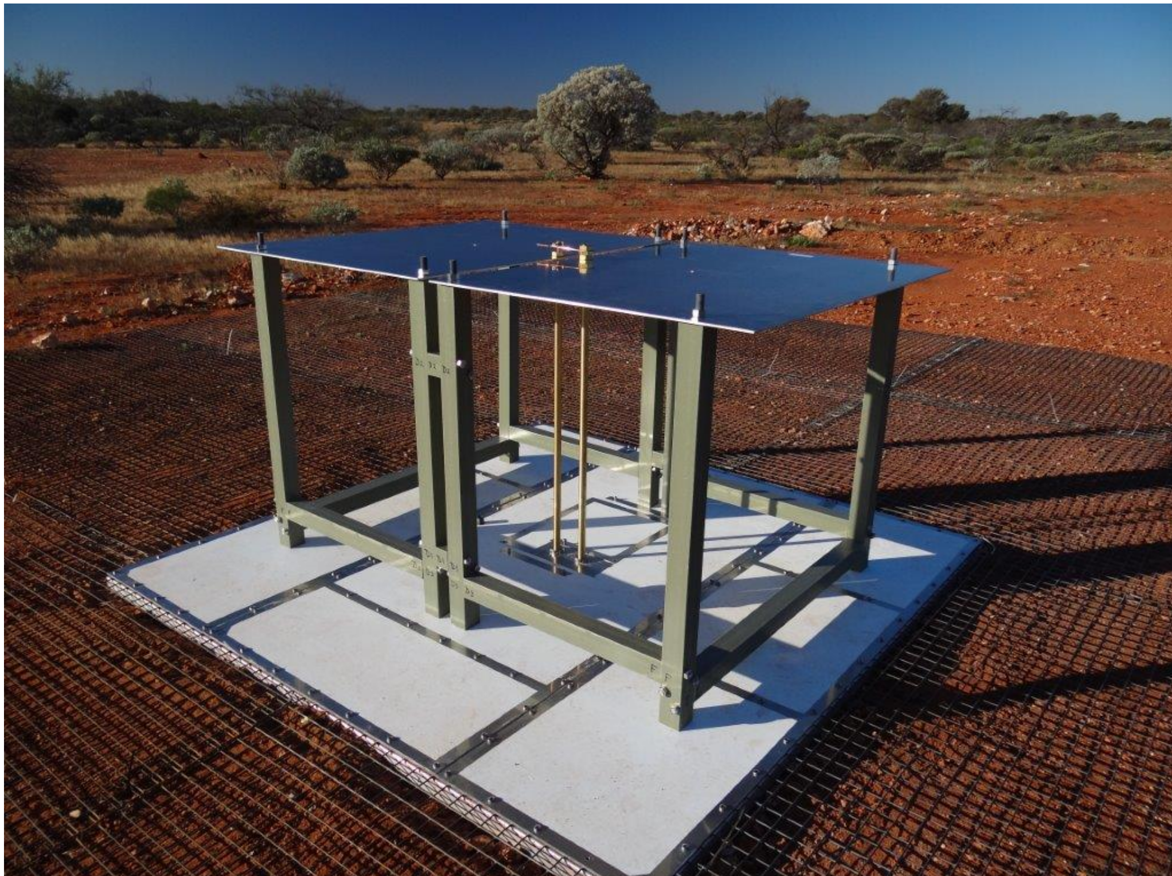
Two EDGES Instruments



Location


EDGES
MRO
A
Western Australia
Northern Territory
Australia
Queensland
South Australia
New South Wales
Victoria
Australian Capital Territory
Perth
Adelaide
Melbourne
Sydney
Brisbane
Gold Coast
Great Australian Bight
Map data ©2014 GBRMPA, Google

EDGES 2015-2017



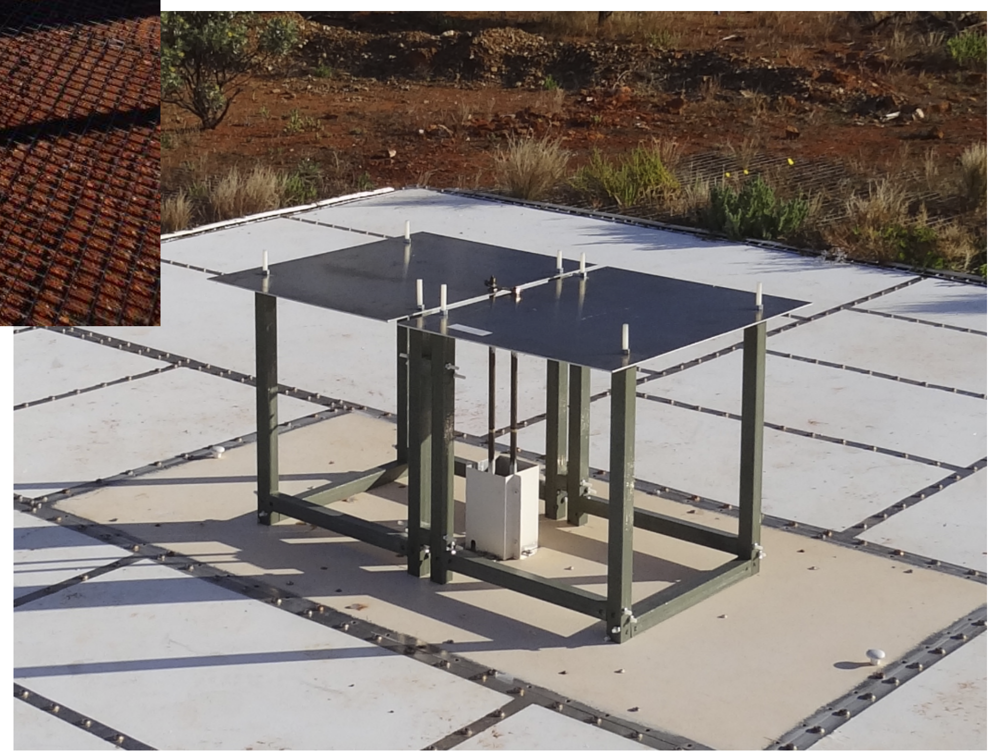
Low-Band Antenna

Antenna size:

2m long / 1m high

Ground plane:

25m x 25m



High-Band Antenna

Antenna size:

1m long / 0.5m high

Ground plane:

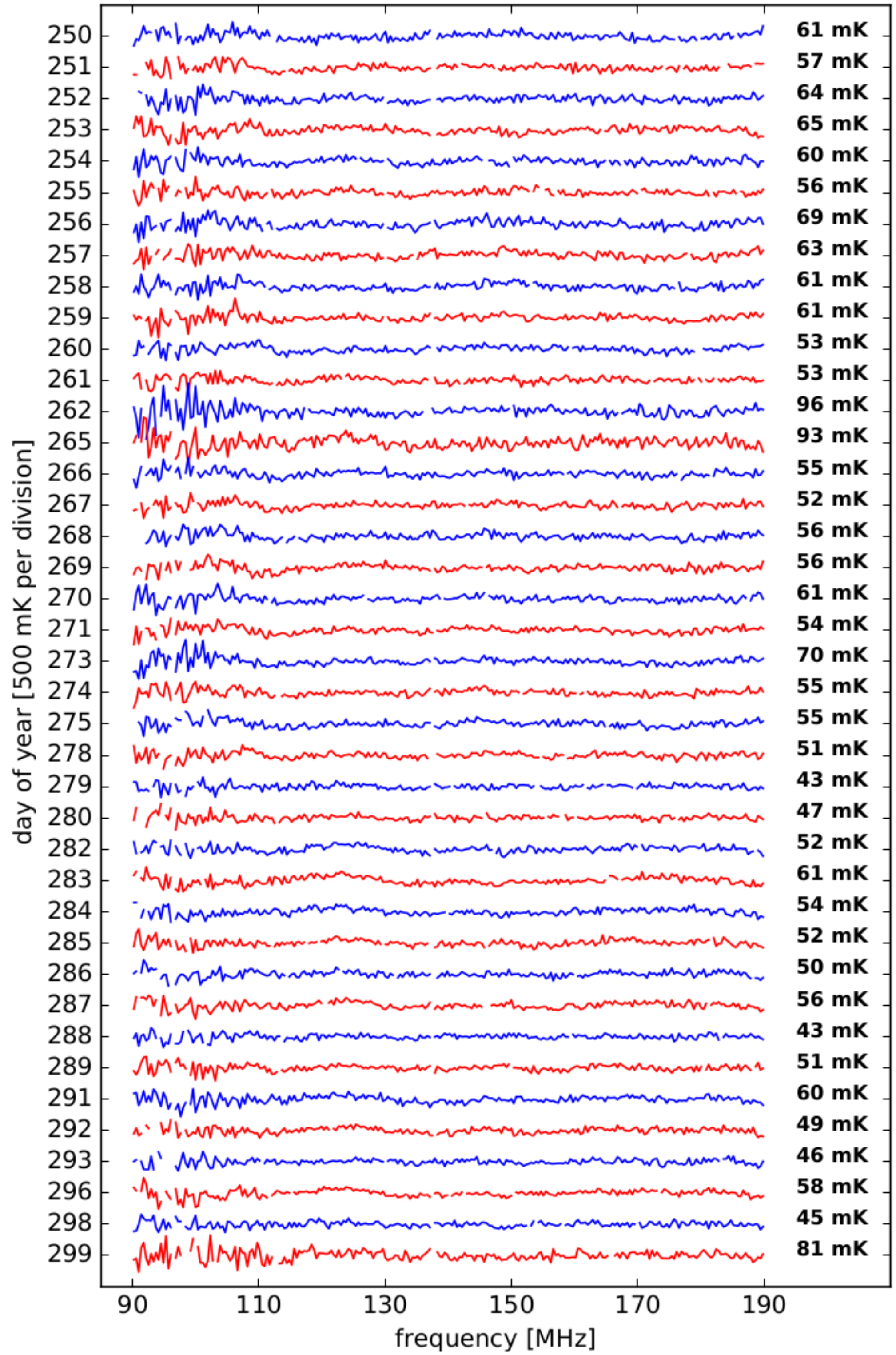
10m x 10m

Sample of EDGES High-Band Observations

1. Residuals to 5-term polynomial
2. 40 days of nighttime
3. 6-hr averages
4. Low foregrounds
5. Typical daily RMS residuals ~60 mK

1) EDGES implements an extremely **accurate absolute calibration**.

2) Lunar mission concepts based on **many of these proven techniques**.



Summary

1. The global redshifted 21-cm signal is a powerful tool to explore the **first luminous objects and the intergalactic medium** in the early Universe.

2. **The Lunar farside is an ideal place** to conduct this measurement, with an orbiting instrument such as DARE, as well as from the surface itself.

3. Pristine environment, **free from RFI and ionospheric effects**.

4. **Innovative calibration techniques** are being developed and tested successfully by ground-based precursors such as the CTP and EDGES.

5. Sophisticated **data analysis techniques** are being tested through simulations and soon using real ground-based observations.

We **acknowledge support** for this work from the NASA Ames Research Center.