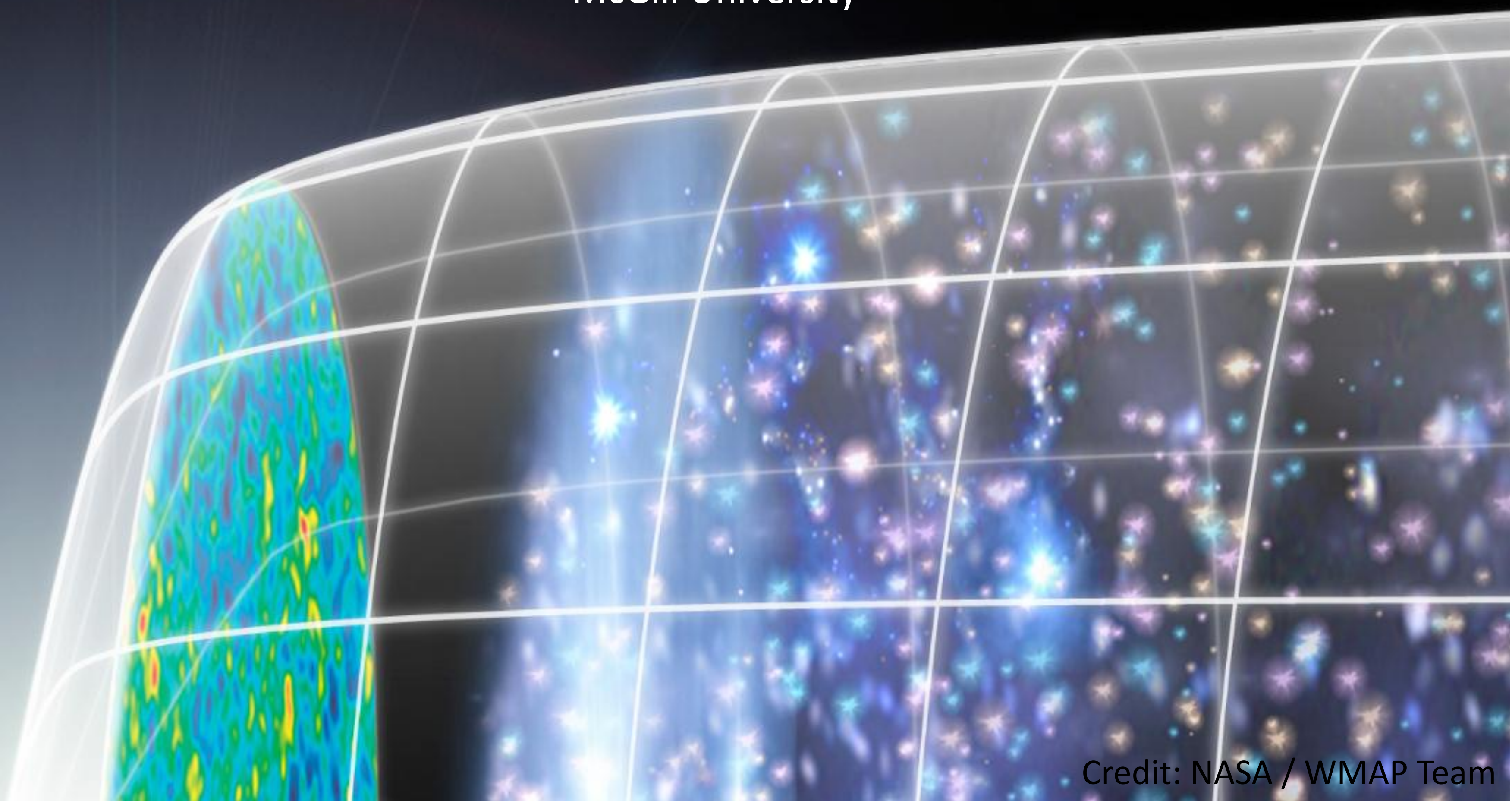
13th Conference on the Intersections of Particle and Nuclear Physics

June 2, 2018

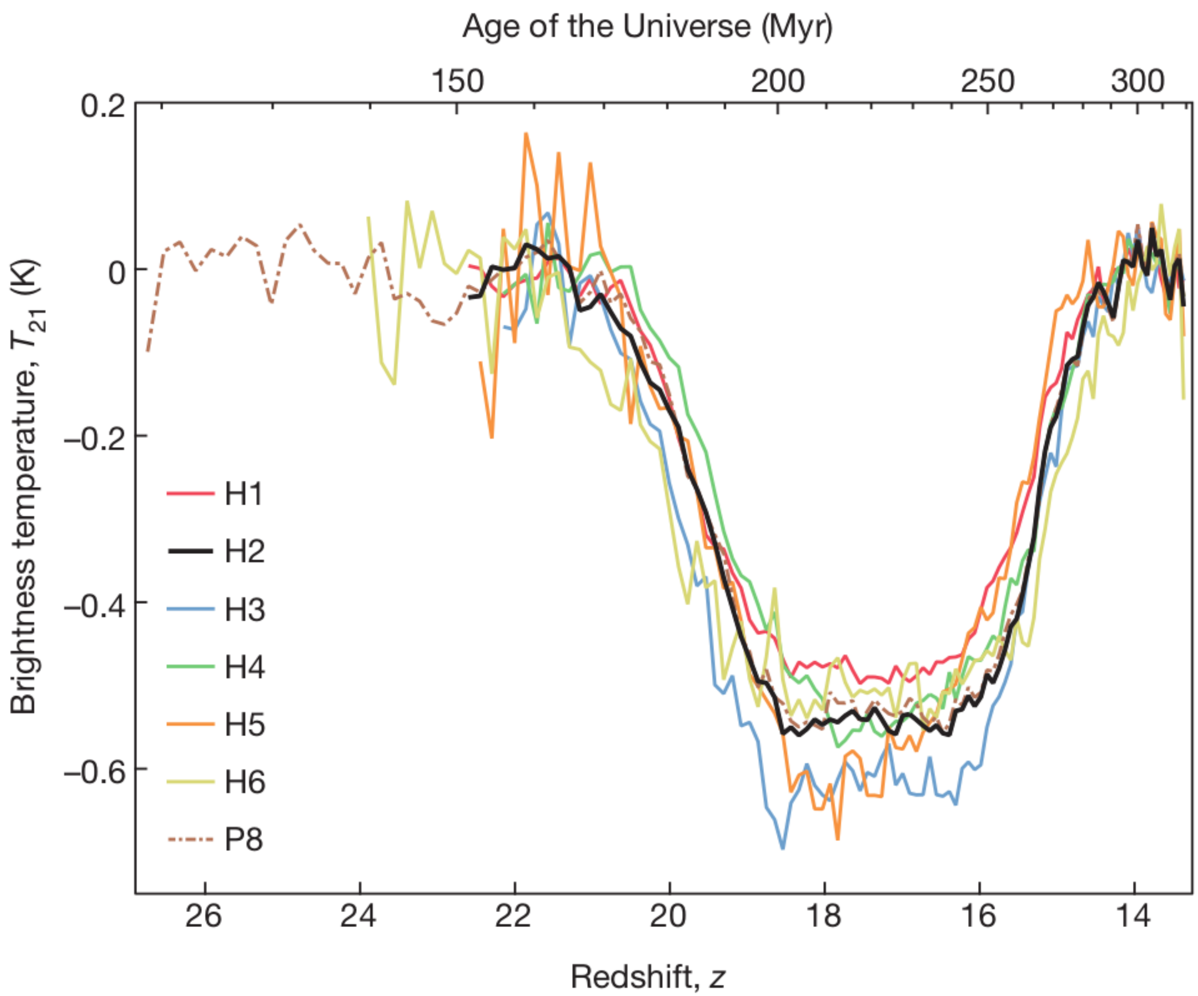
Fingerprints of the First Stars in the Sky-Averaged Radio Spectrum

Raul A. Monsalve

McGill University



Credit: NASA / WMAP Team



J. Bowman, A. Rogers, **R. Monsalve**, T. Mozdzen, N. Mahesh 2018, **Nature**, 555, 67

Summary

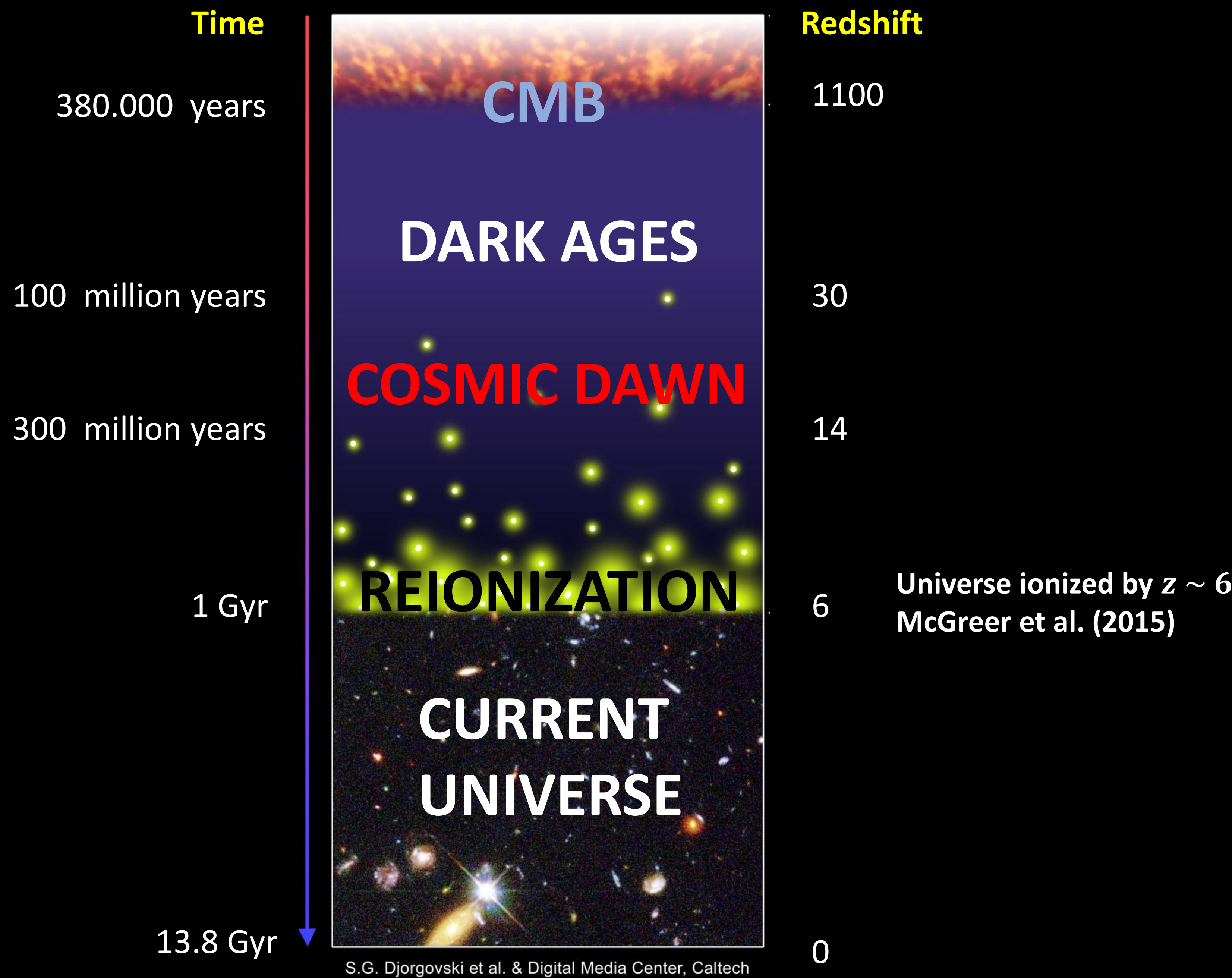
1) The **EDGES experiment** has **detected an absorption feature** in the sky-averaged spectrum centered at 78 MHz.

2) This is **consistent with stars forming by 180 Myrs after the Big Bang**.

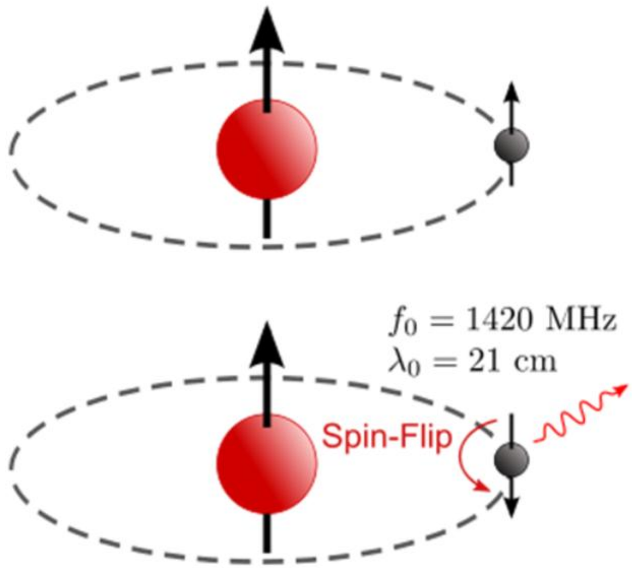
3) Feature is **deeper, sharper, and earlier** than expected.

4) We **remain agnostic** regarding the **interpretation**.

5) We are **working to verify the measurement**.


Time
380.000 years
100 million years
300 million years
1 Gyr
13.8 Gyr
CMB
DARK AGES
COSMIC DAWN
REIONIZATION
CURRENT
UNIVERSE
Redshift
1100
30
14
6
0
Universe ionized by $z \sim 6$
McGreer et al. (2015)
S.G. Djorgovski et al. & Digital Media Center, Caltech

Emission at 21 cm from Hydrogen Atom



Parallel spins

Upper ground state

Anti-parallel spins

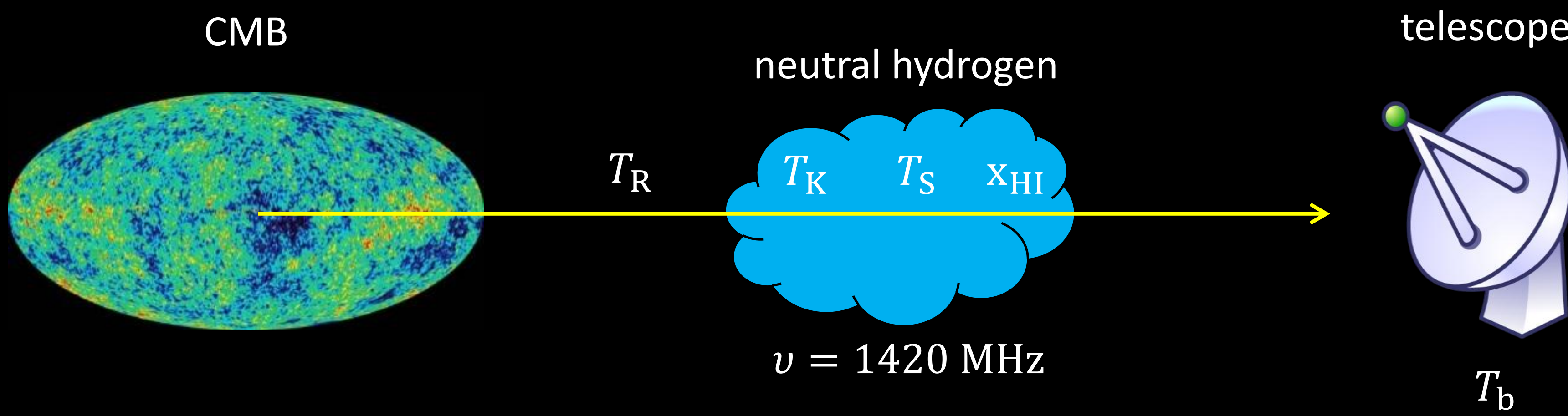
Lower ground state

Due to Cosmological Expansion

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

Redshift	Frequency
0	1420 MHz
6	200 MHz
13	100 MHz
140	10 MHz

21-cm Cosmology



21-cm Brightness Temperature

$$T_{21}(z) \approx 28\ \text{mK} \cdot \sqrt{\frac{1+z}{10}} \cdot x_{HI} \cdot \left(\frac{T_S - T_R}{T_S}\right)$$

radiation temperature

fraction of neutral hydrogen

spin temperature

Spin Temperature (T_S)

$$\frac{n_{\text{upper}}}{n_{\text{lower}}} = 3 \cdot exp\left(-\frac{h \cdot \upsilon_{21\text{cm}}}{k_{\text{b}} \cdot T_S}\right)$$

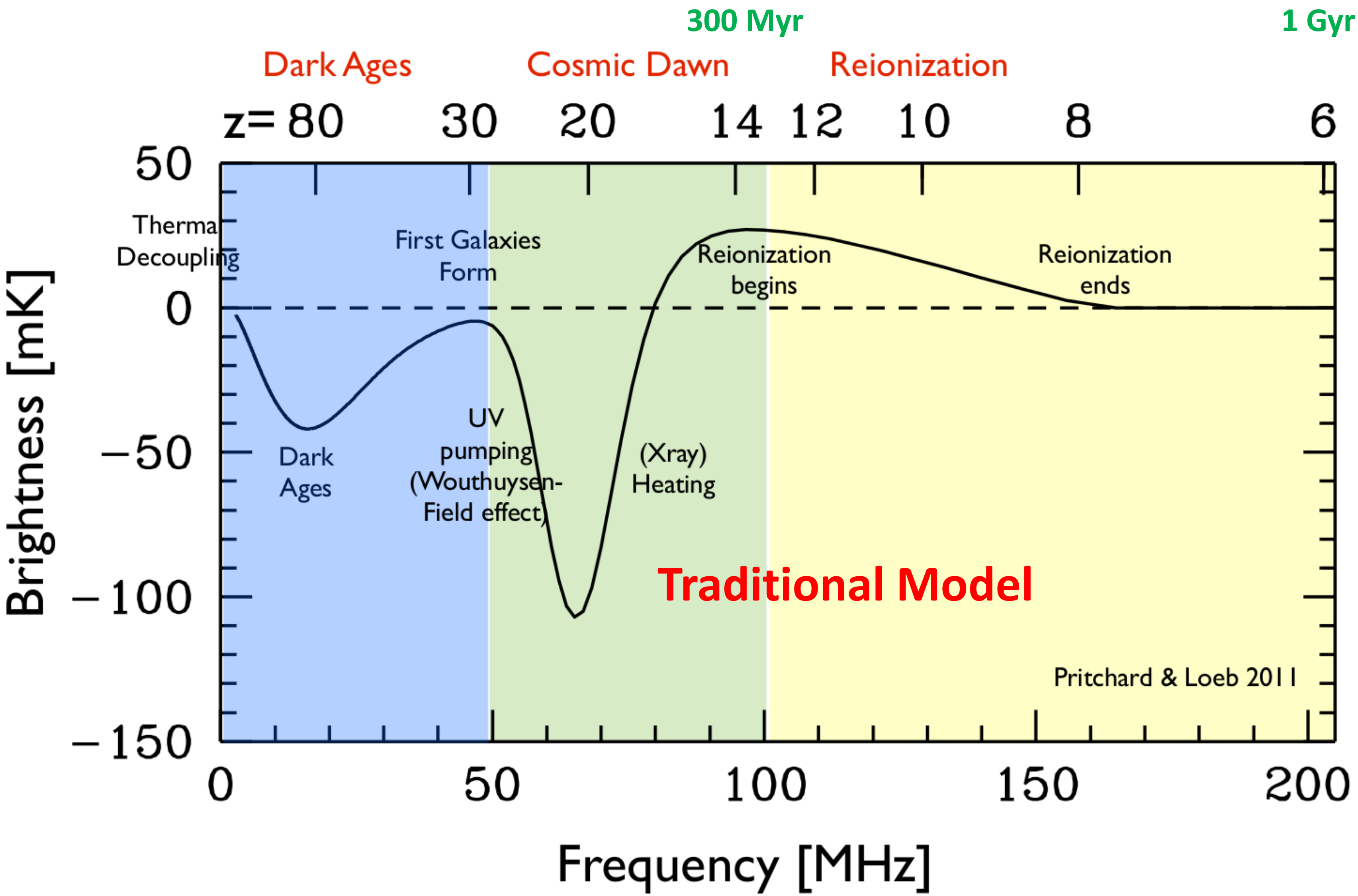
$\upsilon_{21\text{cm}} = 1420\ \text{MHz}$
h : Planck constant
k_{b} : Boltzmann constant

http://www.cv.nrao.edu/course/astr534/HILine.html

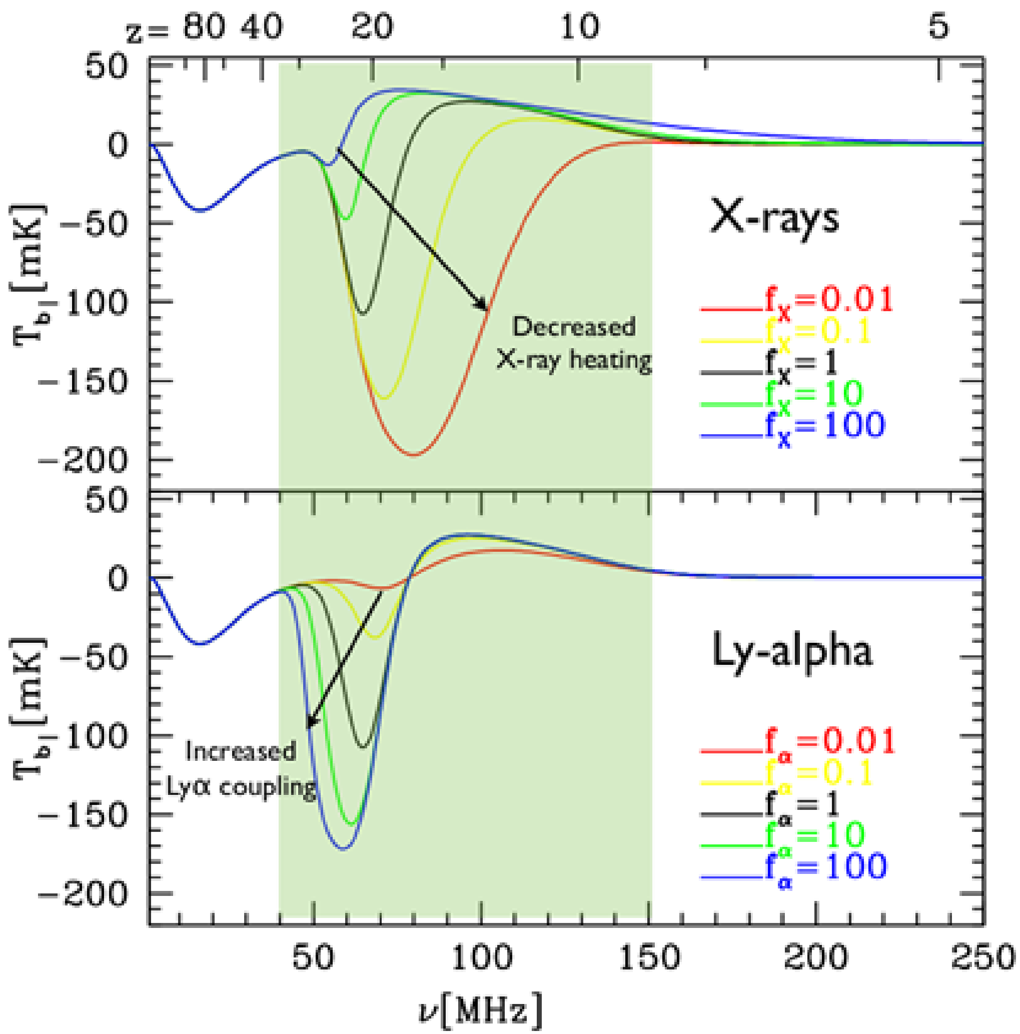
$$T_S^{-1} \approx \frac{T_{\text{R}}^{-1} + x_{\text{c}} T_{\text{K}}^{-1} + x_{\alpha} T_{\alpha}^{-1}}{1 + x_{\text{c}} + x_{\alpha}}$$

T_{R}: temperature of background radiation
T_{K}: kinetic temperature of the gas
T_{α}: color temperature of Lyα photons
x_{c}: coupling due to collisions
x_{α}: coupling due to Wouthuysen-Field effect

Global (sky-average) 21-cm Signal

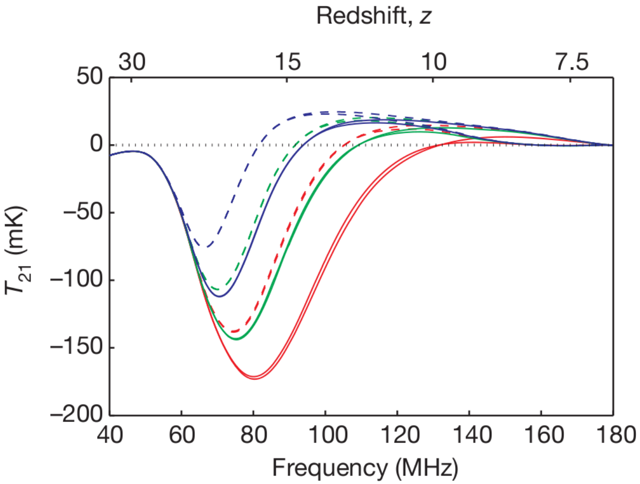


Nature and Timing of First Sources

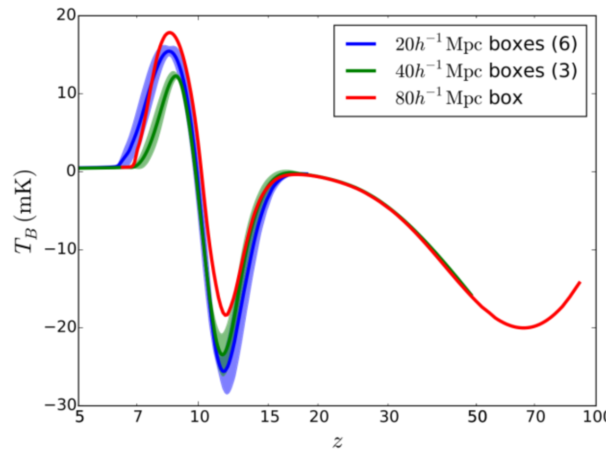


Pritchard & Loeb (2011)

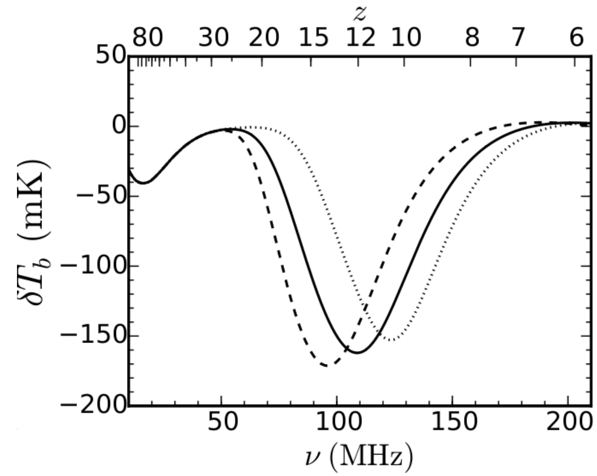
Range of Traditional Models is Wide



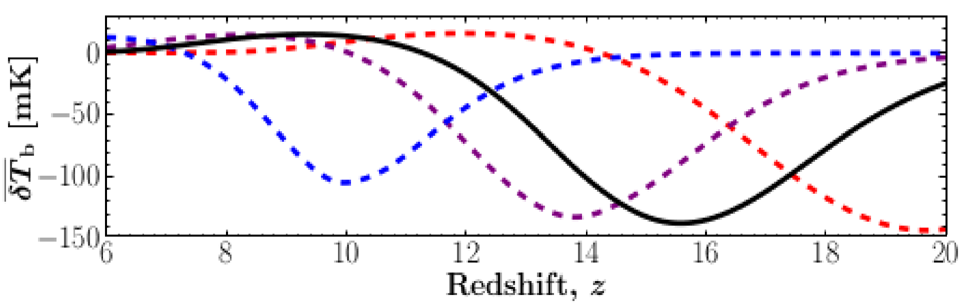
Fialkov et al. (2014)



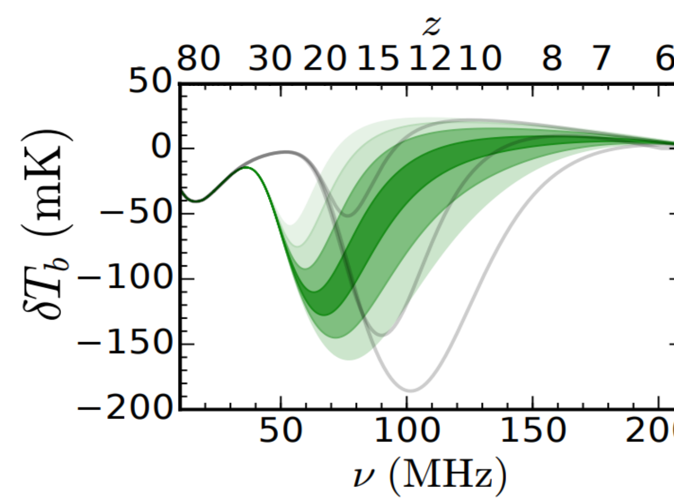
Kaurov & Gnedin (2016)



Mirocha et al. (2017a)

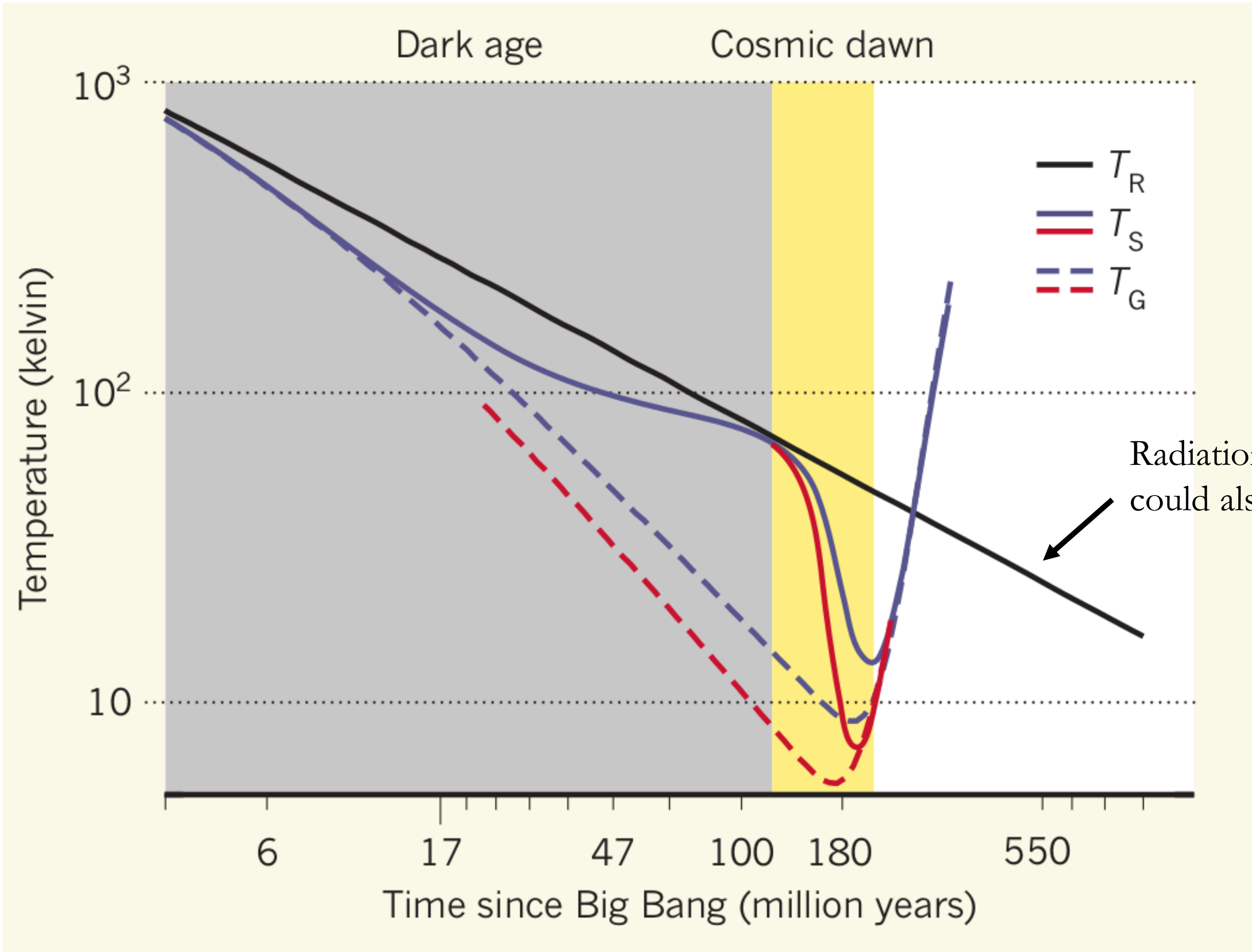


Greig & Mesinger (2017)



Mirocha et al. (2017b)

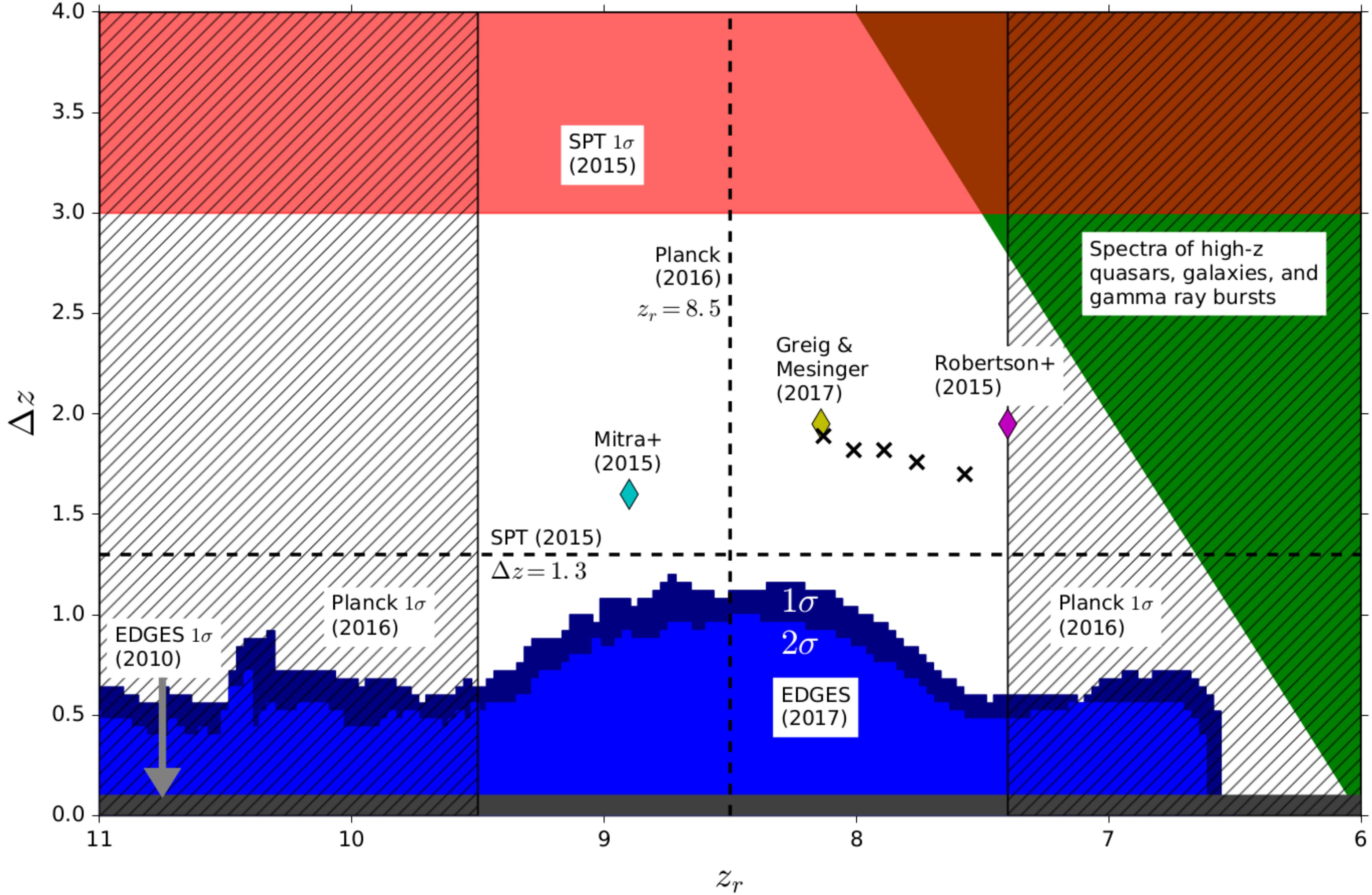
Effect of Lower Gas Temperature



Radiation Temperature could also be different

Greenhill 2018, **Nature**, 555, 38

Epoch of Reionization Constraints (Hot IGM)



R. Monsalve, A. Rogers, J. Bowman, T. Mozdzen (2017)

Global 21-cm Measurements

1) Probe of the average:
    - **Kinetic and Spin Temperature of IGM**
    - **Radiation Background**
    - **Fraction of Neutral Hydrogen**

2) Provides constraints on:
    - **Timing** and **strength** of UV coupling and X-ray heating
    - **Type** of early sources (PopII vs PopIII, Black Holes, X-Ray Binaries, etc.)
    - **Mechanisms** of star formation cooling and feedback
    - **Redshift** and **Duration** of epoch of **Reionization**

3) **"Simpler" instrumentation** than arrays.

4) **One of few current alternatives** to probe **Cosmic Dawn** ($z > 14$) period.

Challenges

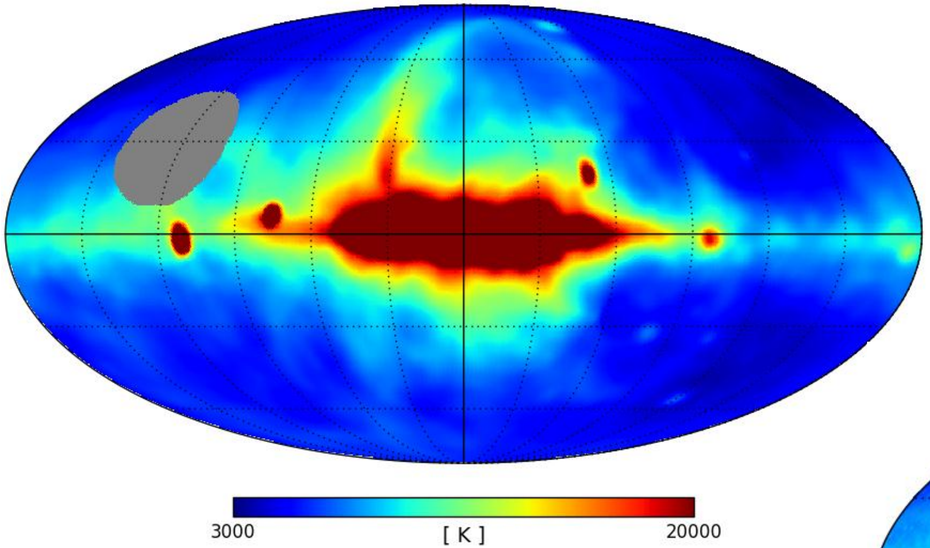
1) **Hard instrument calibration** problem.

2) **Strong diffuse foregrounds** compared to 21-cm signal.

Diffuse Foregrounds

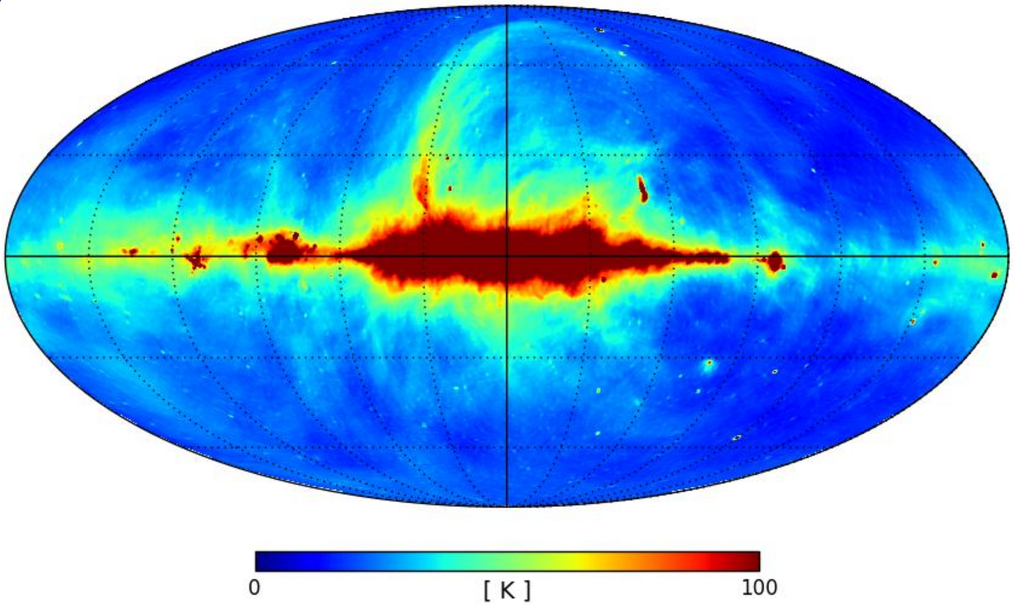
45-MHz Map

Guzmán et al. (2011)



408-MHz Map

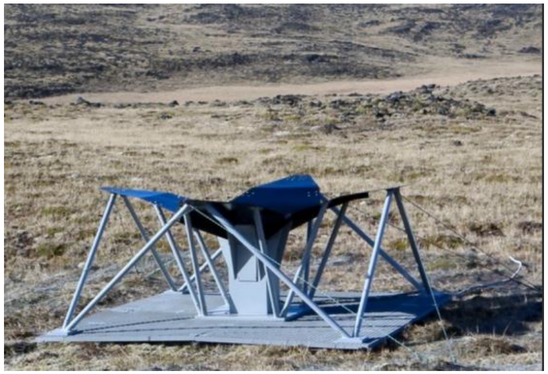
Haslam et al. (1982)



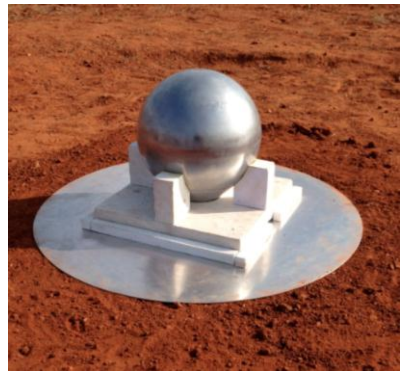
1) From **hundreds to thousands of Kelvins**.
2) Include **Galactic and Extragalactic**.
3) Mostly **Galactic synchrotron radiation**.
4) **Spectrally smooth** (e.g., Fornengo et al. 2014)
5) Might need **several terms** to model (Bernardi et al. 2015)
6) Large **spatial gradients**.

Global 21-cm Experiments

PRI^{Z}M
(Kwazulu-Natal, Sievers et al.)



SARAS 2
(RRI, Subrahmanyan et al.)



LEDA
(Harvard, Greenhill et al.)

SCI-HI
(Carnegie Mellon, Peterson et al.)

HYPERION
(Berkeley, Parsons et al.)

CTP
(NRAO, Bradley et al.)

EDGES

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

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

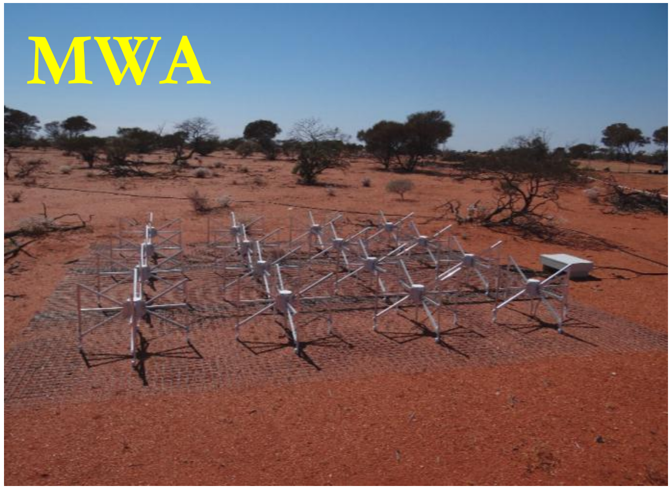
ASU
Arizona State University

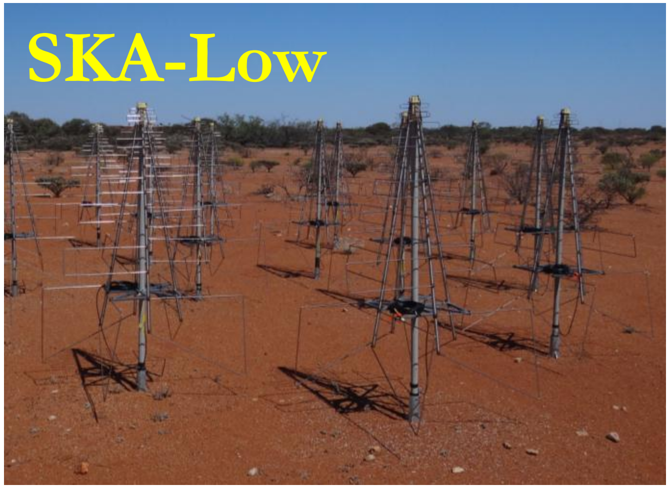
MIT
Haystack Observatory

Western Australia

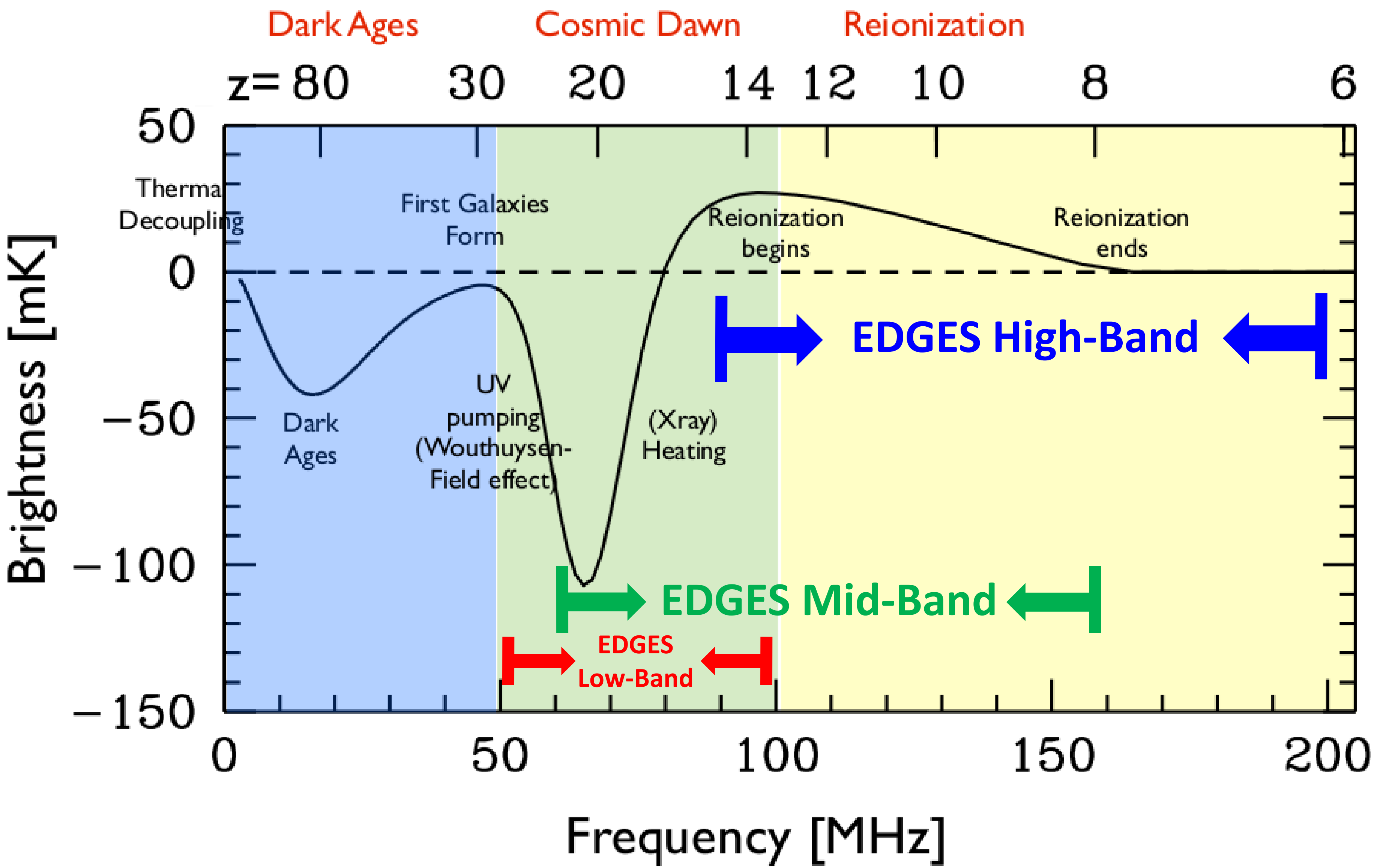
Radio-Quiet Site

Murchison Radio-astronomy Observatory (MRO)



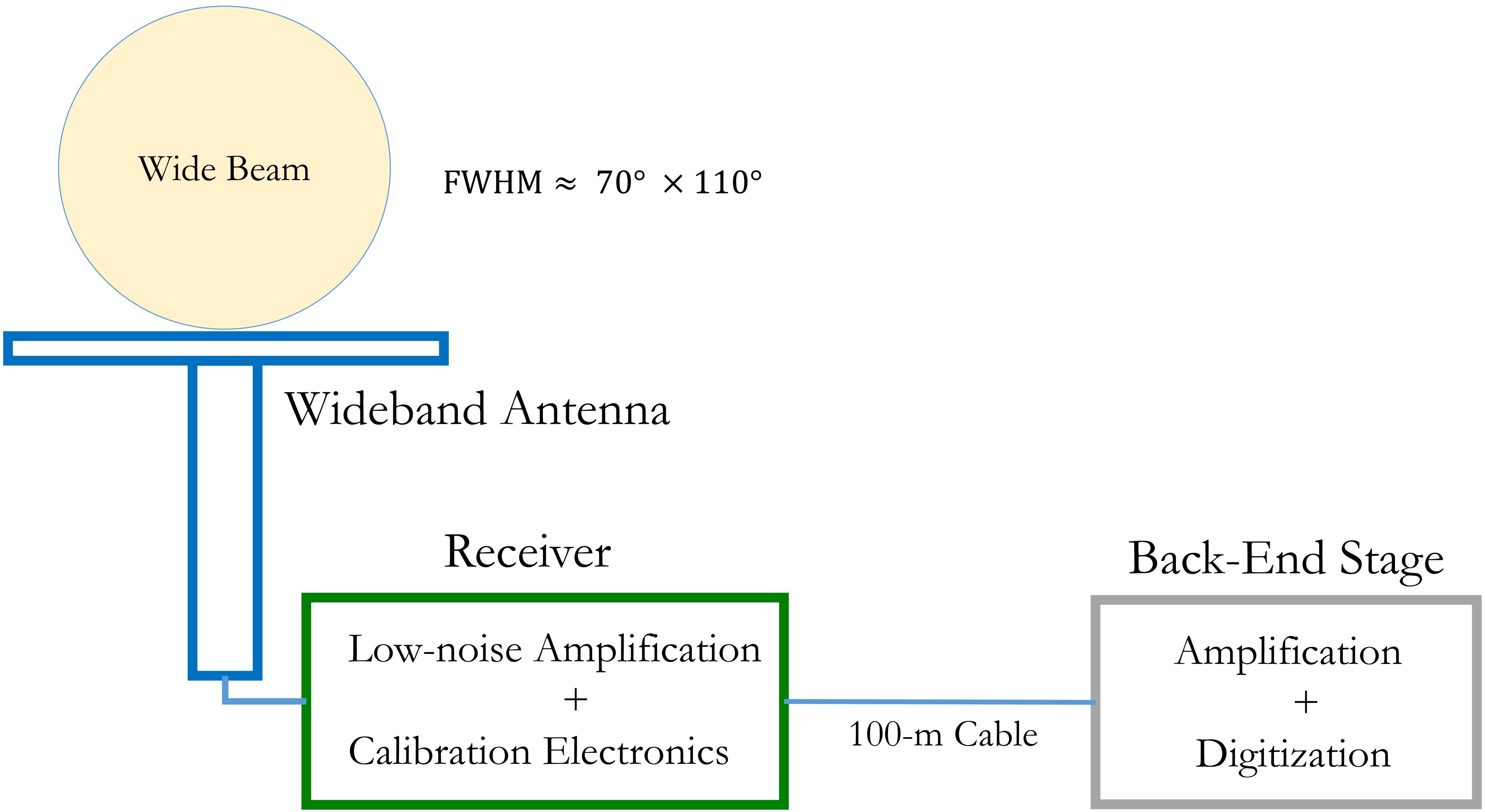


EDGES Instruments

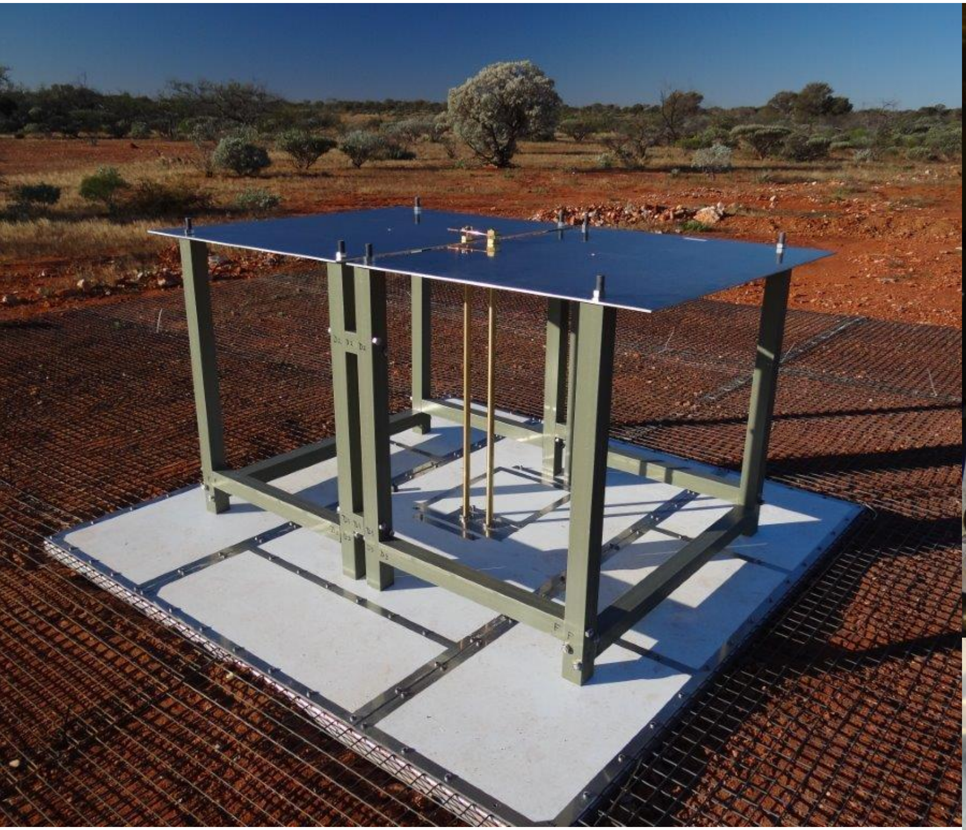


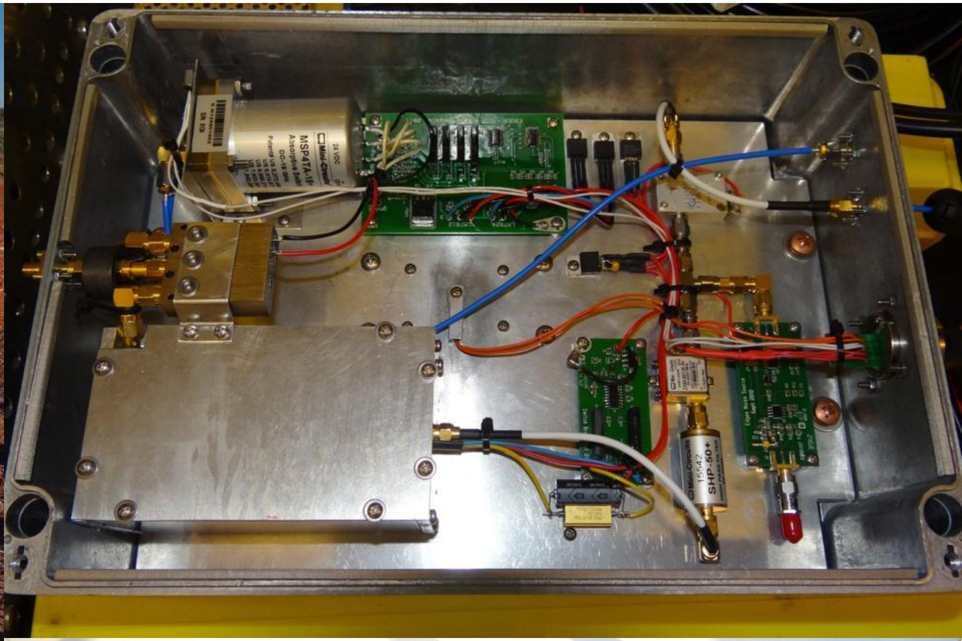
Adapted from Pritchard & Loeb (2011)

EDGES Block Diagram



EDGES **Low-Band**

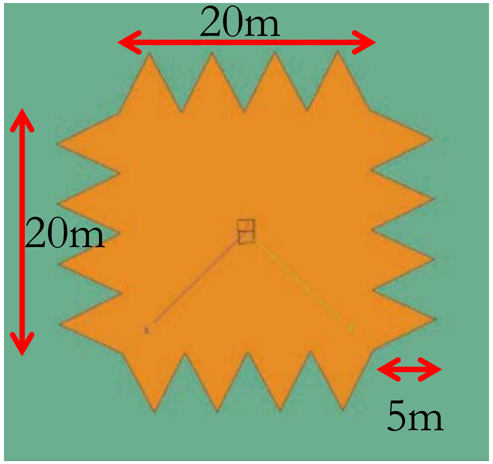


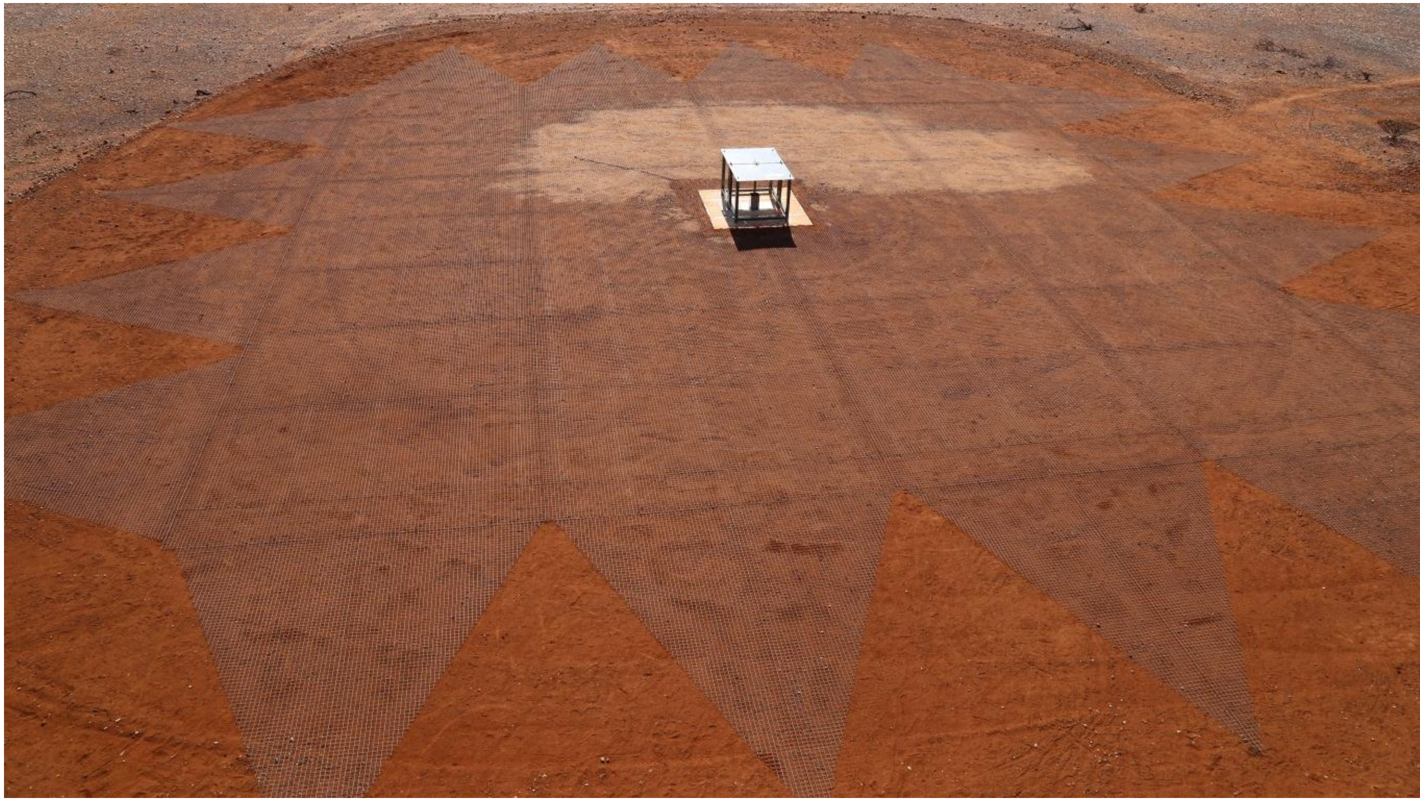


Antenna size:
2m long / 1m high

Ground Plane

Extended Ground Plane:
Central Square: 20m x 20m
16 Triangles: 5m-long





Instrumental Calibration

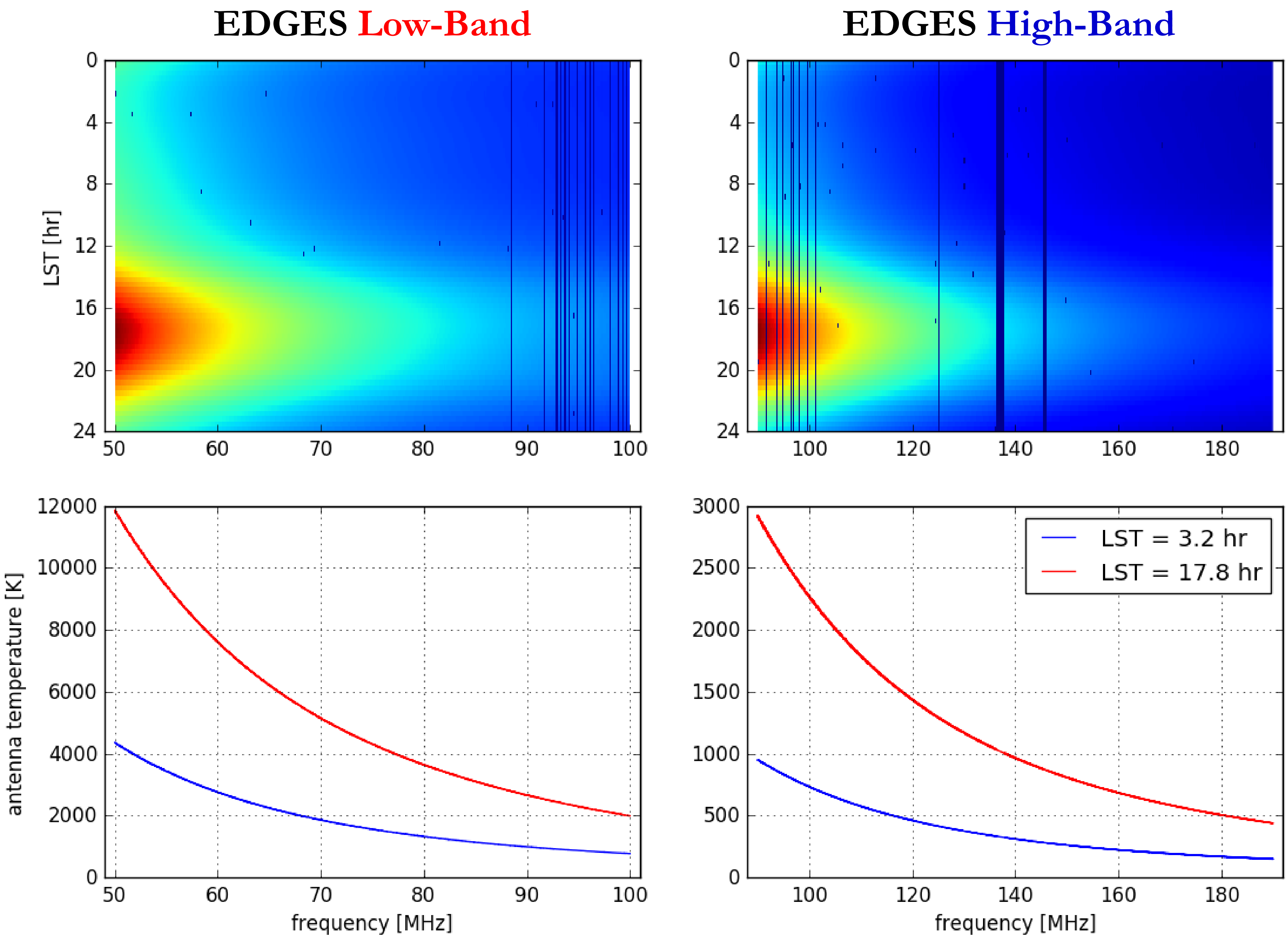
1) **Receiver gain and offset.**

2) **Impedance mismatch between receiver and the antenna.**

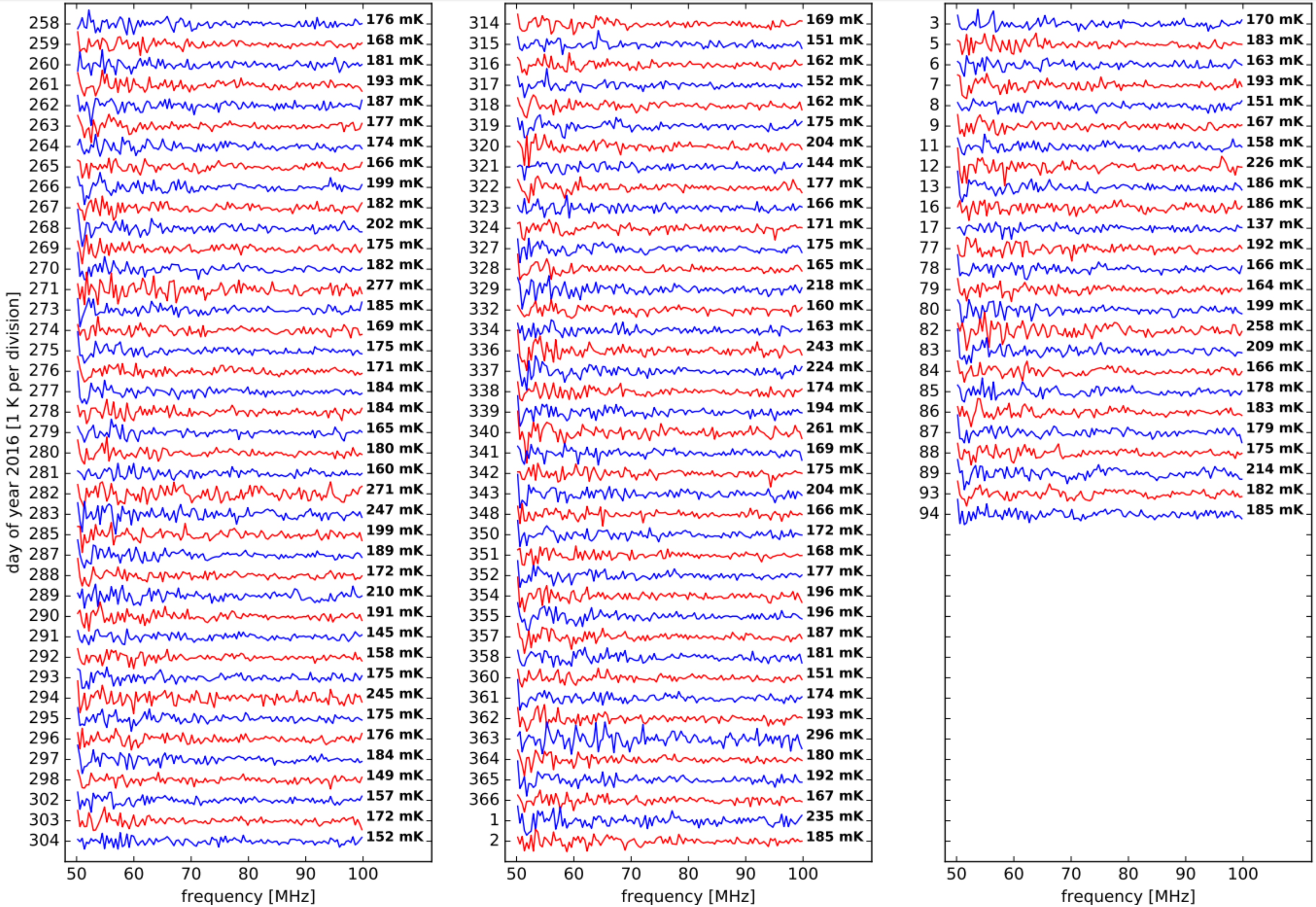
3) **Antenna and ground losses.**

4) **Frequency-dependence of the antenna beam.**

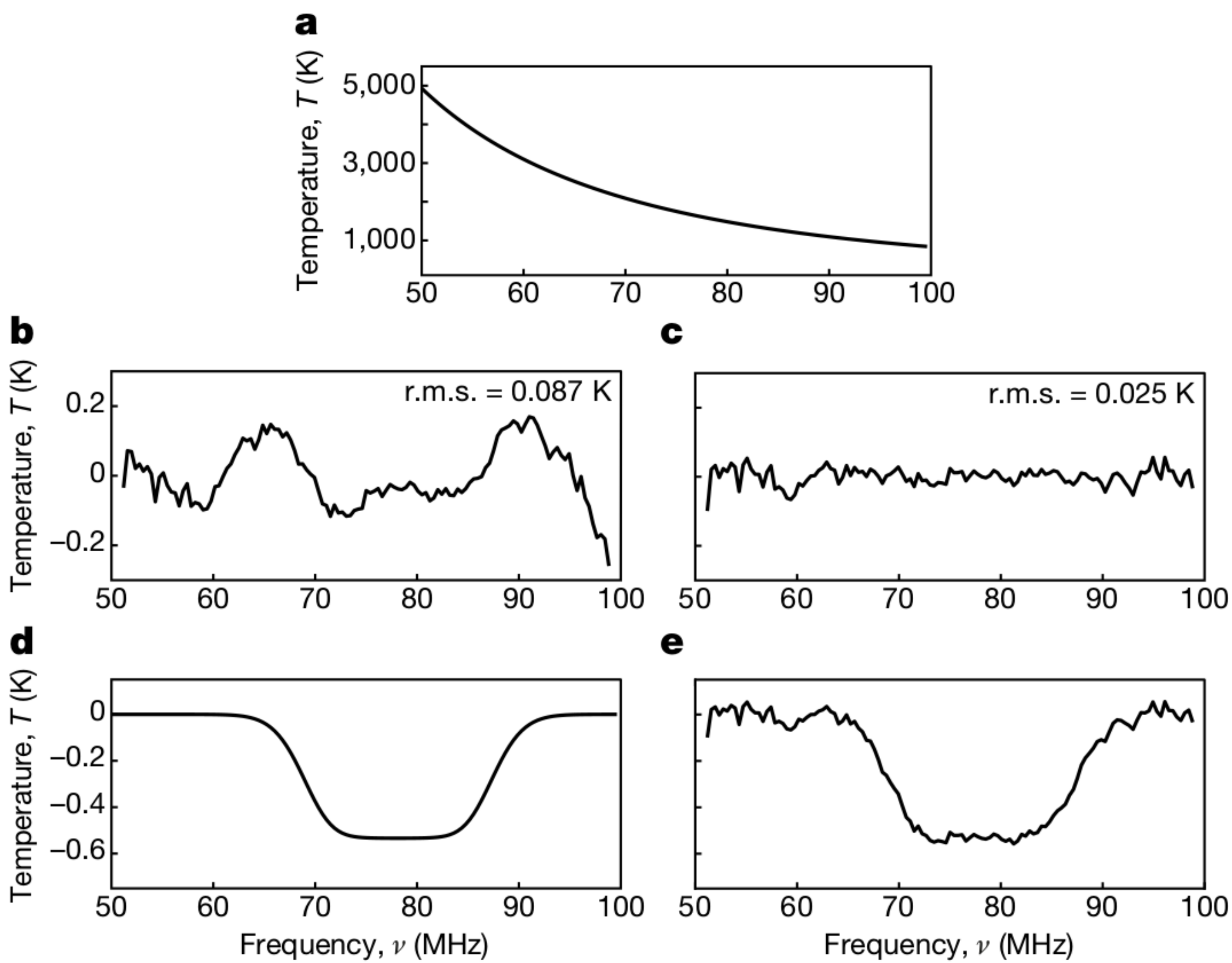
Observations



Daily Low-Band Residuals



Summary of the Detection



J. Bowman, A. Rogers, **R. Monsalve**, T. Mozdzen, N. Mahesh 2018, **Nature**, 555, 67

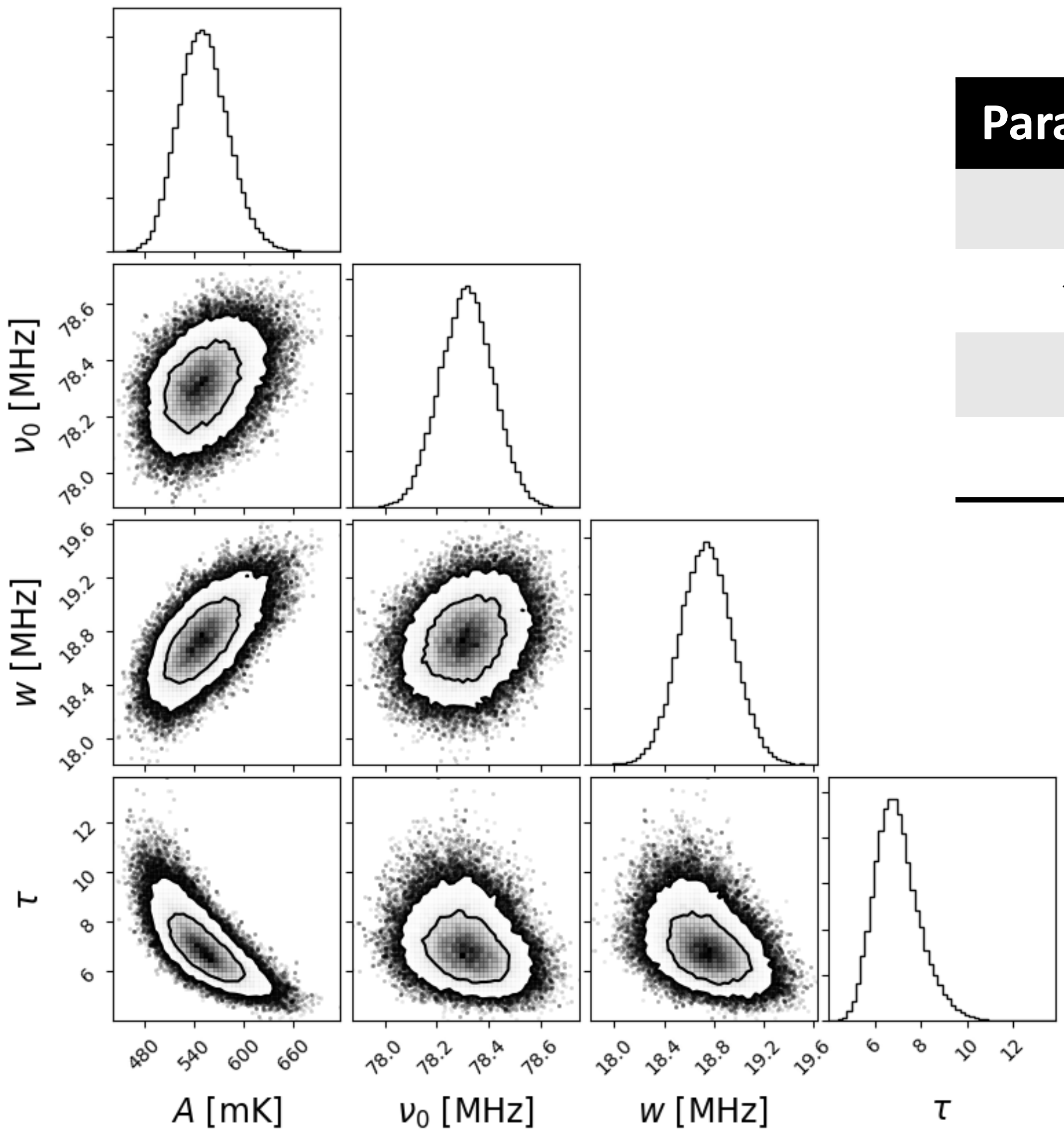
Phenomenological 21-cm Model

$$m_{21}(\nu, \boldsymbol{\theta_{21}}) = -\boldsymbol{A} \left(\frac{1 - e^{-\boldsymbol{\tau}\, e^{B}}}{1 - e^{-\boldsymbol{\tau}}} \right)$$

$$B = \frac{4\,(\nu - \boldsymbol{\nu_0})^2}{\boldsymbol{w}^2} \quad \ln\left[-\left(\frac{1}{\boldsymbol{\tau}}\right) \ln\left(\frac{1 + e^{-\boldsymbol{\tau}}}{2}\right) \right]$$

Parameter Estimates

Estimates from Nominal Spectrum



Reported Estimates

Parameter	Best Fit	Uncertainty (3σ)
A	0.5 K	+0.5/-0.2 K
ν_0	78 MHz	+/-1 MHz
w	19 MHz	+4/-2 MHz
τ	7	+5/-3

Sensitivity to Possible Calibration Errors

Error source	Estimated uncertainty	Modelled error level	Recovered amplitude (K)
LNA S11 magnitude	0.1 dB	1.0 dB	0.51
LNA S11 phase (delay)	20 ps	100 ps	0.48
Antenna S11 magnitude	0.02 dB	0.2 dB	0.50
Antenna S11 phase (delay)	20 ps	100 ps	0.48
No loss correction	N/A	N/A	0.51
No beam correction	N/A	N/A	0.48

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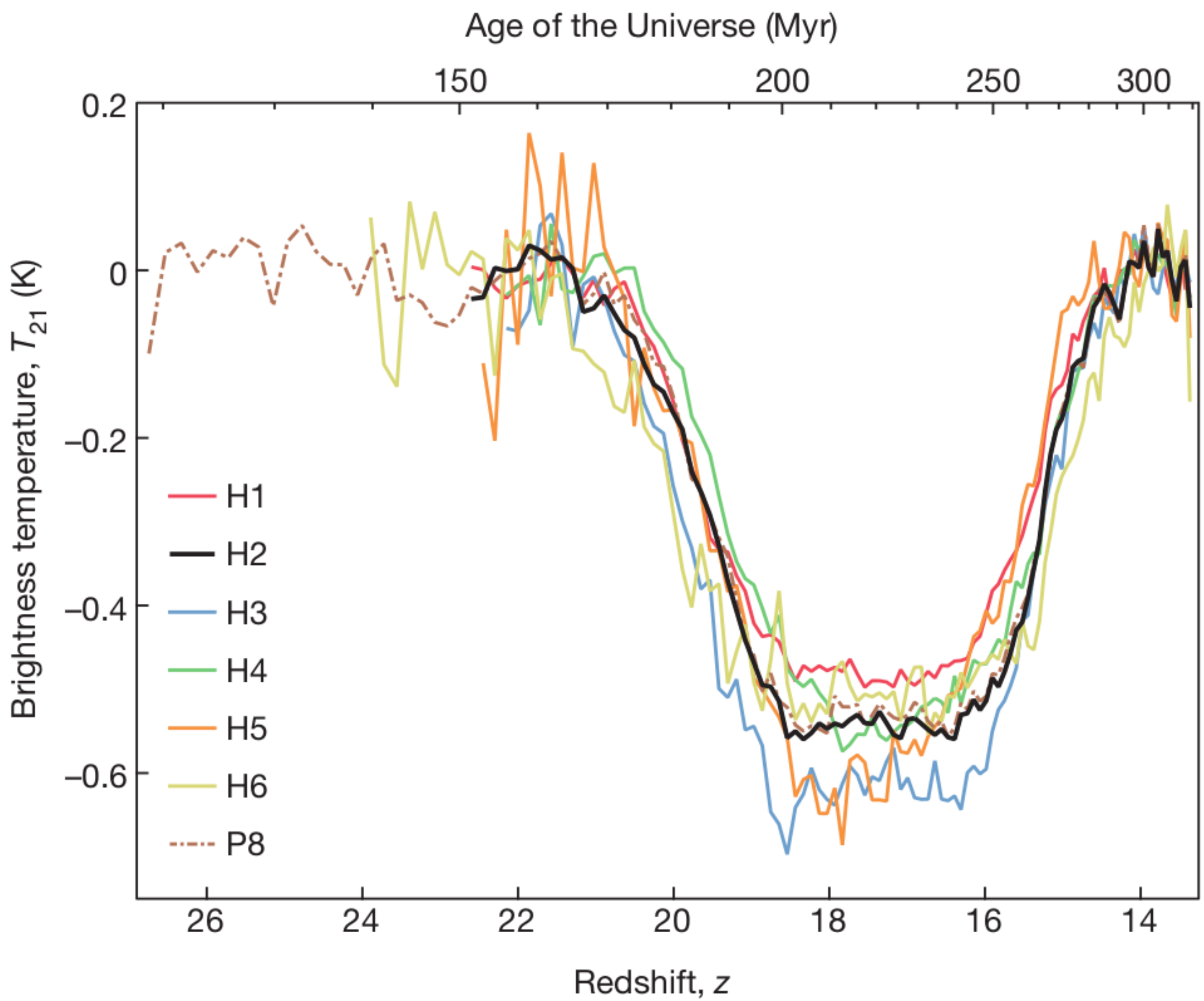
Different Hardware Cases



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Hardware and Processing Cases

Configuration			Sky Time (hours)	SNR	Centre Frequency (MHz)	Width (MHz)	Amplitude (K)
Hardware configurations (all P6)							
H1 – low-1 10x10 ground plane			528	30	78.1	20.4	0.48
H2 – low-1 30x30 ground plane			428	52	78.1	18.8	0.54
H3 – low-1 30x30 ground plane and recalibrated receiver			64	13	77.4	19.3	0.43
H4 – low-2 NS			228	33	78.5	18.0	0.52
H5 – low-2 EW			68	19	77.4	17.0	0.57
H6 – low-2 EW and no balun shield			27	15	78.1	21.9	0.50
Processing configurations (all H2 except P17)							
P3	–	No beam correction		19	78.5	20.8	0.37
		No beam correction (65-95 MHz)		25	78.5	18.6	0.47
		HFSS beam model		34	78.5	20.8	0.67
		FEKO beam model		48	78.1	18.8	0.50
P4	–	No loss corrections		25	77.4	18.6	0.44
P7	–	5-term foreground polynomial (60-99 MHz)		21	78.1	19.2	0.47
P8	–	Physical foreground model (51-99 MHz)		37	78.1	18.7	0.53
P14	–	Moon above horizon		44	78.1	18.8	0.52
		Moon below horizon		40	78.5	18.7	0.47
P17	–	15°C calibration (61-99 MHz, 5-term)		25	78.5	22.8	0.64
		35°C calibration (61-99 MHz, 5-term)		16	78.9	22.7	0.48

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Absorption Amplitude for Various GHA

Galactic Hour Angle (GHA)	SNR	Amplitude (K)	Sky Temperature (K)
6-hour bins			
0	8	0.48	3999
6	11	0.57	2035
12	23	0.50	1521
18	15	0.60	2340
4-hour bins			
0	5	0.45	4108
4	9	0.46	2775
8	13	0.44	1480
12	21	0.57	1497
16	11	0.59	1803
20	9	0.66	3052

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How to Explain Deep Signal?

$$T_{21}(z) \propto \left(1 - \frac{T_{\rm CMB} + \boldsymbol{T_{\rm EXCESS}}}{\boldsymbol{T_S}}\right)$$

Higher than zero

Lower than expected

$\boldsymbol{T_S}$ can only be as low as kinetic temperature of IGM

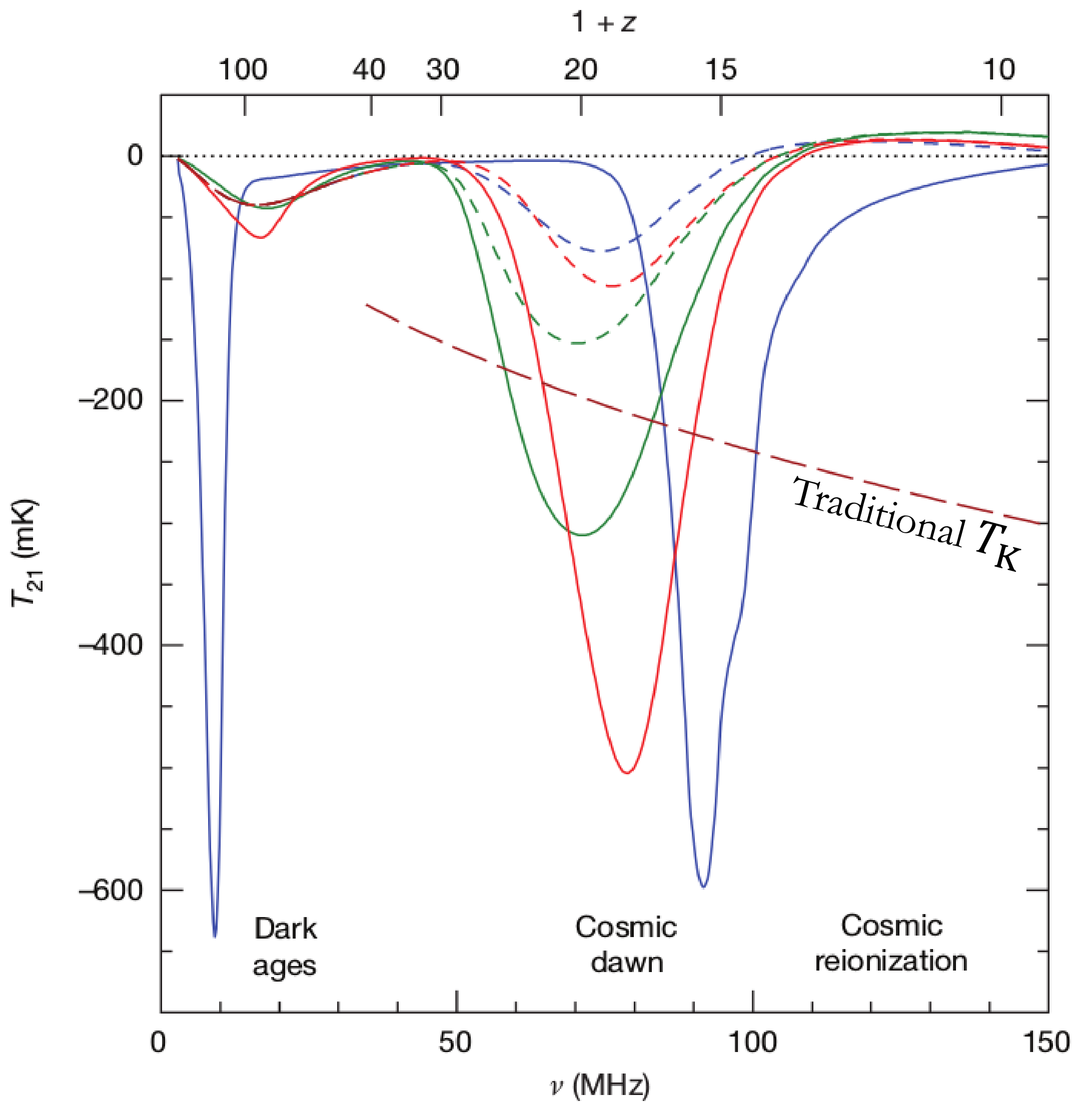
Interaction of Baryons with Dark Matter?

First proposed by
Tashiro, Kadota, & Silk,
Phys. Rev. D 90, 083522 (2014)

Also
Muñoz, Kovetz, & Ali-Haimoud,
Phys. Rev. D 92, 083528 (2015)

This produces lower T_K

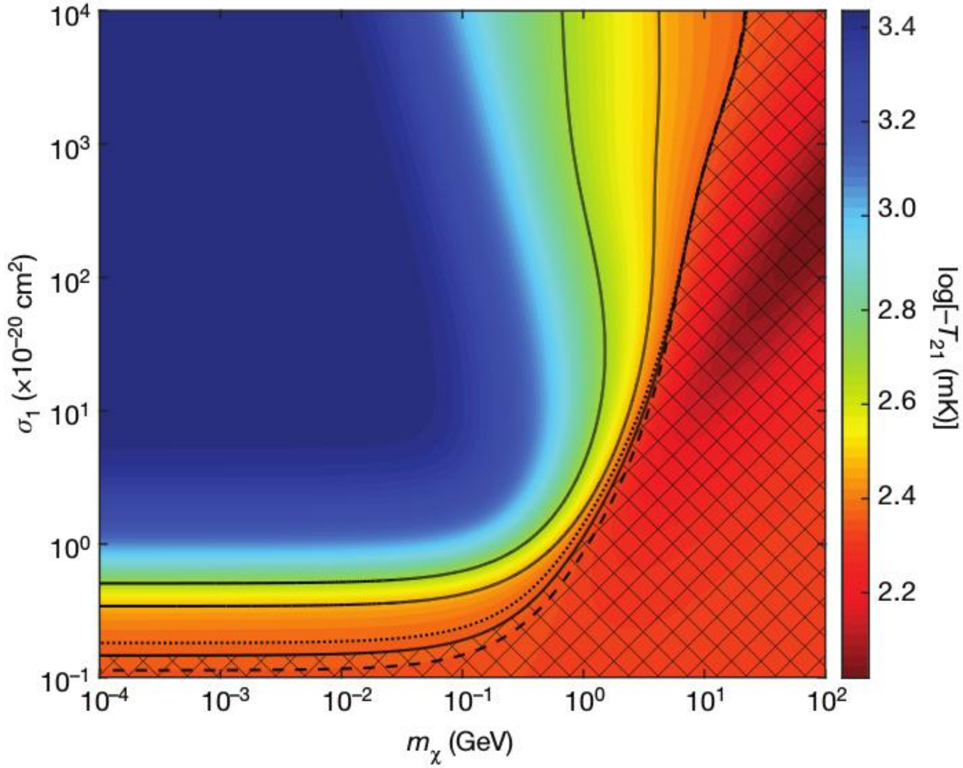
$$T_{21}(z) \propto \left(1 - \frac{T_{CMB}}{T_S}\right)$$



R. Barkana 2018, **Nature**, 555, 71

Interactions of Baryons with Dark Matter?

R. Barkana 2018, **Nature**, 555, 71



σ_1: cross-section of interactions at relative velocity of 1 km/s

m_χ: mass of dark matter particle

Constraints

$$m_\chi < 1.5 \text{ GeV}$$

$$\sigma_1 > 5 \times 10^{-21} \text{ cm}^2$$

Interactions of Baryons with Dark Matter?

Nature of the interaction being debated

Talks on May 30th by Julian Muñoz and Sam McDermott

Current consensus is that enough IGM cooling can be achieved if a small fraction (~1%) of DM particles posses electric minicharge ($\sim 10^{-6}$ the charge of an electron).

The DM mass is constrained to ~ 1-60 MeV (Muñoz & Loeb 2018, **arXiv: 1802.10094v2**)

Stronger Radiation Background ?

$$T_{21}(z) \propto \left(1 - \frac{T_{\mathrm{CMB}} + \boldsymbol{T_{\mathrm{EXCESS}}}}{T_S}\right)$$

T_{CMB} at $z \approx 17$ is 45 K.

For an absorption deeper by a factor ≥ 2 we need $T_{\mathrm{EXCESS}} \geq T_{\mathrm{CMB}}$.

A. Ewall-Wice, T.-C. Chang, J. Lazio, O. Dorie, M. Seiffert, R. A. Monsalve (arXiv: 1803.01815v1)

1) **Black Holes from Pop-III stars, formed at $z \approx 30 - 20$** could produce enough background radiation.

2) In some scenarios, **$T_{\mathrm{EXCESS}} >> T_{\mathrm{CMB}}$. Large absorption reduced** by X-ray heating, and reionization from same sources.

3) In some scenarios, **reionization from these X-rays is consistent with Planck** estimates for τ_e.

4) Broadly **consistent with Source Populations, CXB, CIB, and Radio Background** at $z \approx 0$.

Problems?

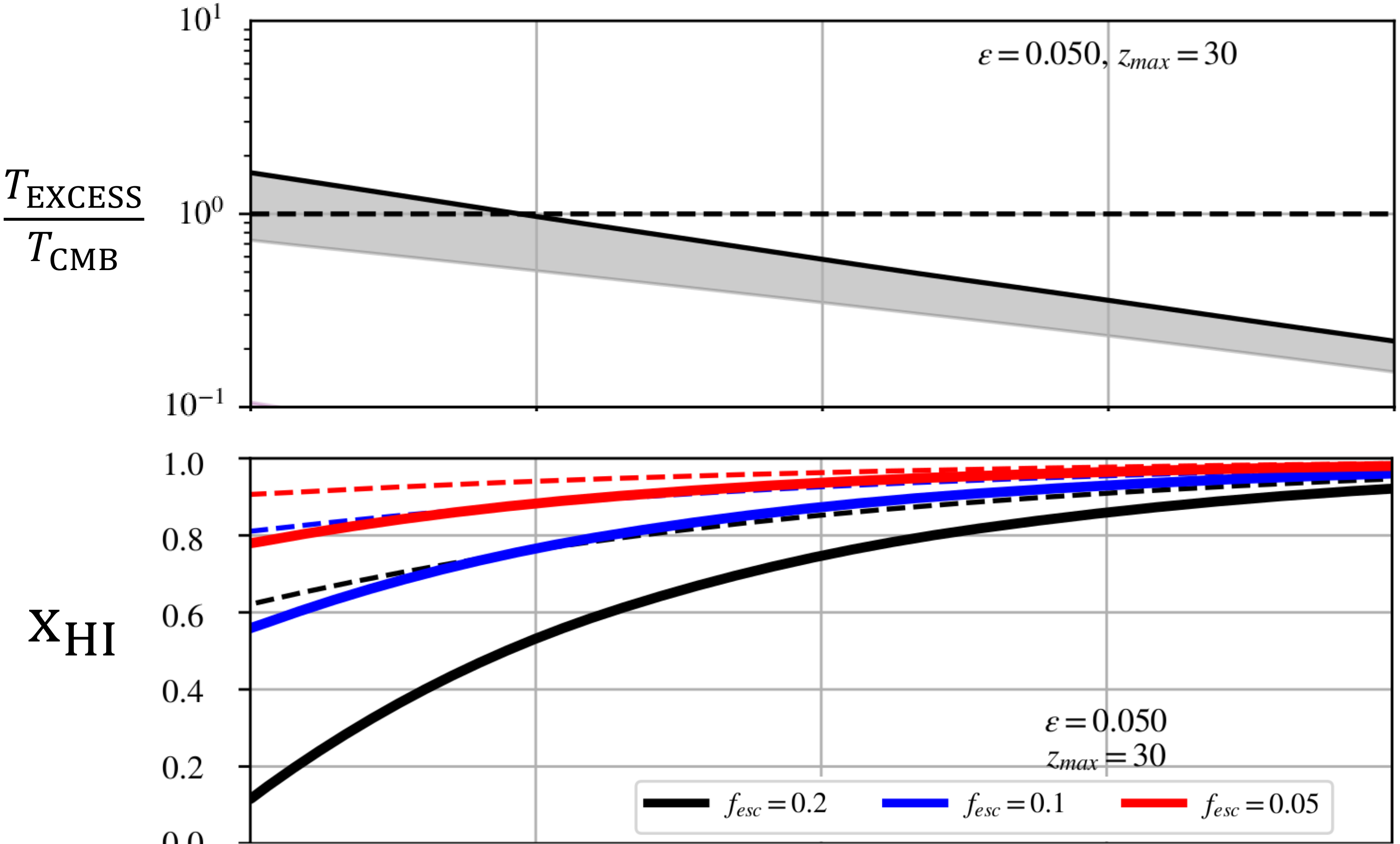
1) Models producing required excess radiation by $z \approx 17$, **could over-produce the measured black hole density at low z.**

2) Some mechanism necessary to **supress black hole formation at $z < 17$.**

3) If metallicity is high (0.001 of Solar), **Pop-III formation should cease.**

Stronger Radiation Background ?

A. Ewall-Wice, T.-C. Chang, J. Lazio, O. Dorie, M. Seiffert, **R. A. Monsalve** **(arXiv: 1803.01815v1)**



Gray range:
$f_{\text{edd}} = 10^{-2} - 1$

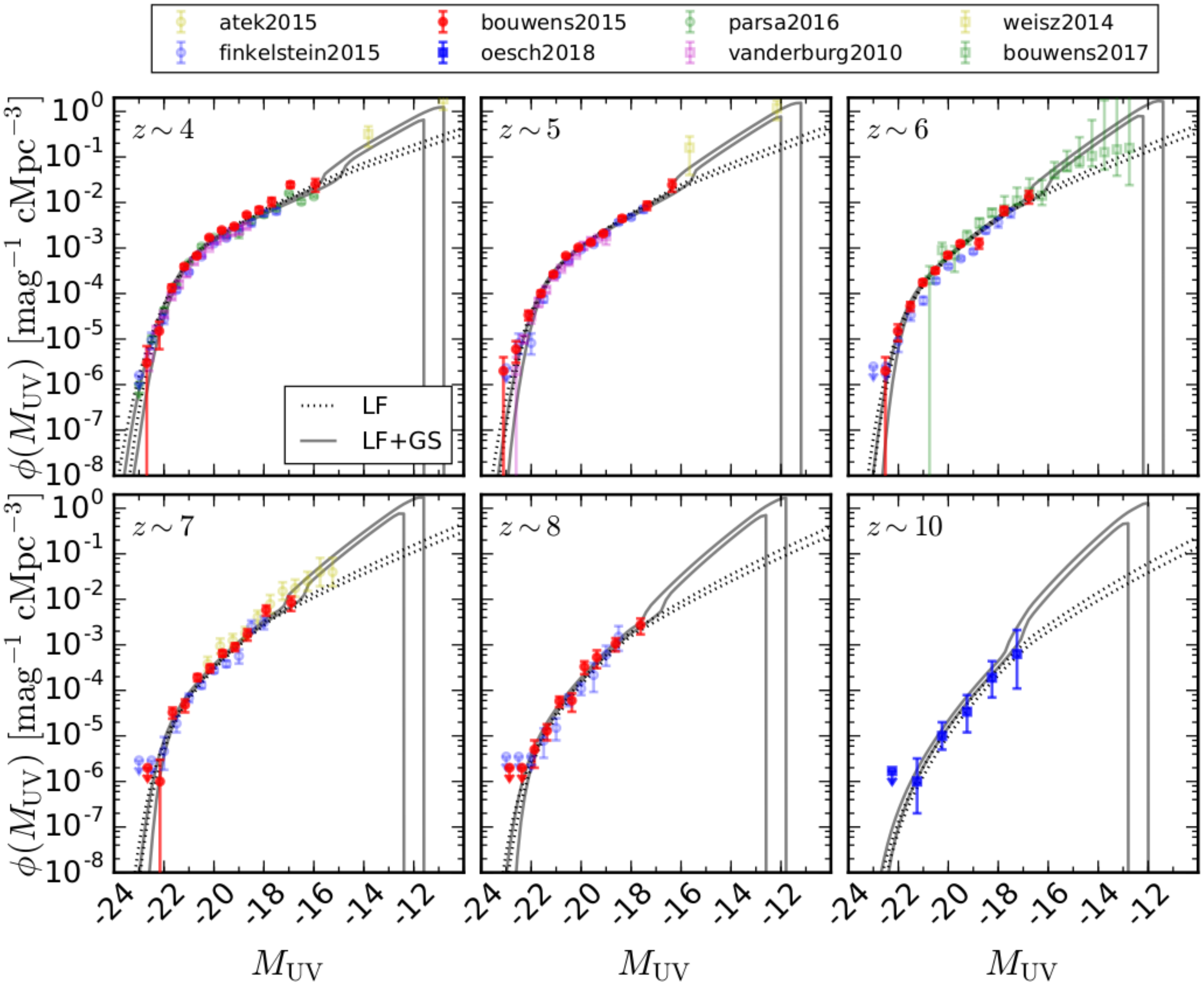
ϵ: radiative efficiency. Fraction of infalling mass radiated away.

Dashed:
$f_{\text{edd}} = 10^{-2}$

Solid:
$f_{\text{edd}} = 1$

Cases with $\frac{T_{\text{EXCESS}}}{T_{\text{CMB}}} \geq 1$ are consistent with absorption feature.

UV Luminosity Functions



1) Feature at 78 MHz **is not expected** by extrapolation of **Galaxy Luminosity Functions** (LF)s at $z \leq 10$.

2) **Consistency possible** for **enhanced star formation** in galaxies beyond the current detection limits.

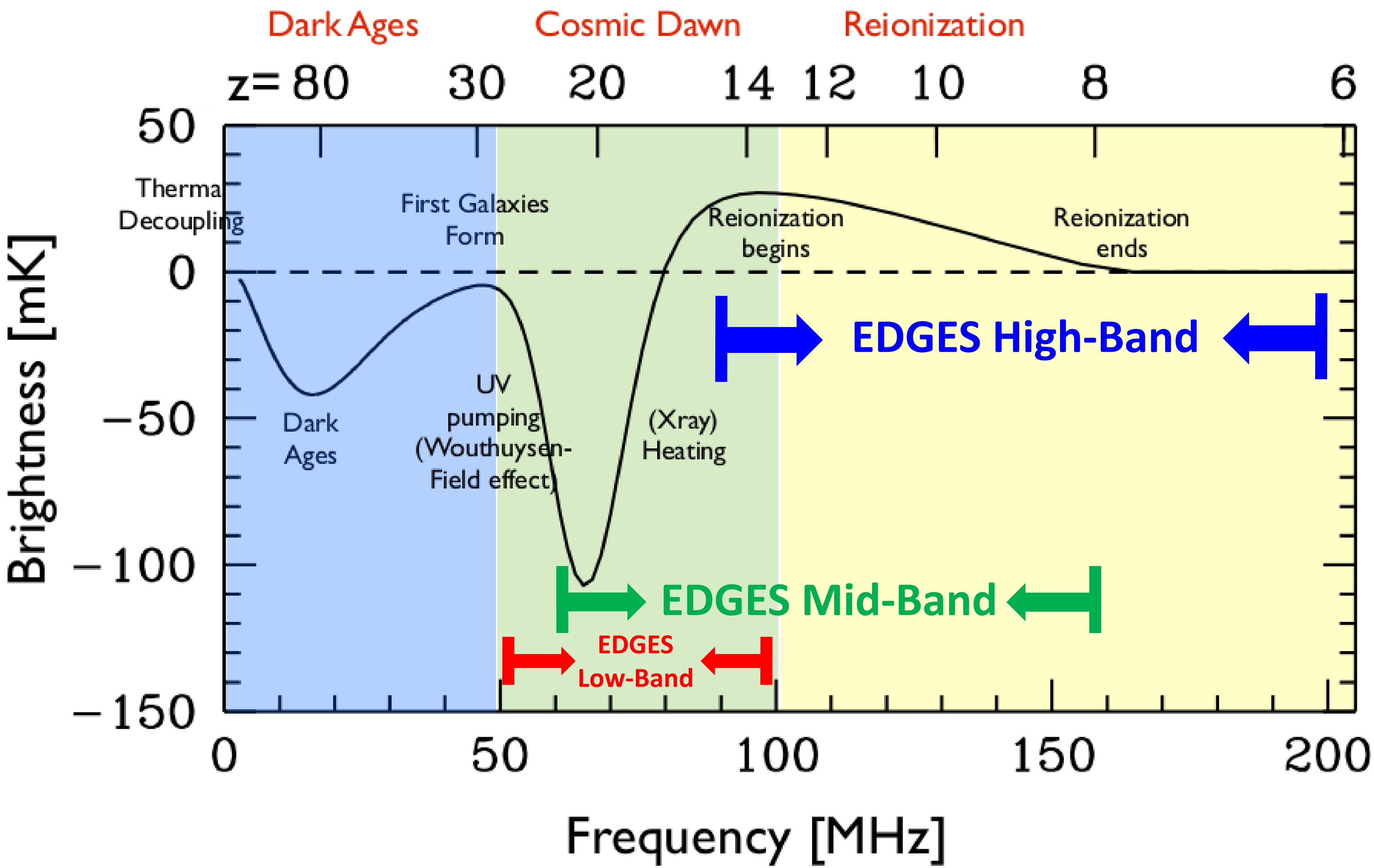
3) **Timing conflict** is independent of exotic 21-cm amplitude.

Mirocha & Furlanetto (2018) (arXiv:1803.03272)

With EDGES **we remain agnostic** about the cosmological/astrophysical explanations, and focused on the verification of our measurement.

Other experiments trying to verify the measurement include PRI^{Z}M, LEDA, and SARAS 2

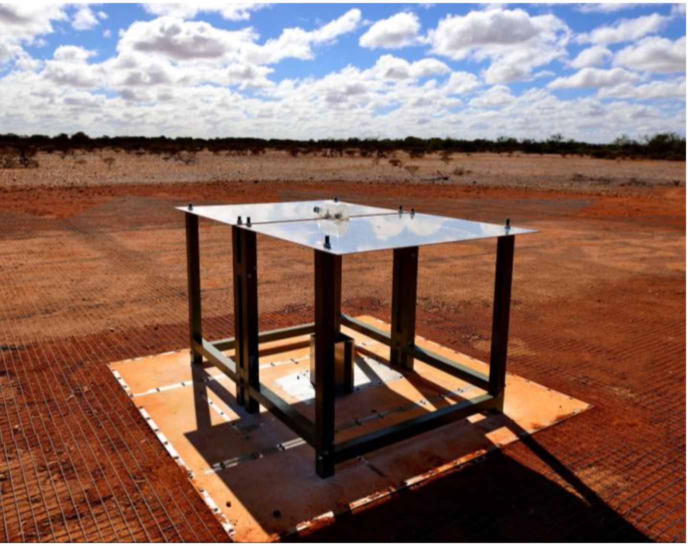
EDGES Instruments



Adapted from Pritchard & Loeb (2011)

EDGES Mid-Band

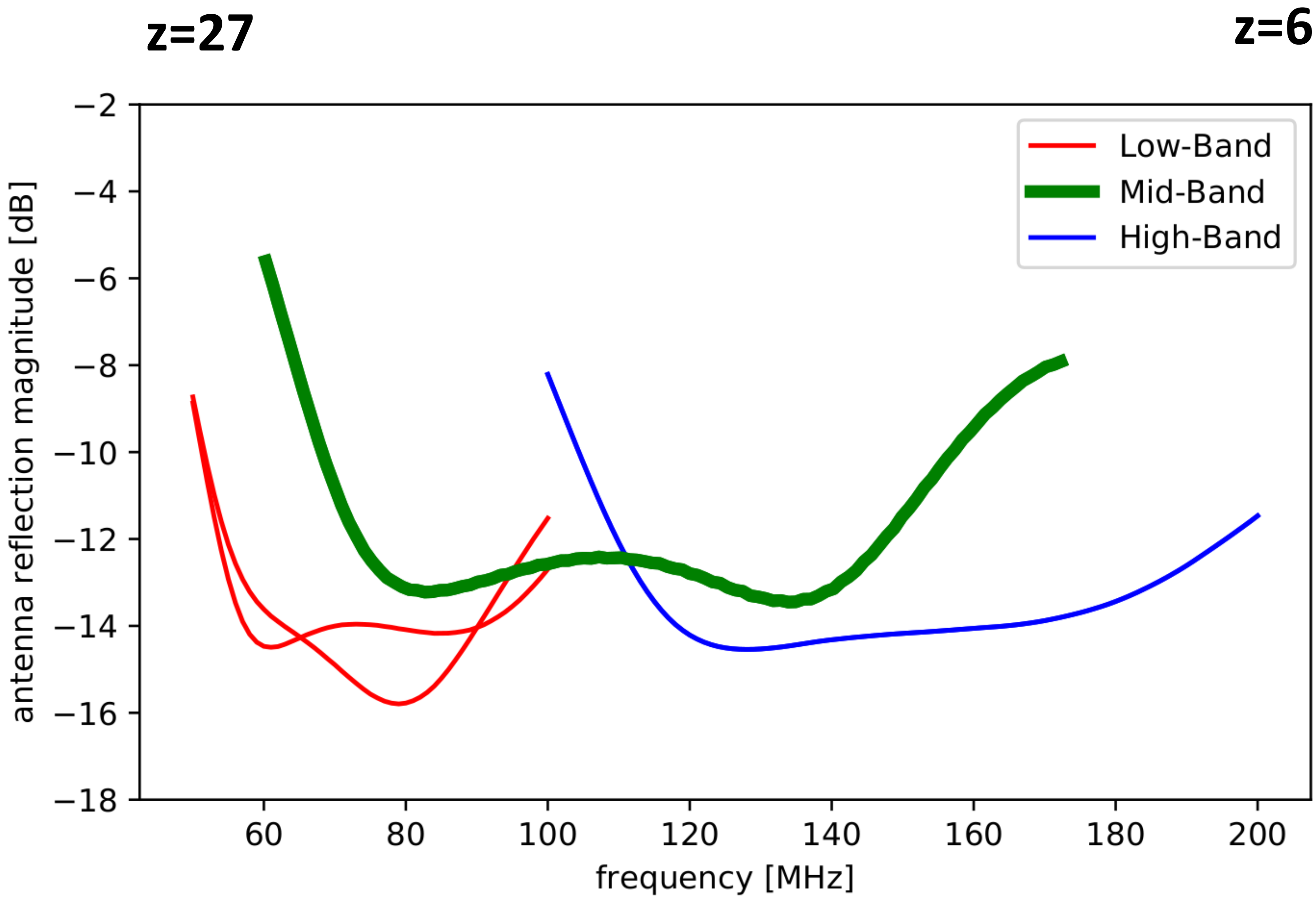
Low-Band



High-Band

Mid-Band

Antenna Reflection Coefficients



Summary

1) The **EDGES experiment** has **detected an absorption feature** in the sky-averaged spectrum centered at 78 MHz.

2) This is **consistent with stars forming by 180 Myrs after the Big Bang**.

3) Feature is **deeper, sharper, and earlier** than expected.

4) We **remain agnostic** regarding the **interpretation**.

5) We are **working to verify the measurement**.

Thank You