HIGH REDSHIFT 21-CM ABSORPTION MEASUREMENTS

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Outline

1. Hydrogen 21-cm Introduction
2. The Global Redshifted 21-cm Signal
3. Observations of the 21-cm Signal
4. Conclusion

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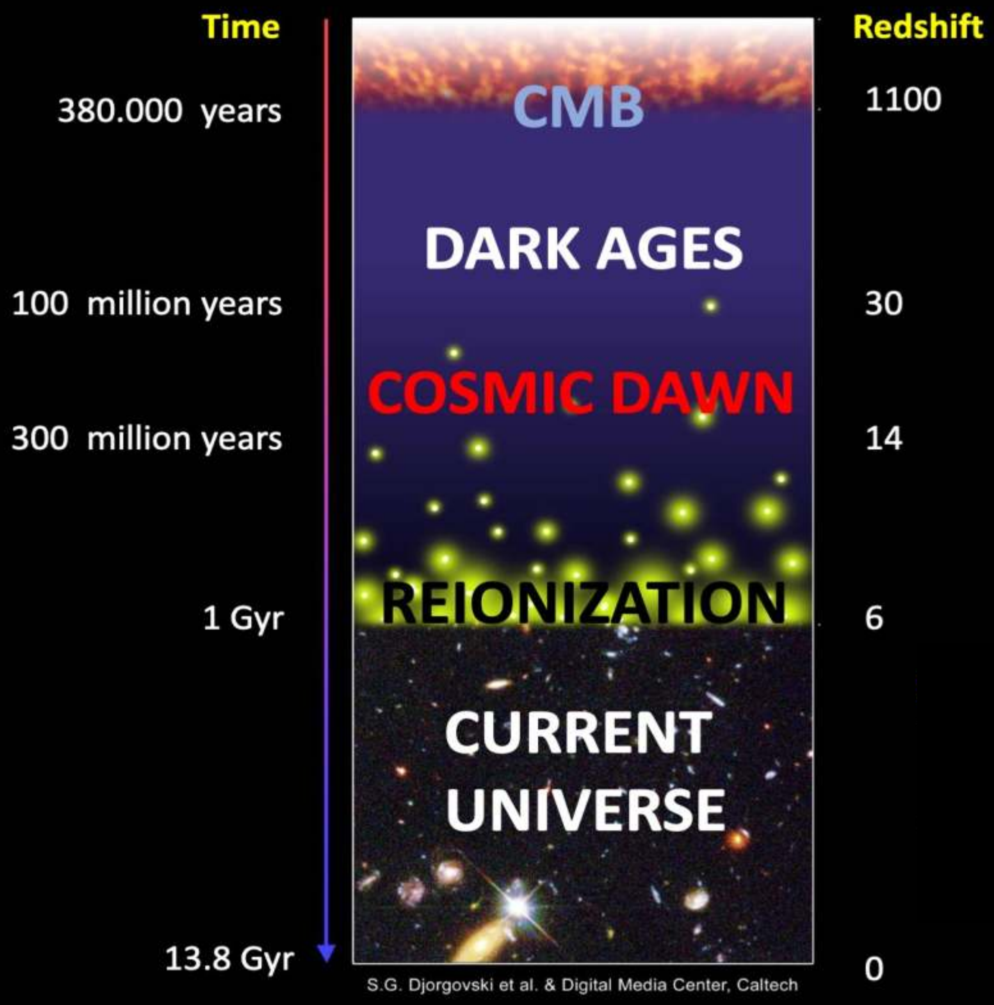
Hydrogen 21-cm Introduction

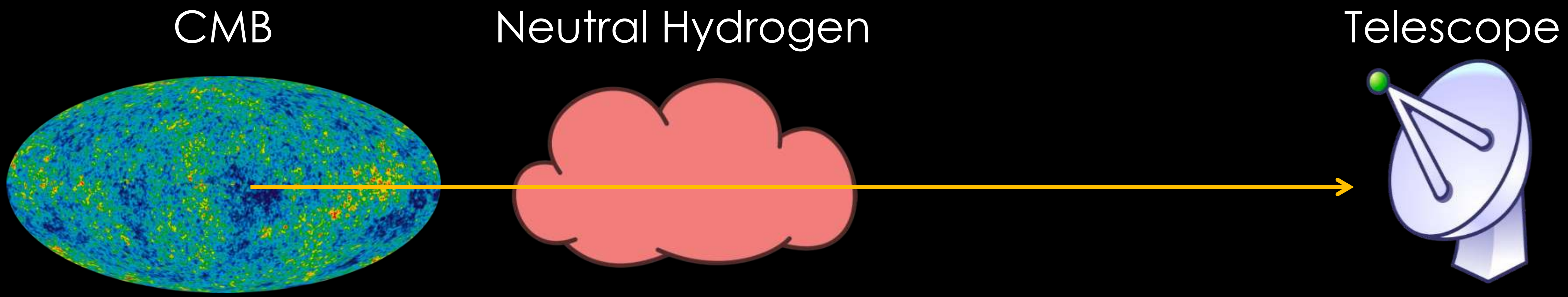
What do we know about Cosmic Dawn?



Constraints

- Universe reionized by $z \sim 6$ from Gunn-Peterson trough (Fan et al. 2002)
- Reionzation between $z \sim 7.8 - 8.8$ from CMB (Planck collaboration et al. 2016)
- JWST detecting first galaxies up to $z \lesssim 15$

What can Probe Cosmic Dawn?



Global measurement of neutral hydrogen at high redshift

Why Global Measurements of Neutral Hydrogen

Constraints

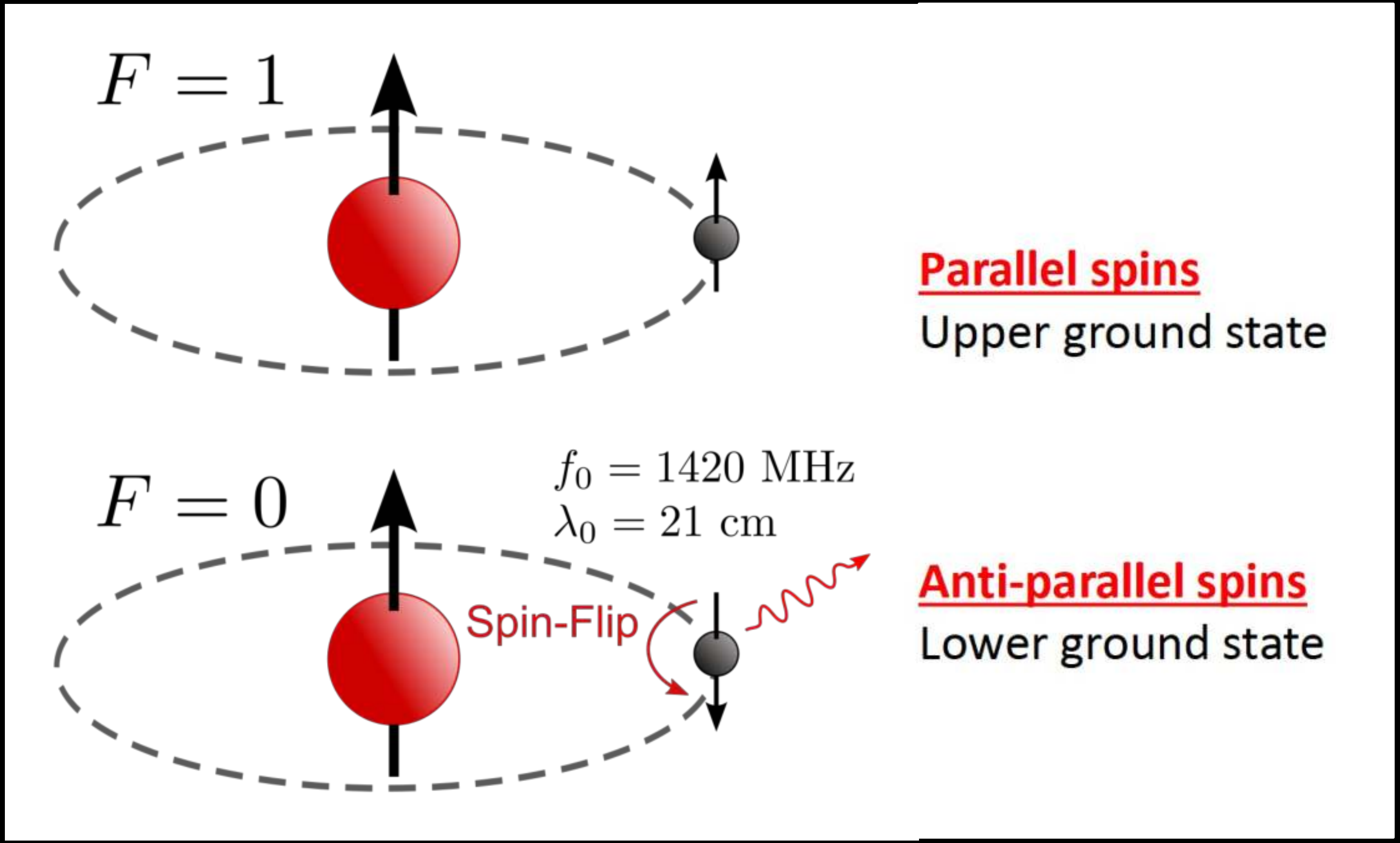
- Redshift & duration of EOR
- Star/Galaxy formation history
- Heating of the IGM

Estimates

- Fraction of neutral hydrogen
- Gas Temperature

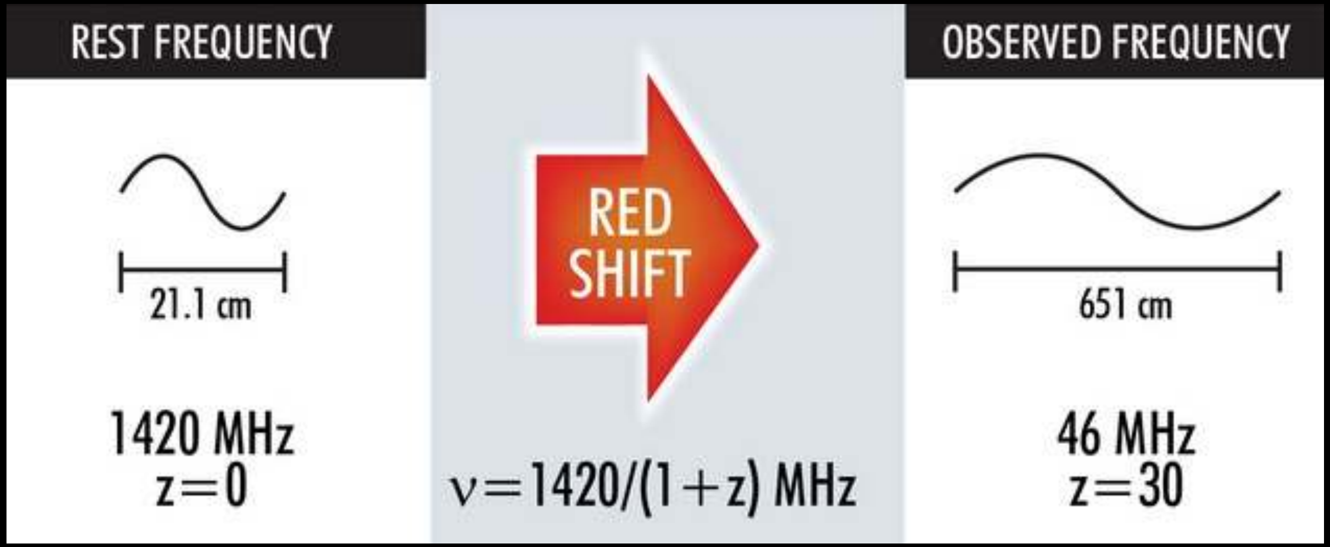
How do we get these measurements?

21-cm Emission from Neutral Hydrogen



- Takes ~10 million years for spontaneous spin flip
- Still significant due to lots of hydrogen in IGM

Redshifted 21-cm Emission



- Expansion of the universe redshifts 21-cm line
- Between $6 < z < 30$, line redshifts from 200 – 46 MHz
- Signal present in wide band of radio frequencies

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The Global Redshifted 21-cm Signal

Understanding the Global Redshifted 21-cm Signal

How is 21-cm Detected

- Spin Temperature T_S
- Differential Brightness Temperature

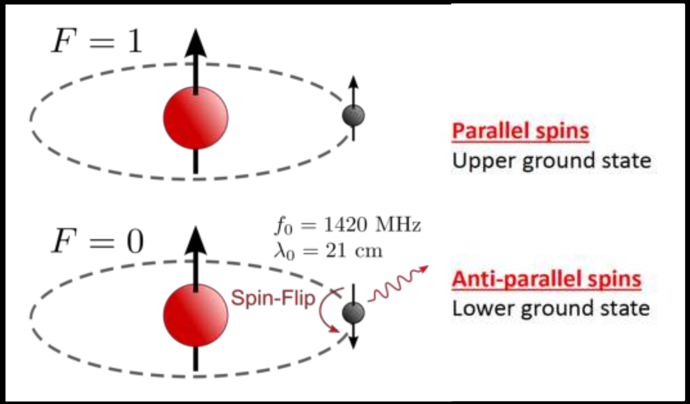
What Determines T_S

- Absorption/Emission of 21-cm from/to radio background
- Collisions with H & e^-
- Wouthuysen-Field effect

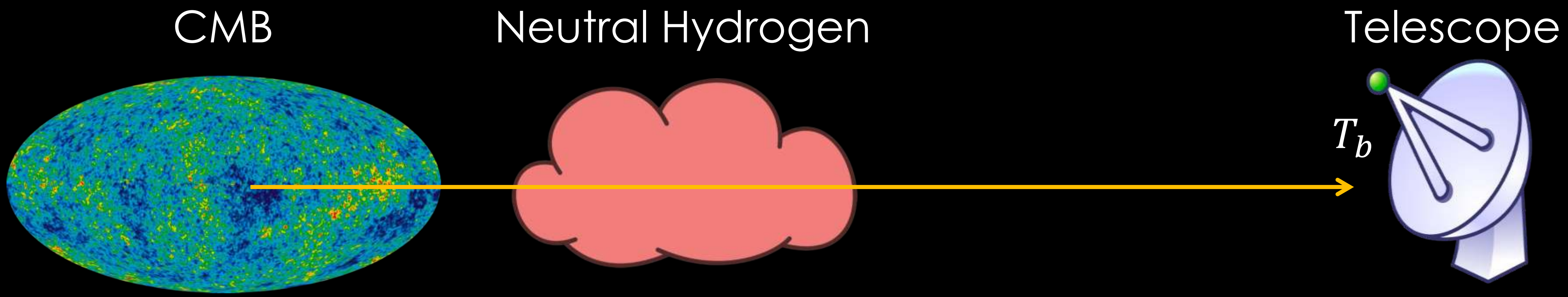
Spin Temperature (Relative Level Occupation)

$$\frac{n_{upper}}{n_{lower}} = 3 \times exp\left(\frac{-h\nu_{21}}{k_b T_S}\right)$$

spin temperature

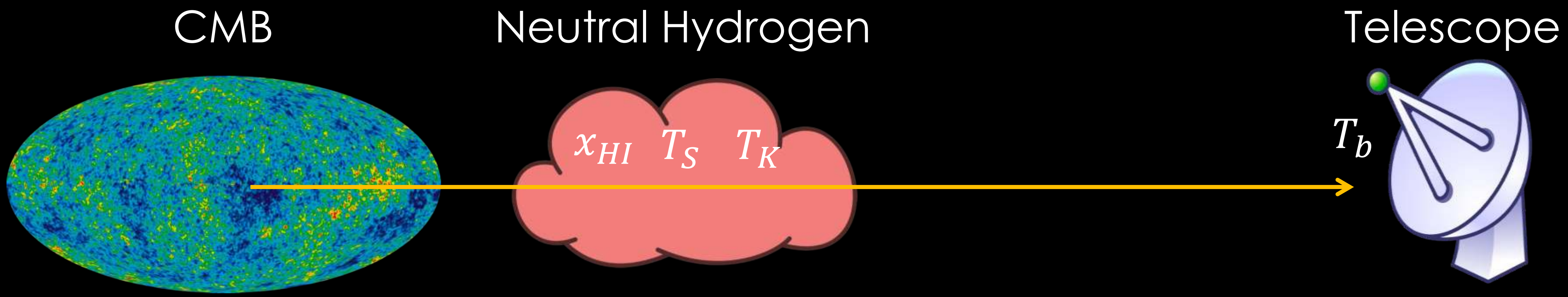


CMB Brightness Temperature (Radio Intensity)



- Measure $T_b \approx 2.7\text{K}$ from the CMB
- Optical depth of spin flip transition is extremely small

Differential Brightness Temperature



$$\underbrace{\delta T_b}_{\text{Deviation from CMB temperature}} \approx 27\ \mathrm{mK} \times (1 + \delta_b) \times \underbrace{\sqrt{\frac{1+z}{10}}}_{\text{redshift}} \times x_{HI} \times \left(\frac{T_S - T_{CMB}}{T_S}\right)$$

fractional baryon overdensity

neutral hydrogen fraction

spin temperature

Processes that Impact Spin Temperature

21-cm Detection

- Spin Temperature T_S
- Differential Brightness Temperature δT_b

What Determines T_S

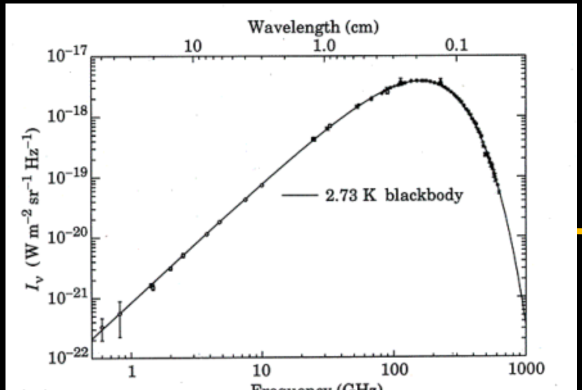
- Absorption/Emission of 21-cm from/to radio background
- Collisions with H & e^-
- Wouthuysen-Field effect

Spin Temperature Breakdown

Spin Temperature = CMB Radio Background

CMB

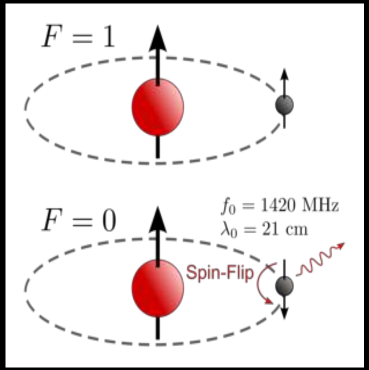
T_{CMB}



COBE

Neutral Hydrogen

Direct Radiative Transitions



Spin Temperature Breakdown

Spin Temperature $=$ CMB Radio Background $+$ Collisions

Total collisional coupling coefficient

$$x_c = x_c^{HH} + x_c^{eH} + x_c^{pH}$$

Dependence on

Number density: n_i

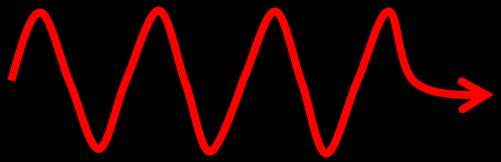
Gas Kinetic Temperature: T_K

Spin Temperature Breakdown

Spin Temperature = CMB Radio Background + Collisions + Resonant Scattering of Lyα causing spin flip

First Stars Form

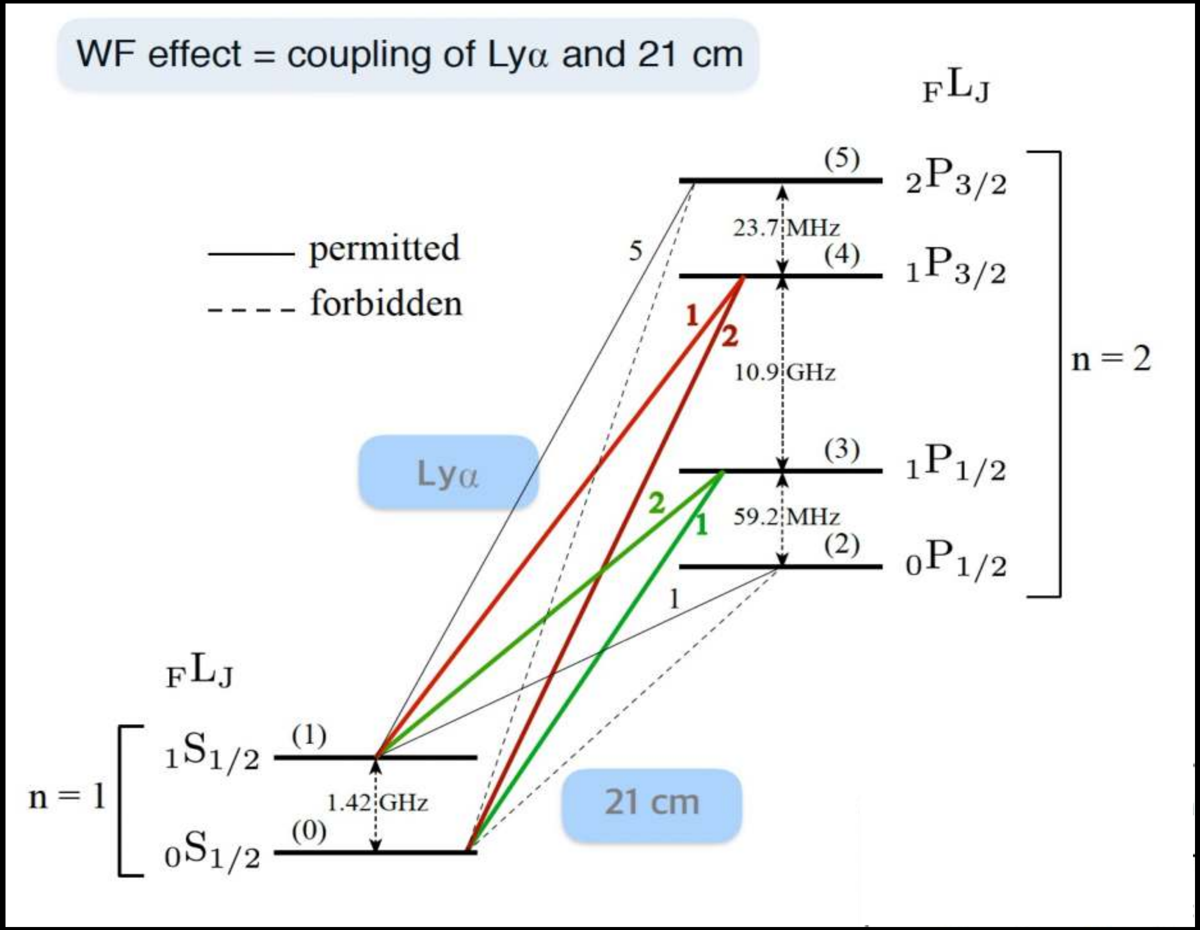
Lyα Emission



Wouthuysen-Field Effect

Wouthuysen-Field Effect

(Wouthuysen 1952; Field 1958,1959)

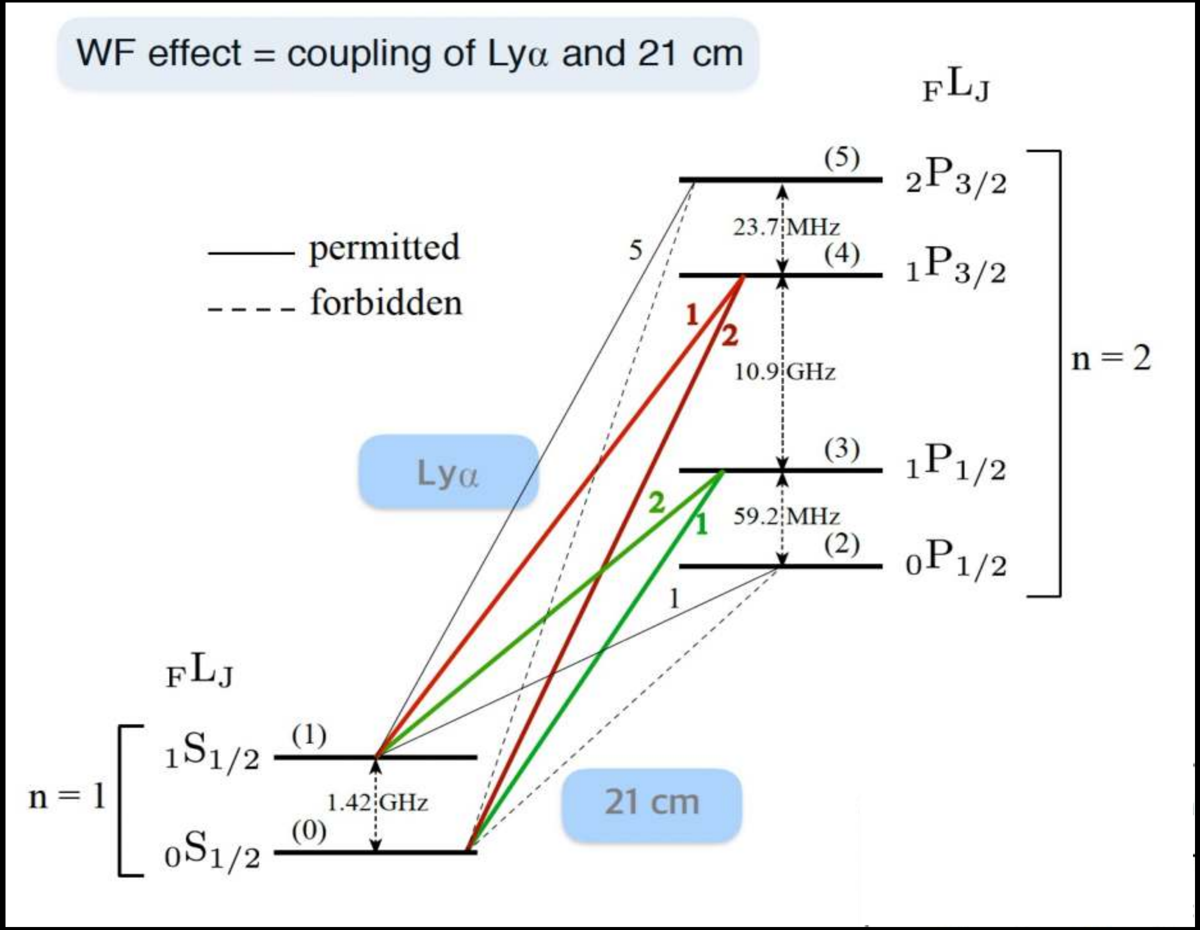


Credit: Kwang-il Seon (KASI)

- Lyα photon absorption excites atom to 2P hyperfine states
- Emission of Lyα can relax atom to ground state hyperfine levels
- A spin-flip will occur when relaxing to ground state from certain hyperfine levels

Wouthuysen-Field Effect

(Wouthuysen 1952; Field 1958,1959)



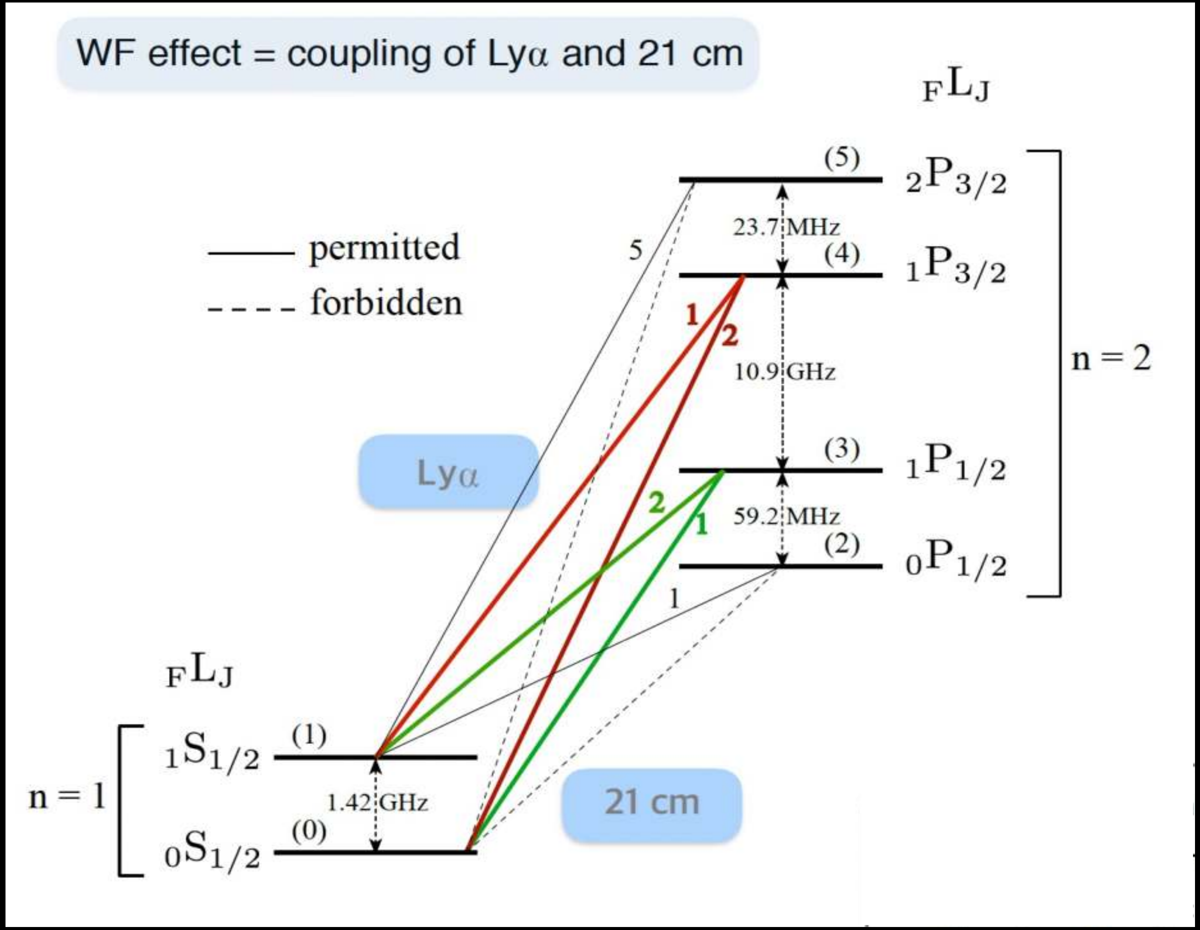
Credit: Kwang-il Seon (KASI)

<u>Thermodynamic Equilibrium</u>

- Large number of scatterings leads to blackbody-like spectrum corresponding to T_K
- Lyα couples with the hyperfine state of hydrogen
- Spin temperature equals gas kinetic temperature

Wouthuysen-Field Effect

(Wouthuysen 1952; Field 1958,1959)



Credit: Kwang-il Seon (KASI)

Takeaway

- Lyα pumping of the 21-cm spin temperature
- Lyα photons couple T_S with T_K

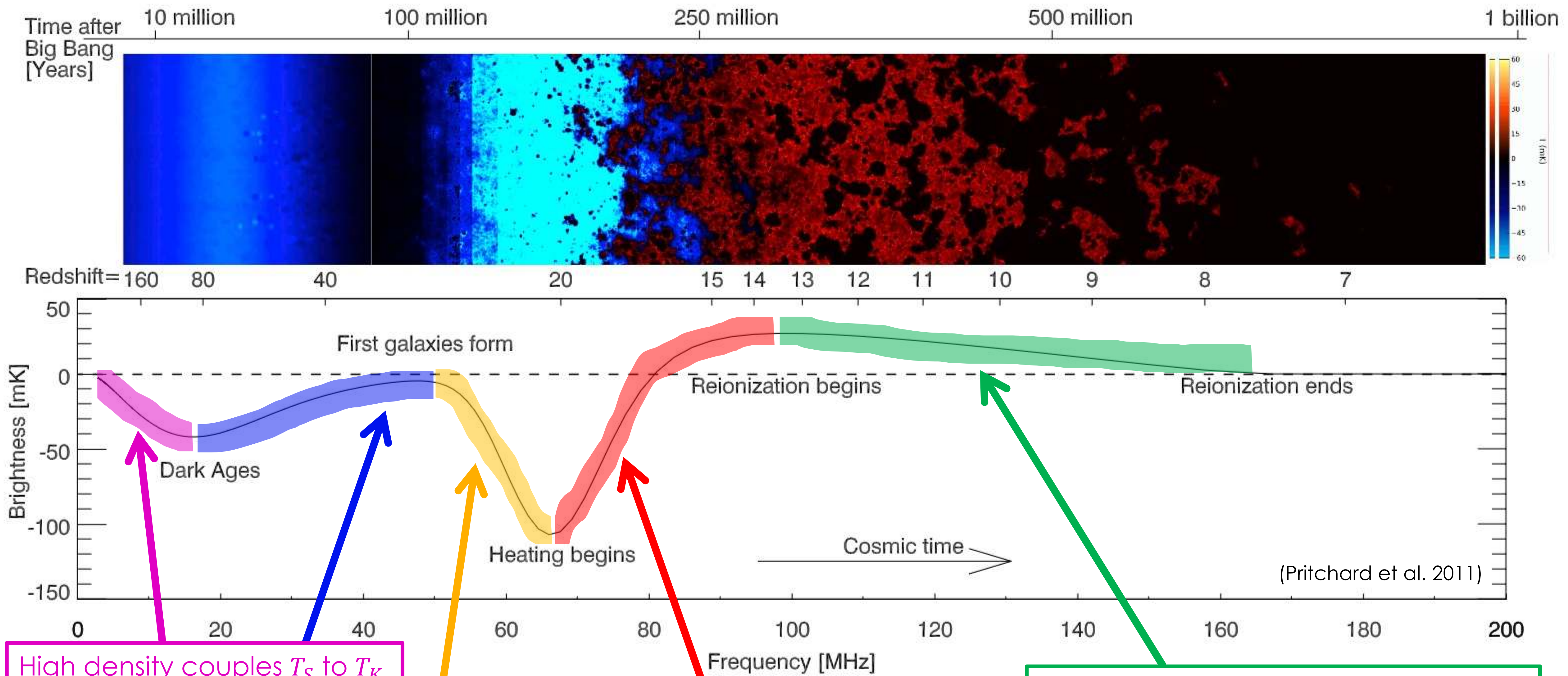
x_α: Coupling coefficient due to scattering of Lyα photons

T_α: Color temperature of Lyα radiation field at Lyα freqiency

Spin Temperature Breakdown

Spin Temperature = CMB Radio Background + Collisions + Resonant Scattering of Lyα causing spin flip

$$T_S^{-1} = \frac{T_{CMB}^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$



High density couples T_S to T_K but gas cools adiabatically as universe expands

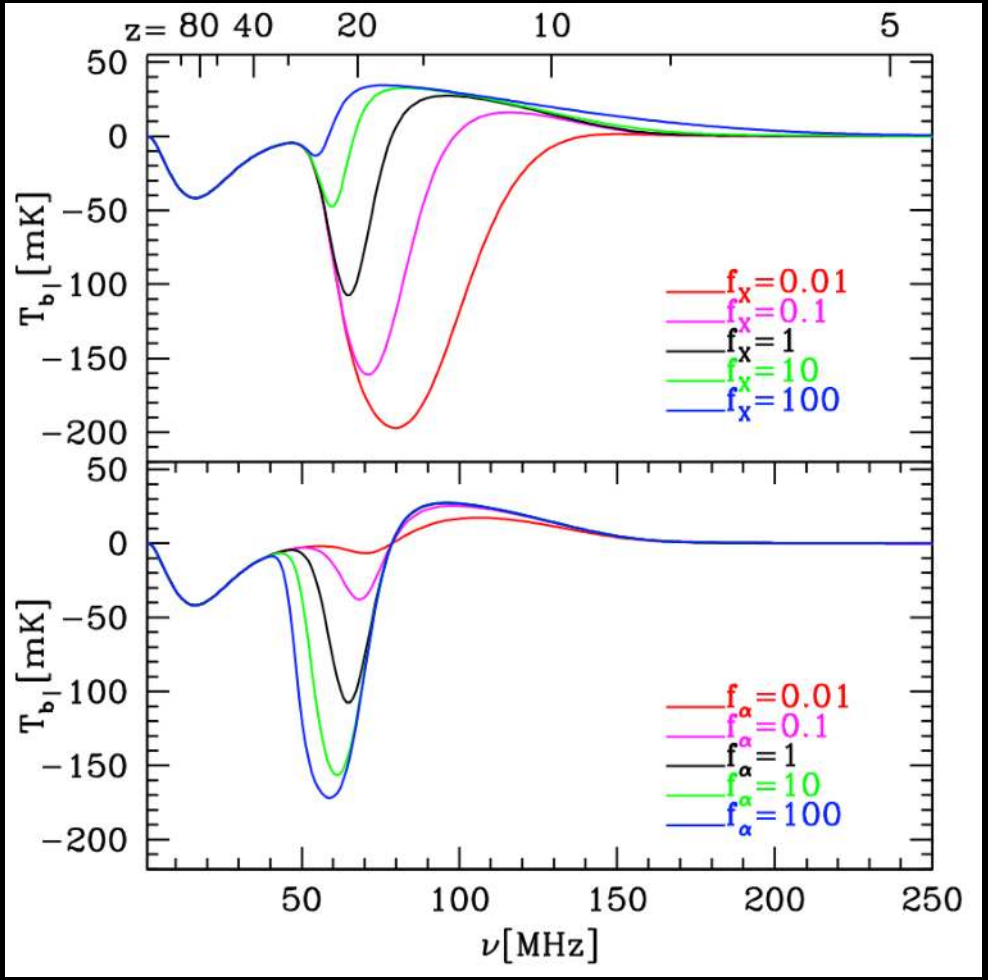
Density too low for collisions, so T_S starts to follow T_{CMB}

First stars produce Lyα, which makes T_S couple to T_α, which in turn is coupled to T_K

Luminous sources heat IGM (shocks & X-rays from AGN/SNRs). T_S increases with T_{IGM} until $T_S \gg T_{CMB}$

Reionization → less & less HI until only signal is from small dense pockets

Impact of Lyα & X-ray Emission on Signal



(Pritchard et al. 2011)

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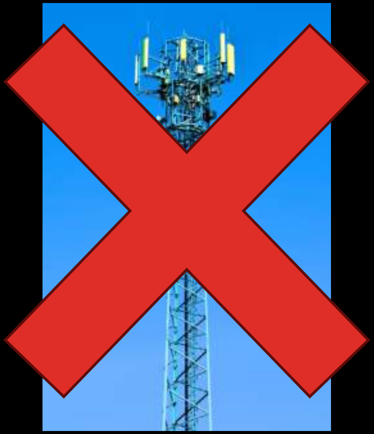
Observation of 21-cm Signal with EDGES

Experiment to Detect the Global EoR Signature

Radio Telescope Requirements to Observe 21-cm Signal

- Need to detect a globally averaged signal over a wide band of frequencies

Can't use radio interferometers (LOFAR & HERA)

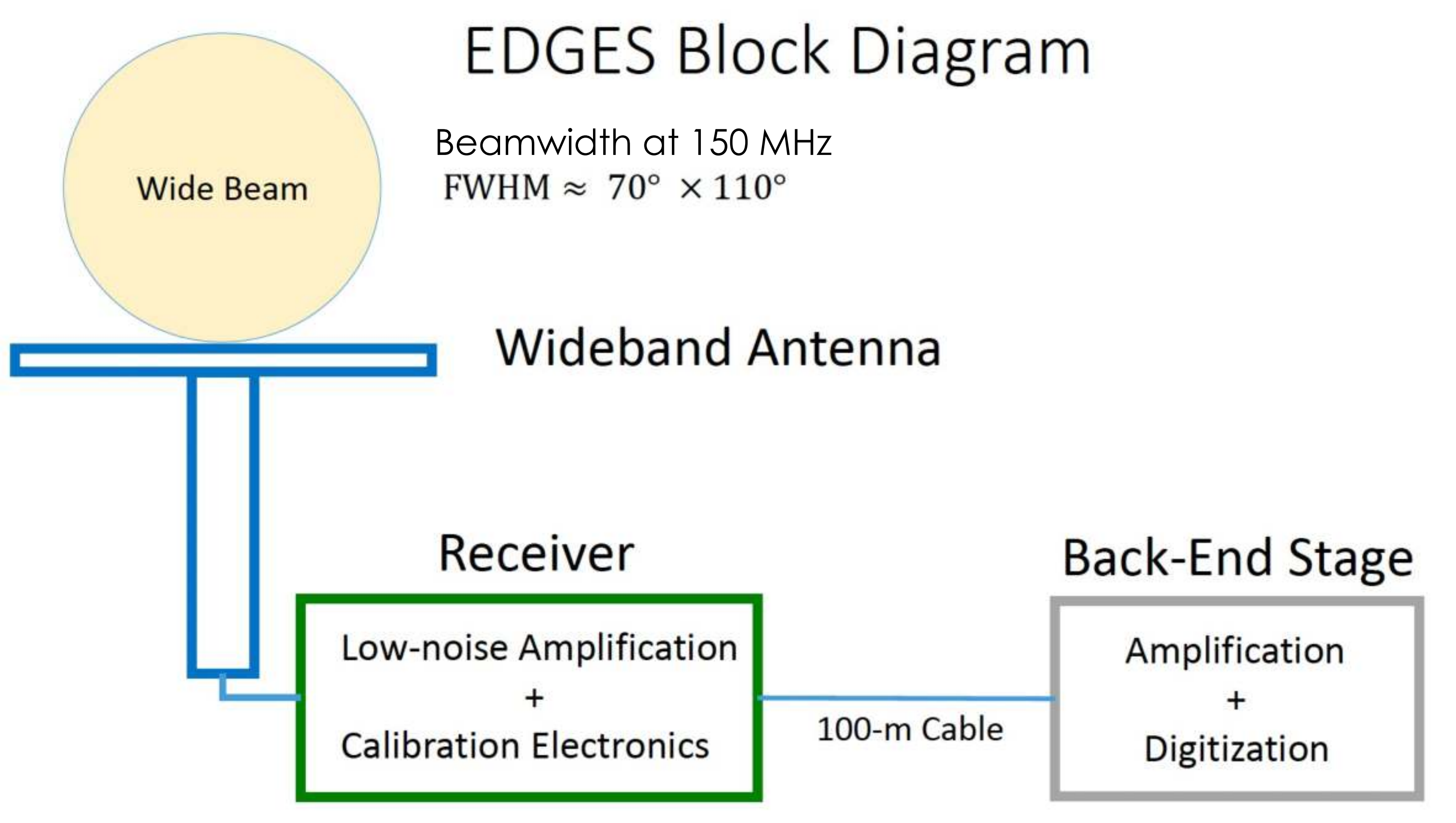


- Need radio-quiet conditions below 200 MHz

Telescope must be in a remote location

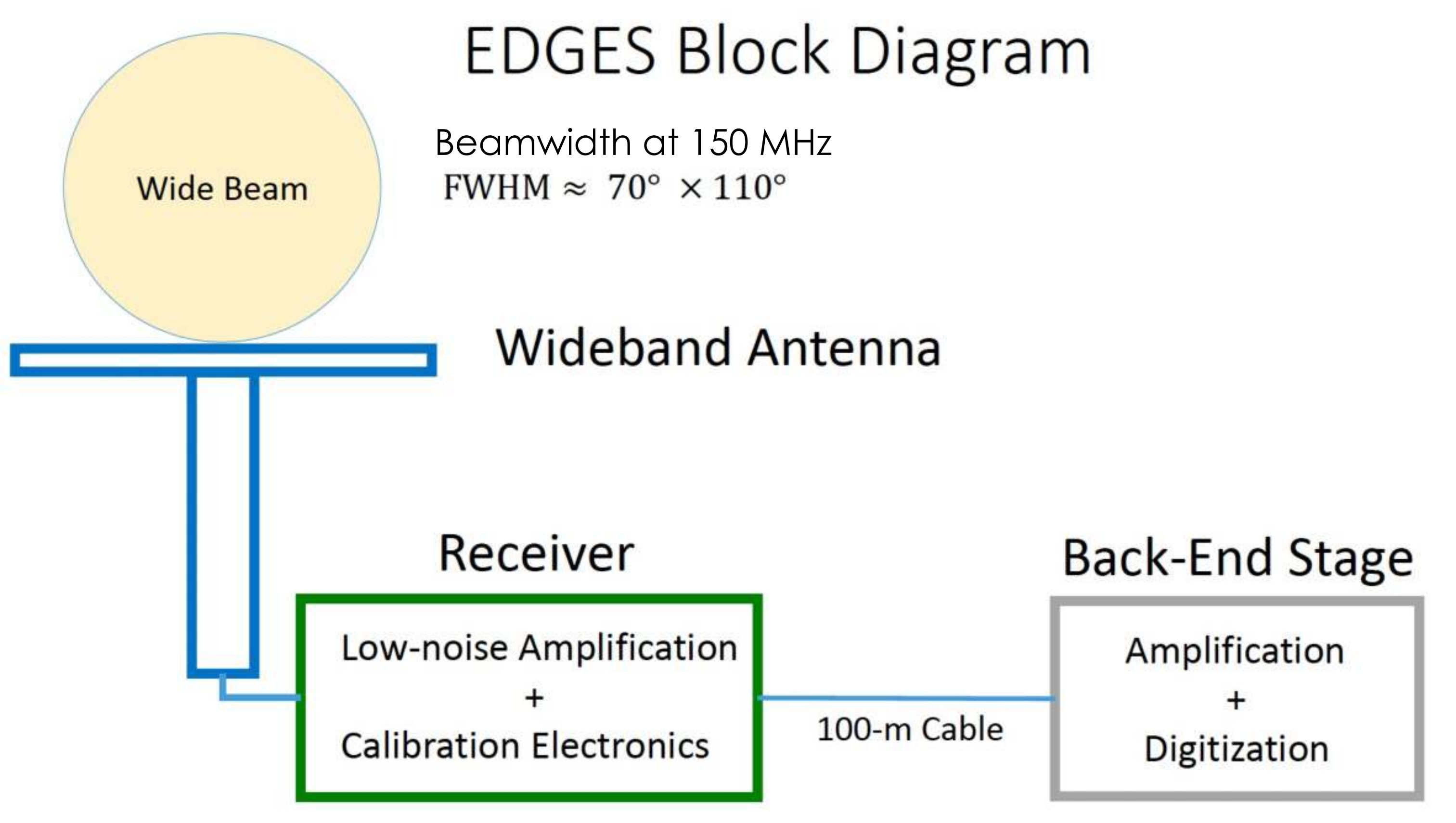
EDGES Location

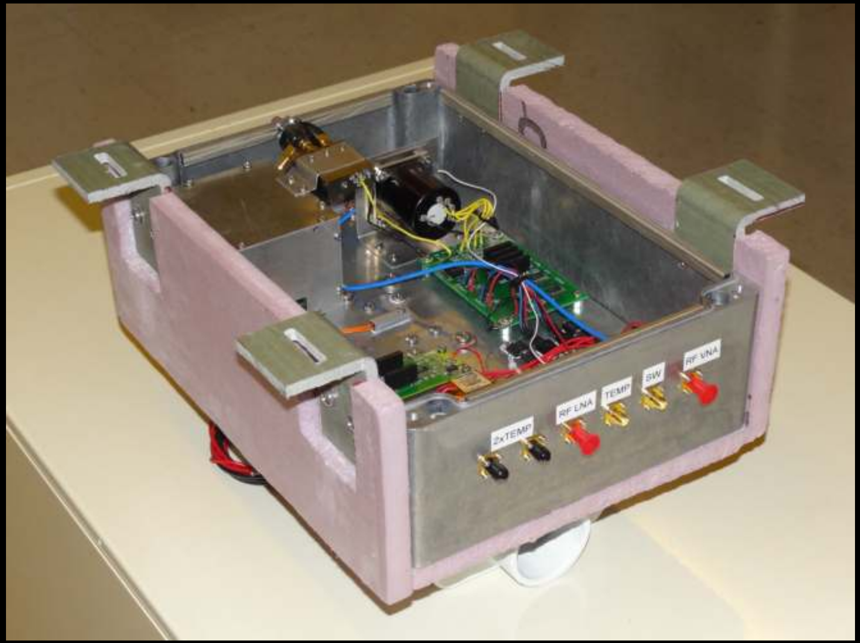
EDGES Design: Antenna & Ground Plane



(Mozdzen et al. 2016; Monsalve et al. 2017)

EDGES Design: Receiver & Data Output

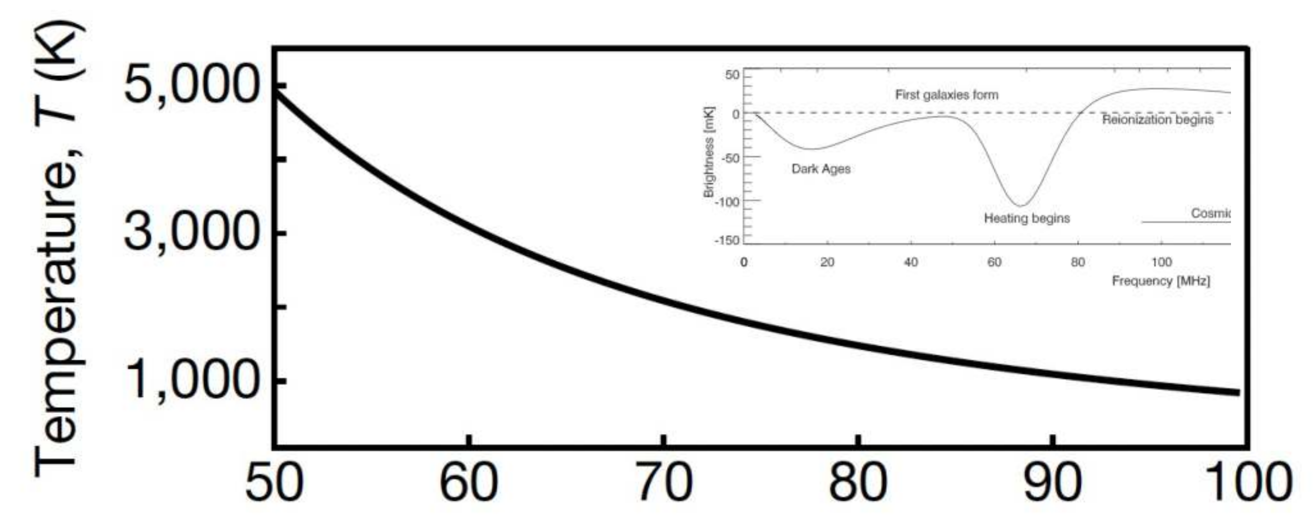




(Mozdzen et al. 2016; Monsalve et al. 2017)

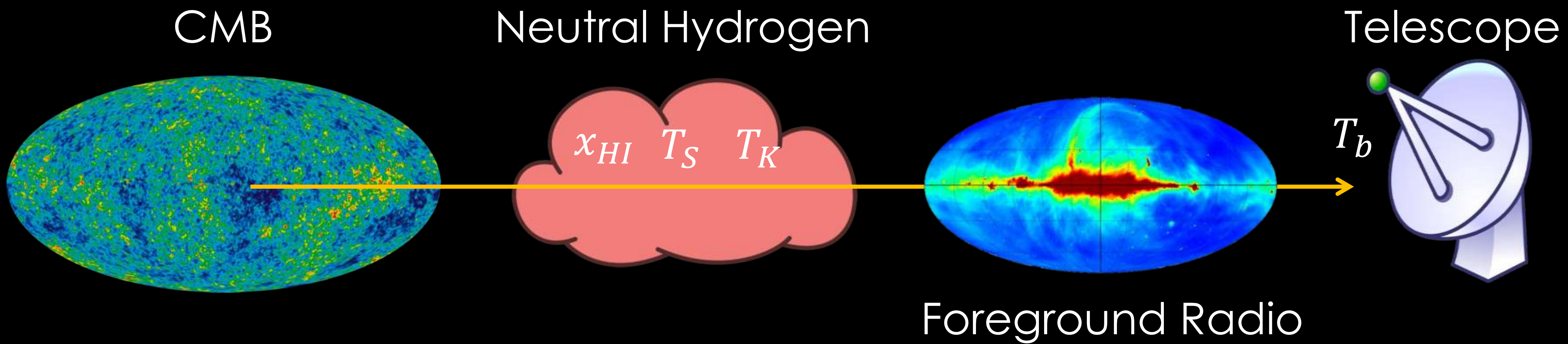
EDGES 21-cm Signal Observation

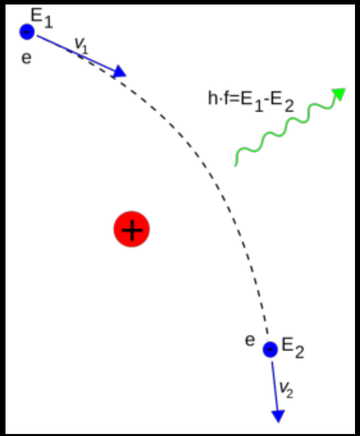
(Bowman et al. 2018)



- EDGES sky measurement in units of brightness temperature
- Power-law spectrum differs from predicted 21-cm signal

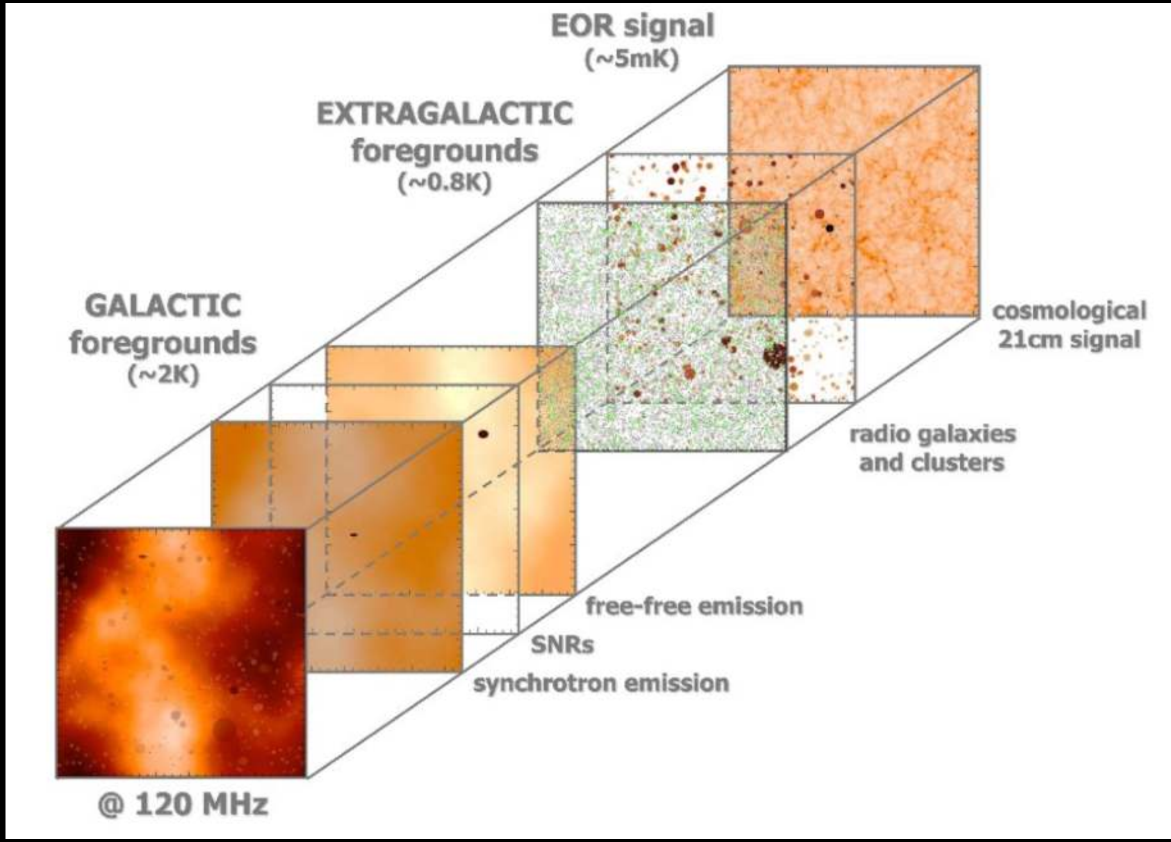
What about Foreground Radio Emission?



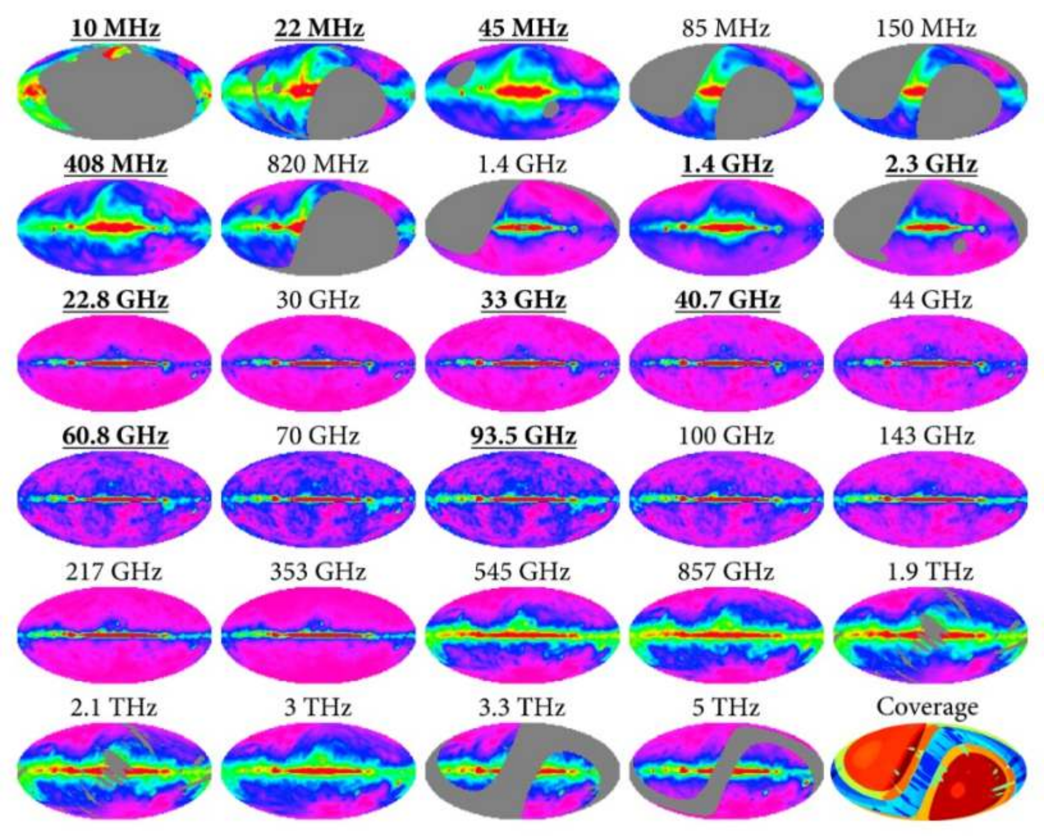


- Galactic synchrotron & free-free emission
- Present at the same frequencies as 21-cm signal

Sources of Foreground Radio Signal

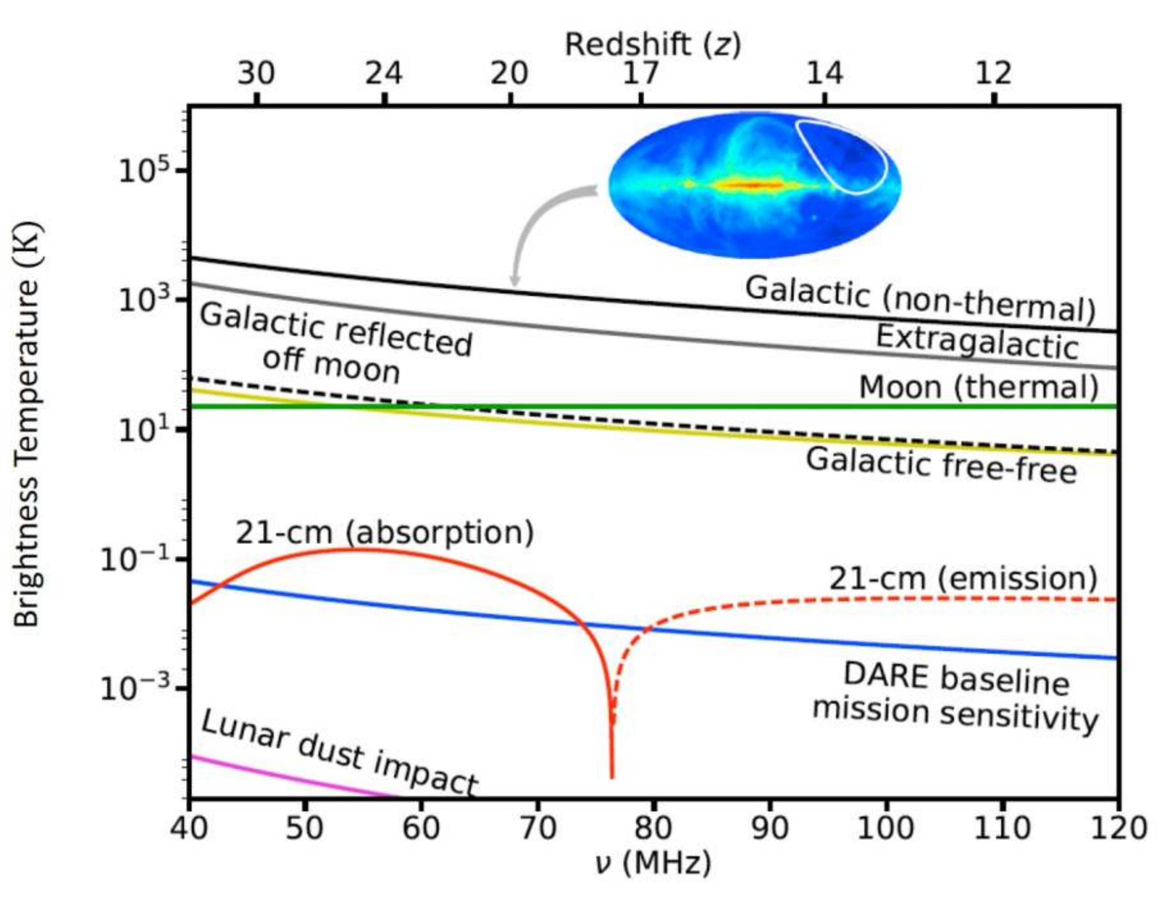


(Mellema et al. 2013)



(Zheng et al. 2017)

How Bright is the Foreground Radio Emission?



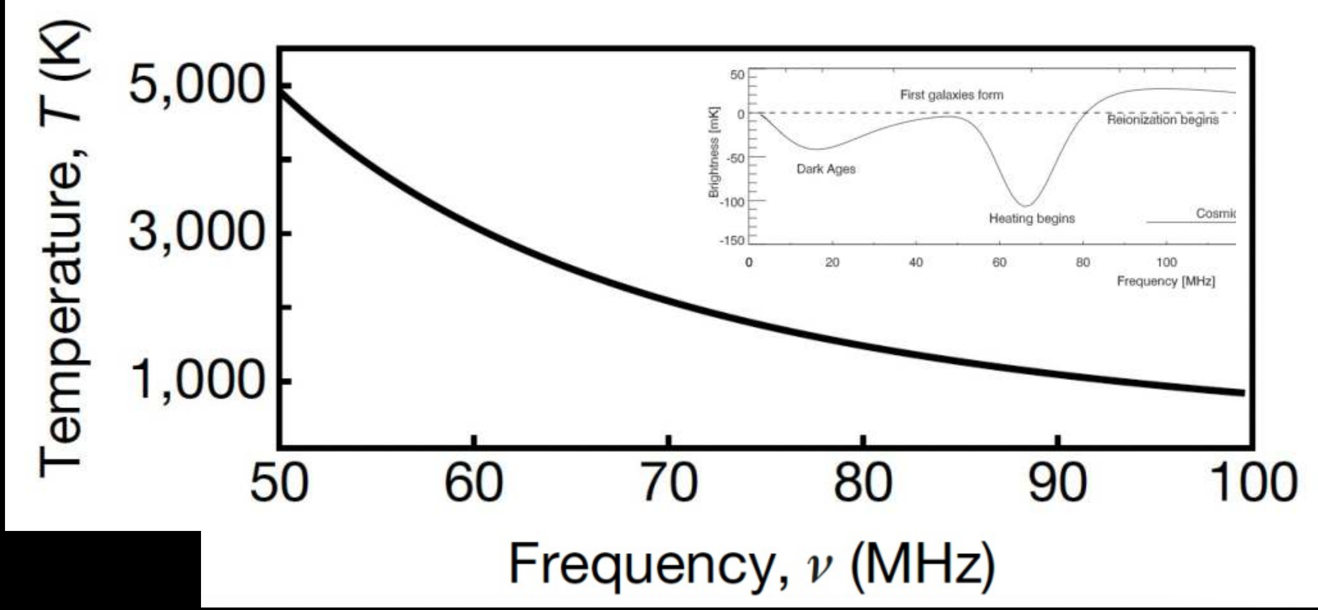
Dark Ages Radio Explorer (University of Colorado Boulder)

- Galactic free-free emission is 4 orders of magnitude larger!
- Global 21-cm signal can be distorted & weakened by ionosphere (Shen et al. 2021)

EDGES 21-cm Signal Observation

(Bowman et al. 2018)

Observation with Foreground Emission

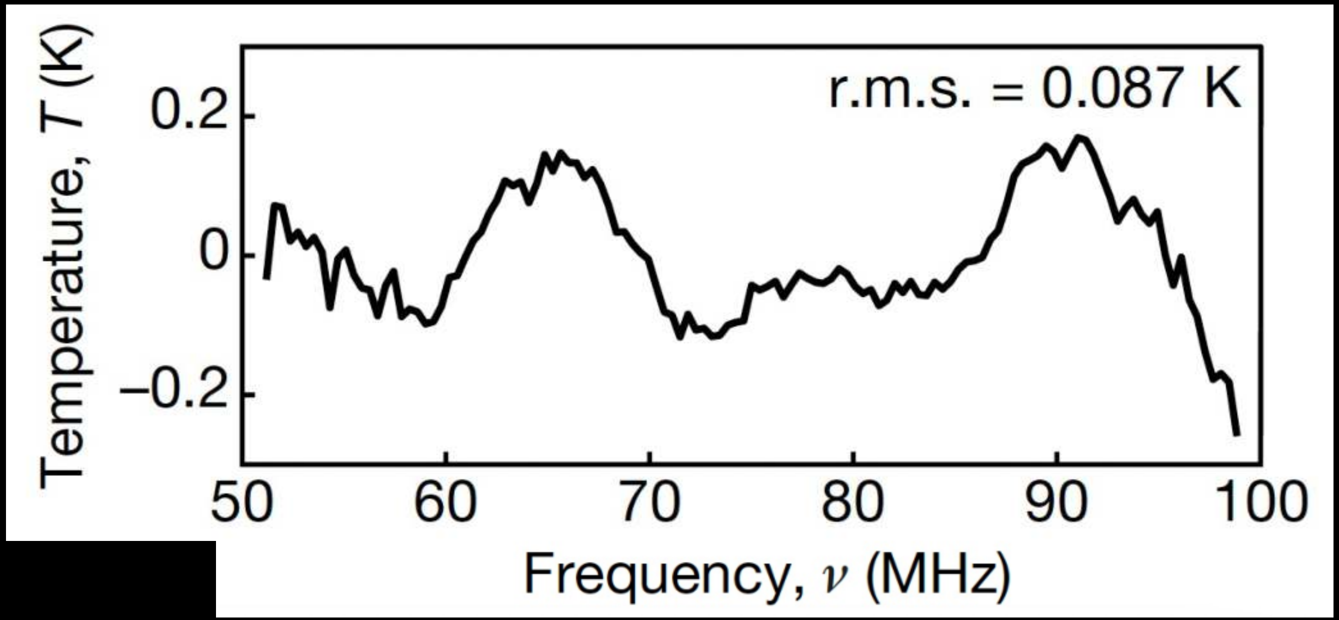


- At high galactic latitudes, foreground emissions should be smooth over frequency
- Fit & subtract low order polynomial to remove galactic synchrotron & ionosphere
- Any issues with foreground subtraction has **a large impact** on extracted signal

EDGES 21-cm Signal Observation

(Bowman et al. 2018)

Foreground Emission Subtracted

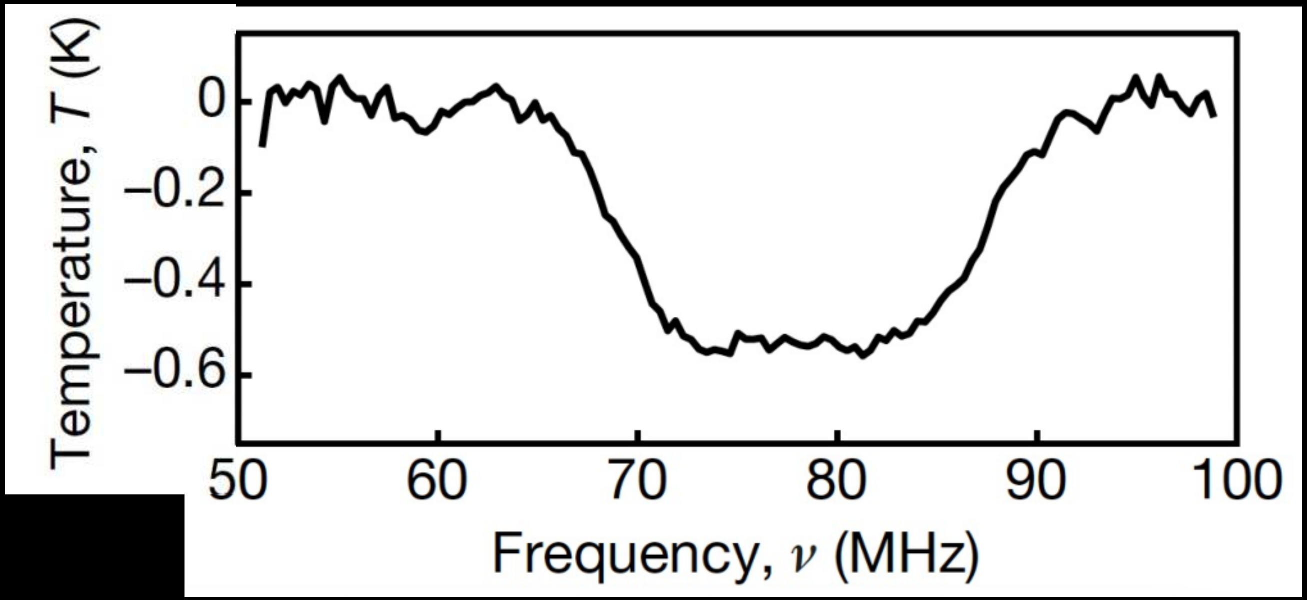


- Residuals after foreground subtracted
- Simultaneously fit foreground & expected 21-cm signal
- Get model of 21-cm absorption with residuals

EDGES 21-cm Signal Observation

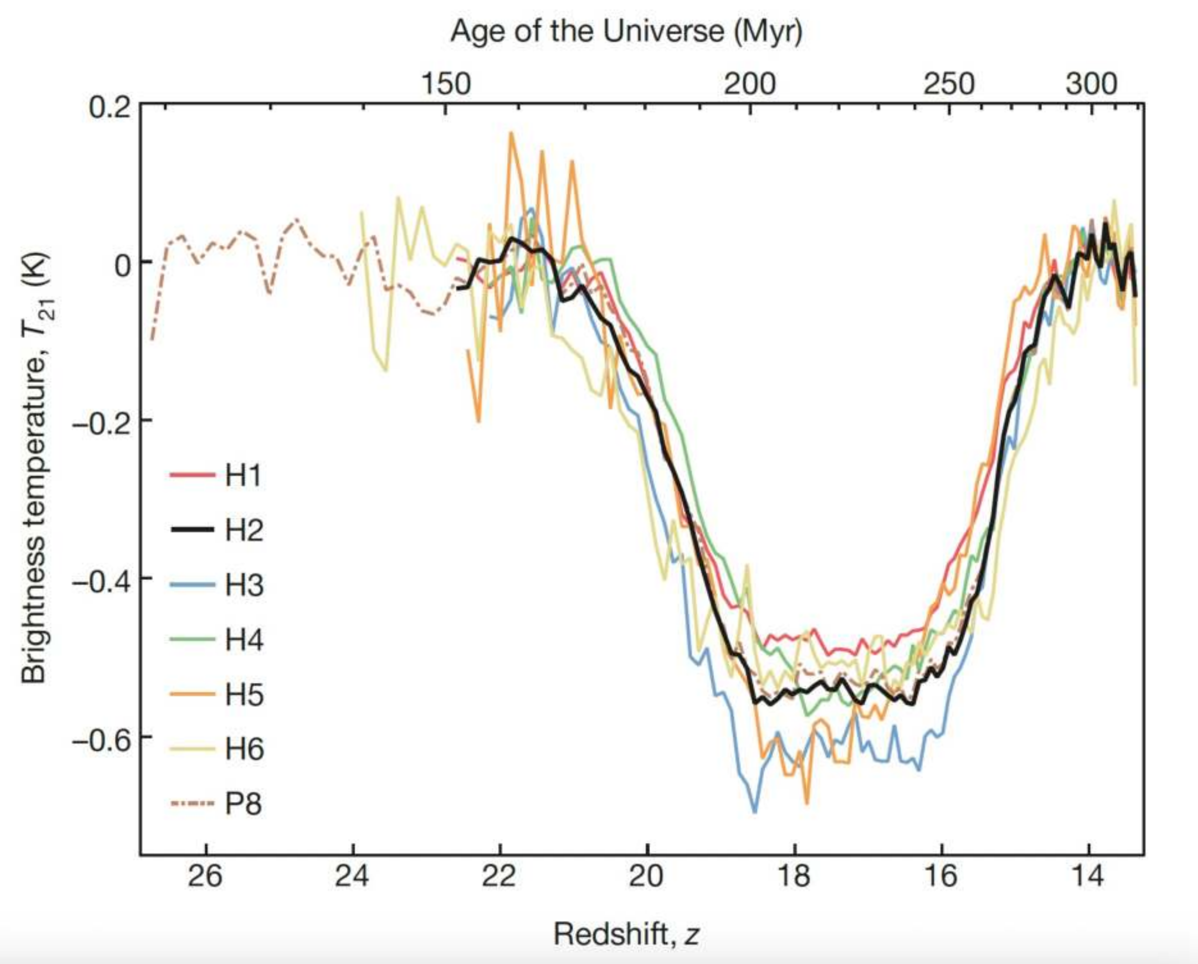
(Bowman et al. 2018)

Best Fit 21-cm Absorption with Residuals



- Residuals after foreground subtracted
- Simultaneously fit foreground & expected 21-cm signal
- Get model of 21-cm absorption with residuals

Implication of EDGES 21-cm Absorption



(Bowman et al. 2018)

- Amplitude of absorption factor of 2 larger than expected
- The absorption amplitude is limited by minimum temperature of neutral hydrogen
- Neutral hydrogen adiabatically cools due to cosmic expansion
- Additional cooling through baryons scattering with dark matter?

21-cm Signal not Observed with SARAS-3

Shaped Antenna measurement of the background RAdio Spectrum 3

SARAS-3 Overview

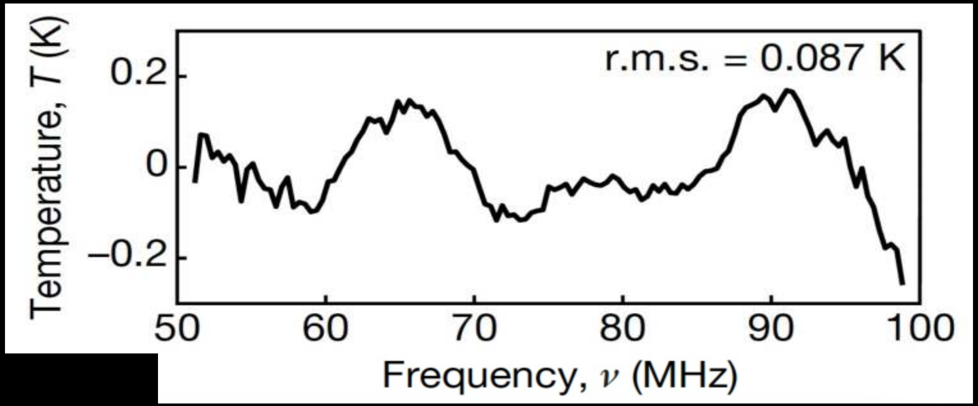
(Singh et al. 2021)

- Calm lake ensures no reflections for more than 100 meters in any horizontal direction
- Nearby faint reflections can enhance specific radio wavelengths
- Varies antenna's observing area & measured brightness

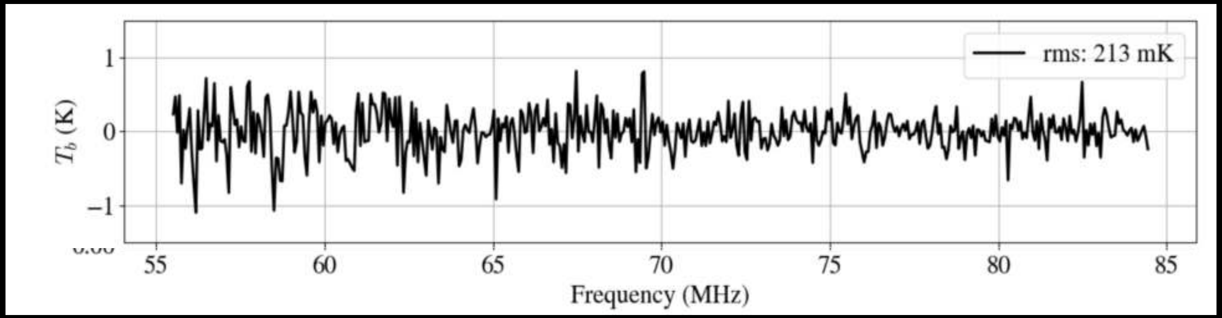
SARAS-3 does not detect EDGES 21-cm Signal

(Singh et al. 2021)

EDGES Foreground Emission Subtracted



SARAS-3 Foreground Emission Subtracted



Possible Origin of EDGES Signal

- Edges of metal mesh to block ground emission had reflections
- Ionosphere can couple with nonuniform foregrounds (Shen et al. 2021)
- Detailed modeling of antenna & instrumental beam response is needed (Mahesh et al. 2021; Antsey et al. 2021)

4

Conclusions

Takeaways

- Global redshifted 21-cm signal is a unique probe of the physics during cosmic dawn

- EDGES claimed to detect 21-cm absorption, but the SARAS-3 team observed no trace of the signal

- Mitigate systematics in measuring 21-cm signal:
  - ➢Using different instruments such as REACH (de Lera Acedo et al. 2022)
  - ➢Observations from the far side of the moon (Burns et al. 2021a)

References

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