TeVPA 2018 Conference Berlin, Germany August 30, 2018

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

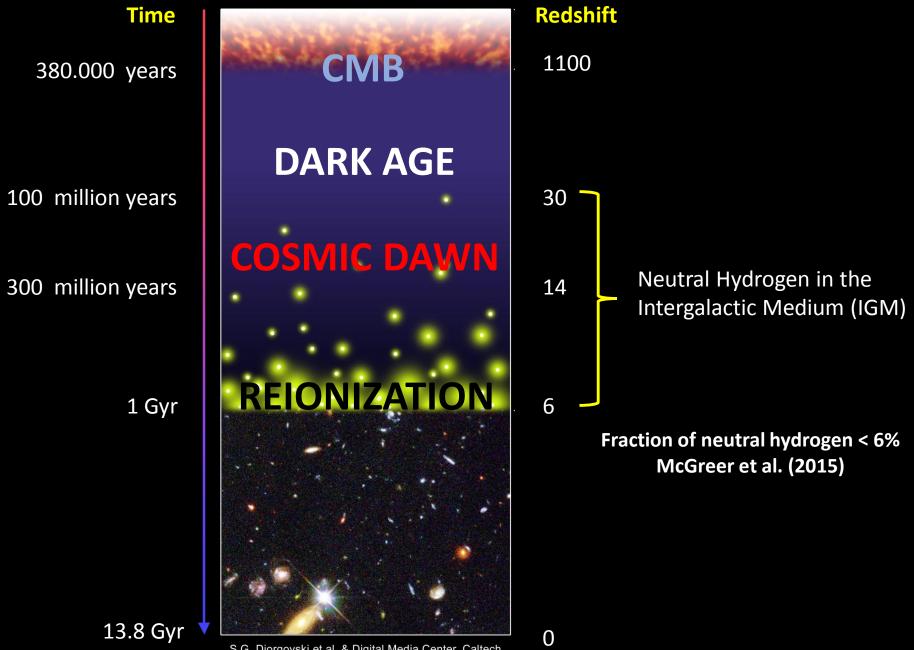
Raul Monsalve<sup>1</sup>, Judd Bowman<sup>2</sup>, Alan Rogers<sup>3</sup>, Thomas Mozdzen<sup>2</sup>, Nivedita Mahesh<sup>2</sup>

<sup>1</sup>McGill University <sup>2</sup>Arizona State University <sup>3</sup>MIT Haystack Observatory

Credit: NASA / WMAP Team

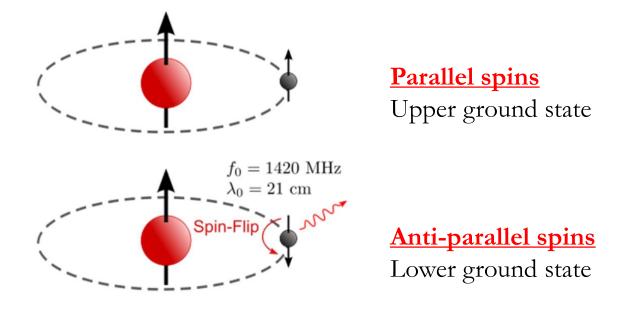
#### Summary

- 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 and sharper** than expected.
- 4) We **remain agnostic** regarding the **interpretation**.
- 5) EDGES and other teams are **working to verify the measurement**.



S.G. Djorgovski et al. & Digital Media Center, Caltech

#### Emission at 21 cm from Hydrogen Atom

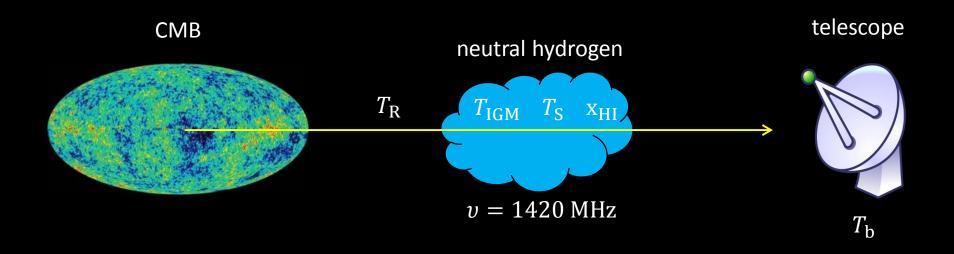


#### Due to Cosmological Expansion

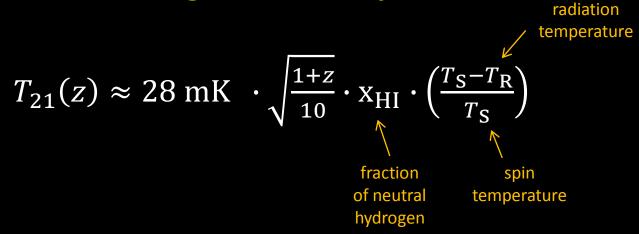
$$v_{\rm obs} = \frac{v_{\rm emit}}{(1+z)}$$

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

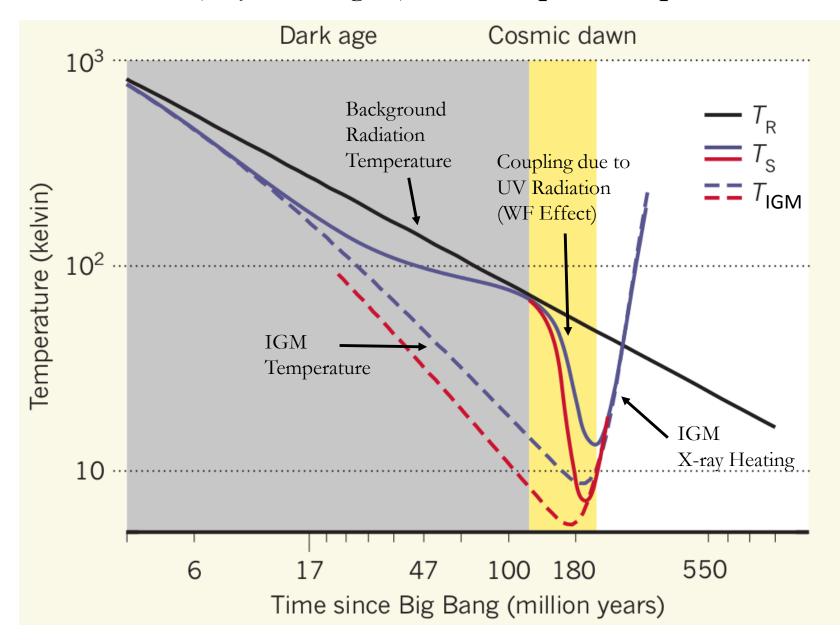
## 21-cm Cosmology



#### **21-cm Brightness Temperature**

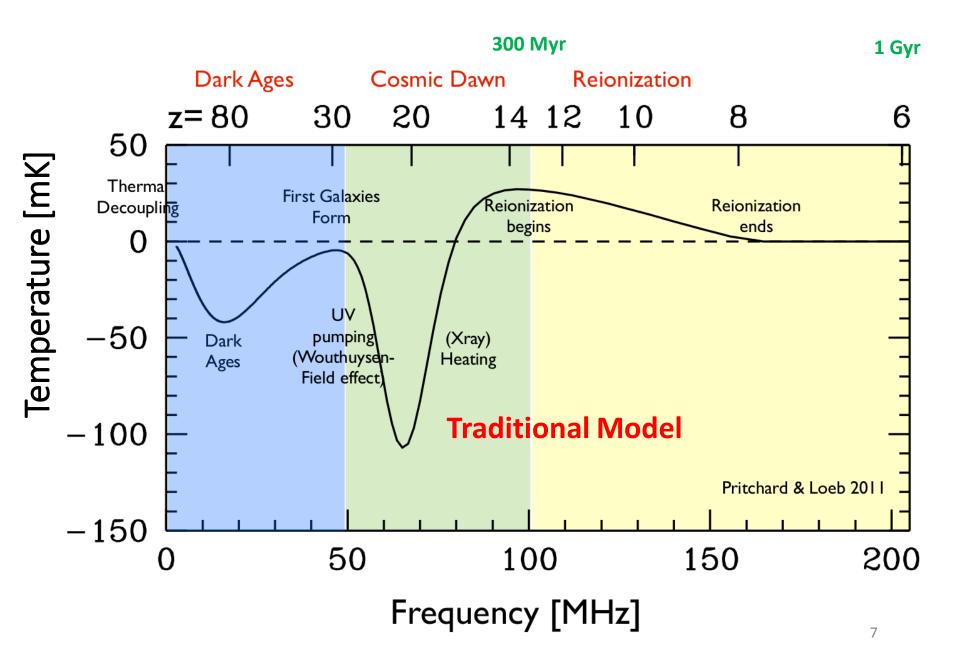


#### Global (Sky-Averaged) 21-cm Spin Temperature



Adapted from Greenhill 2018, Nature, 555, 38

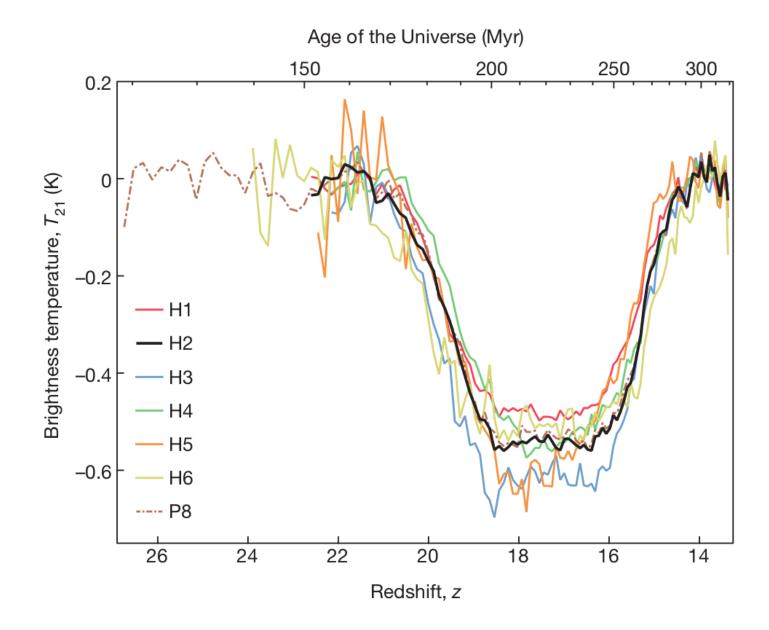
## Global 21-cm Signal



#### Global 21-cm Measurement

- 1) One of few current alternatives to access Cosmic Dawn period (z > 14).
- 2) Probes the (sky-averaged) interaction of :
  - IGM Neutral Hydrogen Fraction
  - IGM Kinetic and 21-cm Spin Temperature
  - Background Radiation Temperature
- 4) 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.)
  - Star formation cooling and feedback mechanisms
  - Redshift and Duration of epoch of Epoch of Reionization

#### EDGES Measurement



Bowman, Rogers, Monsalve, Mozdzen, Mahesh 2018, Nature, 555, 67

## EDGES

#### Experiment to Detect the Global EoR Signature

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





## Western Australia

Radio-Quiet Site Murchison Radio-astronomy Observatory (MRO)





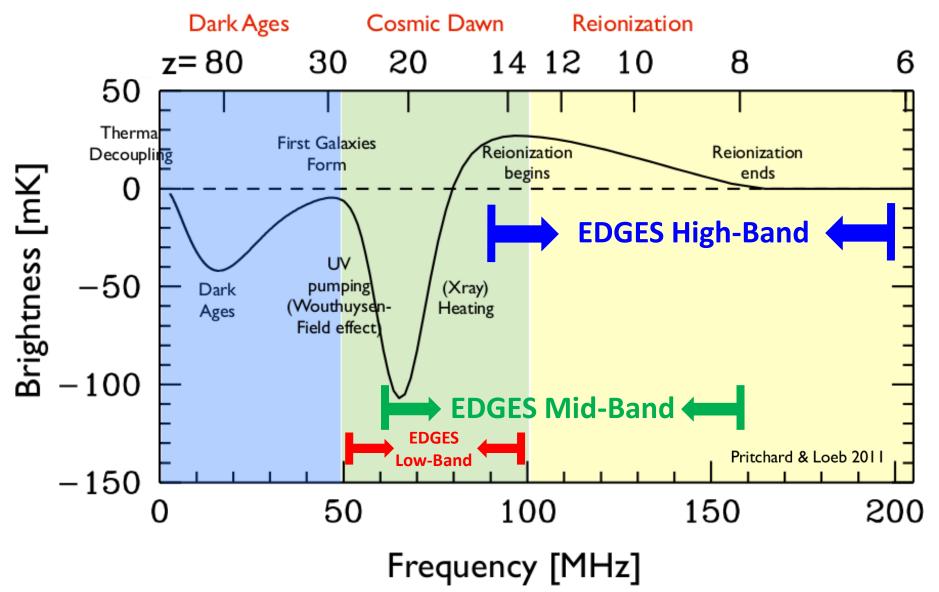
#### MWA



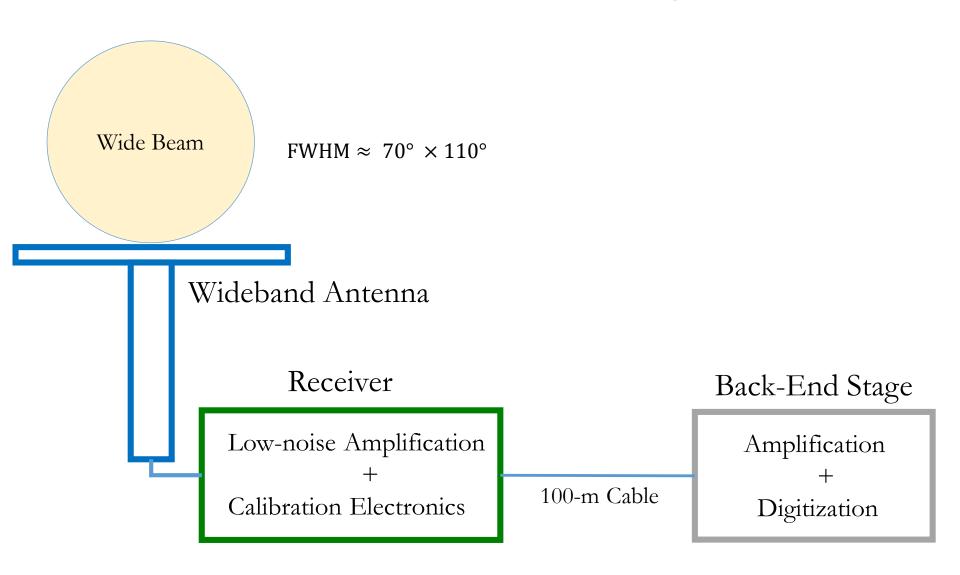
**SKA-Low** 



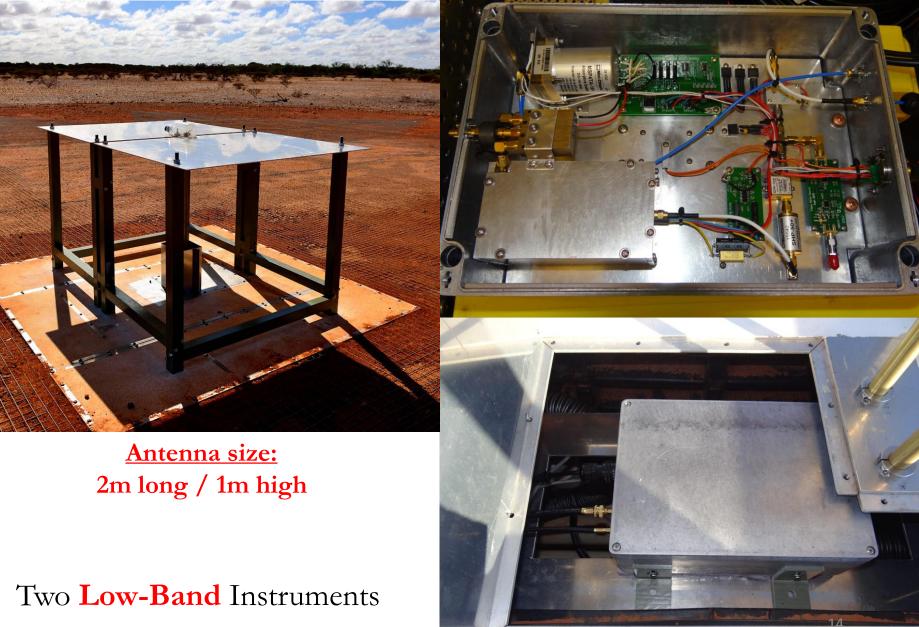
#### **EDGES** Instruments



## EDGES Block Diagram



#### EDGES Low-Band



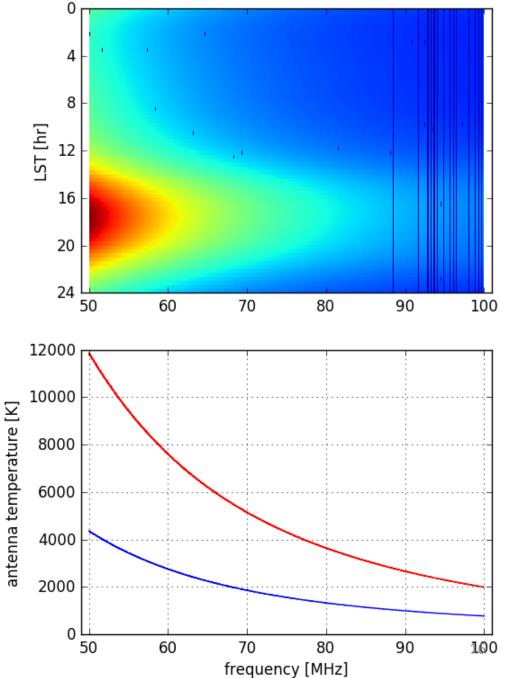
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## Challenges

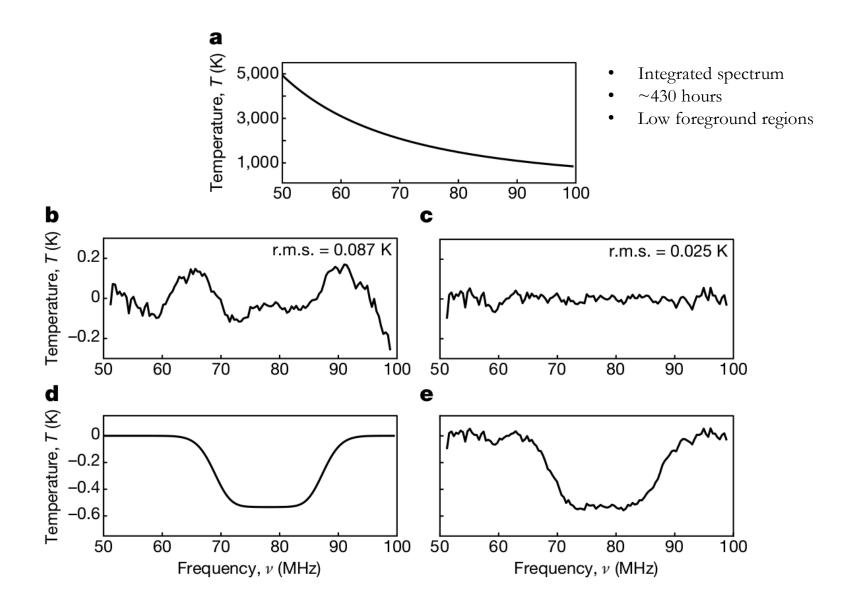
- 1) Hard instrument calibration problem.
- 2) Strong diffuse foregrounds (Galactic and Extragalactic) compared to cosmological 21-cm signal.

### Daily Observations

**EDGES Low-Band** 



#### Summary of the Detection



Bowman, Rogers, Monsalve, Mozdzen, Mahesh 2018, Nature, 555, 67

#### Phenomenological 21-cm Model "Flattened Gaussian"

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

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

- **A** : absorption amplitude
- $v_0$ : center frequency
- **w**: width
- *t*: flattening parameter

## "Foreground" Models

Linearized version of Physically-Motivated foreground model

$$m_{\rm fg}(\boldsymbol{a_i}) = \boldsymbol{a_0} \left(\frac{\nu}{\nu_n}\right)^{-2.5} + \boldsymbol{a_1} \left(\frac{\nu}{\nu_n}\right)^{-2.5} \left[\log\left(\frac{\nu}{\nu_n}\right)\right] + \boldsymbol{a_2} \left(\frac{\nu}{\nu_n}\right)^{-2.5} \left[\log\left(\frac{\nu}{\nu_n}\right)\right]^2 + \boldsymbol{a_3} \left(\frac{\nu}{\nu_n}\right)^{-4.5} + \boldsymbol{a_4} \left(\frac{\nu}{\nu_n}\right)^{-2}$$

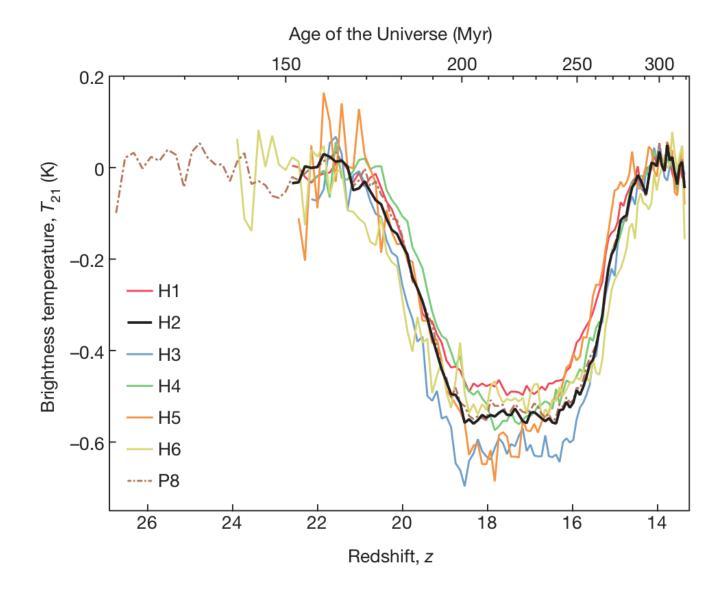
Alternative Polynomial Model

$$m_{\rm fg}(\boldsymbol{a_i}) = \left(\frac{\nu}{\nu_n}\right)^{-2.5} \quad \sum_{i=0}^{N_{\rm fg}-1} \boldsymbol{a_i} \left(\frac{\nu}{\nu_n}\right)^i$$

**Smooth sets of basis functions** that model well, with few terms, the spectrum over wide frequency ranges.

Linear fit coefficients not intended to be assigned physical interpretation.

#### Different Instruments/Hardware Cases

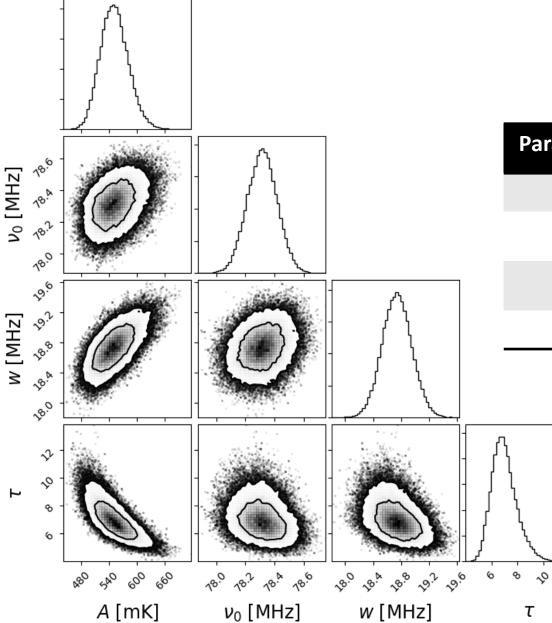


Bowman, Rogers, Monsalve, Mozdzen, Mahesh 2018, Nature, 555, 67

#### Parameter Estimates

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**Estimates from Nominal Spectrum** 



#### **Reported Estimates Including All Cases**

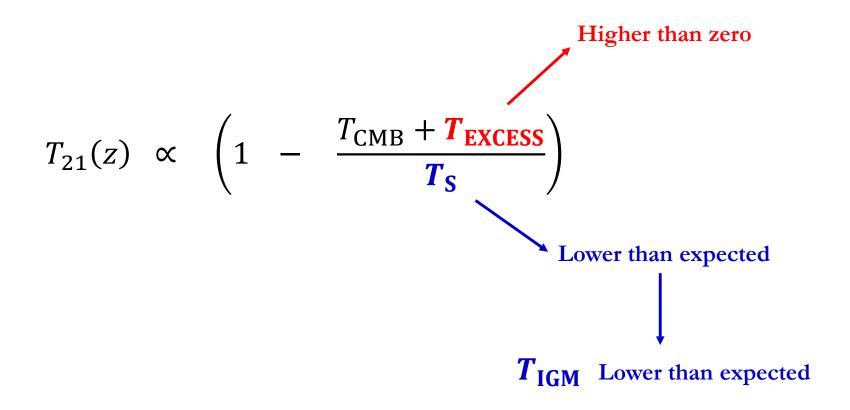
Parameter	Best Fit	Uncertainty (3 $\sigma$ )
A	0.5 K	+0.5/-0.2 K
$\nu_0$	78 MHz	+/-1 MHz
W	19 MHz	+4/-2 MHz
τ	7	+5/-3

## Absorption Amplitude for Various GHA

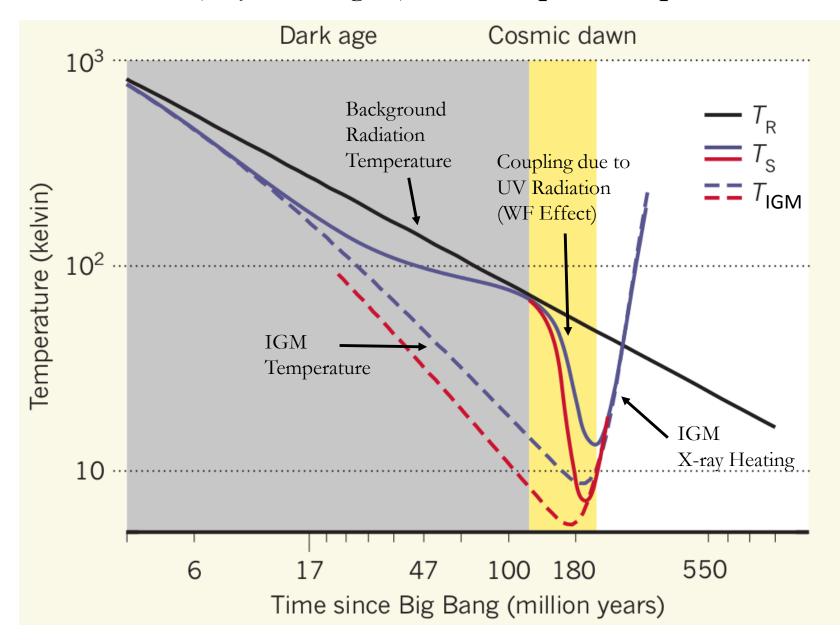
Galactic Hour Angle (GHA)	SNR	Amplitude (K)	Sky Temperature (K)		
6-hour bins		$\bigcap$	$\bigcap$		
0	8	0.48	3999		
6	11	0.57	2035		
12	23	0.50	1521		
18	15	0.60	2340		
4-hour bins					
0	5	0.45	4108		
4	9	0.46	2775		
8	13	0.44	1480		
12	21	0.57	1497		
16	11	0.59	1803		
20	9	0.66	3052		

Bowman, Rogers, Monsalve, Mozdzen, Mahesh 2018, Nature, 555, 67

#### How to Explain Deep Absorption?



#### Global (Sky-Averaged) 21-cm Spin Temperature



Adapted from Greenhill 2018, Nature, 555, 38

## Interactions of Baryons with Dark Matter?

# A small amount of mini-charged dark matter could cool the baryons in the early Universe

Julian B. Muñoz<sup>1\*</sup> & Abraham Loeb<sup>2</sup>

LETTER

NATURE, 557, 31 MAY 2018

https://doi.org/10.1038/s41586-018-0151-x

- 1) Enough IGM cooling achieved if small fraction (<1%) of DM particles posses electric mini-charge (~ $10^{-6}$  the charge of an electron).
- 2) Mass of these DM particles constrained to  $\sim$  1-60 MeV.

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

#### Other Global 21-cm Experiments

PRI<sup>Z</sup>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.)



#### Summary

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## Thank You

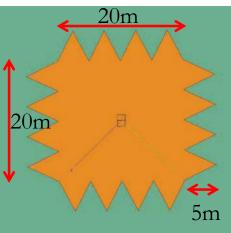
#### Instrumental Calibration

- 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.

#### Low-Band Ground Plane



Central Square: 20m x 20m 16 Triangles: 5m-long



#### Daily Low-Band Residuals

258	- Manaman man	176 mK
259	- LM My mannen	168 mK
260	- holes manufamment	181 mK
261	- La MAMA AMALINA MARINA MARINA	193 mK
262	- ha har a manage and har	187 mK
263		177 mK
263		174 mK
265		166 mK
265	- White and the second second	199 mK
	- 1. www.www.	182 mK
267	- Minmerson	202 mK
268	- Marin manun	175 mK
269	Manneman	182 mK
270	- Martin man	277 mK
<u> </u>	- MM Marsh Marsh Marsh Marsh	
<u>6</u> 273	- M. marken market	185 mK
. <u>s</u> 274	- Mymmy when when we want	169 mK_
·등 275	- M.M. Marine Marine	175 mK
ъ 276	- M.M. Marine Marine	171 mK
<del>0</del> 277	- Man man	184 mK
× 278	- WMMMMmmmmmm	184 mK
<u> </u>	Mannen	165 mK
280	- Munder	180 mK
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፝ 285	- mpanhamman	199 mK
a 287	- My My mon	189 mK
<sup>©</sup> 288	- Murphanen	172 mK
289	- MMM momment	210 mK
290	- 11 Manutan manun	191 mK
291	- way way way way and a second	145 mK
292	- Walth month	158 mK
293	- I Mummmmmmmmmmmmmmmmmmmmmmmmmmmmmmmmmmm	175 mK
294	- laman man announdary an	245 mK
295	- with monorman	175 mK
296	- MANA a margane	176 mK
297	- Man par man and a man	184 mK
298	- Kand and have a man a market	149 mK
302	- hold a designed and a second and	157 mK
303	LIA MA Ashana	172 mK
303	www.www.www.	152 mK
504	had Motors and the survey when the	
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315	- Long	n. ask		~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	man.	151 mK
316	1 M	1. h and	han a ha			162 mK
317	W				~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	152 mK
	, <b>v</b> ''	~~~		~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	~~~~~	162 mK
318	- V ~	hum	~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~		~~~~~	~ 175 mK
319		m	N. Com	~~~~~~	~~~~	204 mK
320	- WVV	han	hum	m	him	
321	- m	m	m	m	m	144 mK
322	- \//~	mm	Low	~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	M 177 mK
323	- 11	Mm	~~~~~	$\sim$	mh	🝌 166 mK
324	- 1mm	Nim	mo	mm	mm	171 mK
327	- hm	mm	m	~~~~~	~~~~	🗸 175 mK -
328	M	im	m	mm	~~~~~	👡 165 mK
329	- TAM	Mann	mm	m	m	🗸 🔨 218 mK
332	- Vin	hm	man	m		160 mK
334	MAN	La mar	M. A.	~~~~~		163 mK
336	M.			Mar	um offen	243 mK
337		Mur of a			~~~~ W	224 mK
338	WAA			~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	174 mK
	- 1/~//	WWW ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	~~~~	~~~~~	~~~w	194 mK
339		www.	www	m	m	261 mK
340	- 4/17	mm	rm	my	m	169 mK
341	- VM	ww	m	m	······	~~ \
342	- 1/1/~	~~~~~	www	m	$\sim \sim $	175 mK
343	- 🇤	mm	mm	m	mi	204 mK
348	- Min	mm	mp	mm	~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	166 mK
350	- h~^	ww	www	m	mm	172 mK
351	- 1MM	mm	m	hmm	~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	<u></u> 168 mK
352	- 1. M~	mm	mm	m	m	👡 177 mK
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362	M	~~~~~			~~~~	193 mK
	· // 'k	and the second	mm		~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	296 mK
363	- M	°₩∿γ	Mar	~~~~~	som.	180 mK
364	- W.*	han	mm	· ·····	mm	~~
365	- W.	mm	hum	~~~~	~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	192 mK
366	- \~W	᠕᠕᠕᠕	have	m	~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	167 mK
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2	- Wh	$\sim \sim $	m	mm	mm	185 mK
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6	- VMV	mm	mm	mm			
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11	- Into	mm	mm	mm	mh	158	mK_
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16	- MAMM	mm	nun	man	mark	186	mK_
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77	- Mm	M	norm	mm			
78	LIMAN	AM MA	1 - m	m		166	mK_
			~~~~	~~~~~~	-	164	
79	- ym	$\sim \sim $	m				
80	- 1760/17	imm	mm	~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~			mK_
82	N.MM	1 1 1 1		man	. M. A.	258	mK
			MM V				mK_
83	- WM	mm	mvv	m	· · ·		
84	- him	Mm	m	m	m	166	mK_
85	Saulat.	and int		m	44.00	178	mК
	- AMMAN		~~~~				
86	- M/ WM	mm	$\sim\sim\sim\sim$	min	mm		mK_
87	- lim	mm	mm	mm	~~~~	179	mK_
88	I. MA	A MARIA		~	1	175	mК
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89	- 1/1/~	mm	www	m			mK_
93	- Cm	mon	i a mm	m	mm	182	mK_
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			rreque	ncy [MHz	1		

## Sensitivity to Possible Calibration Errors

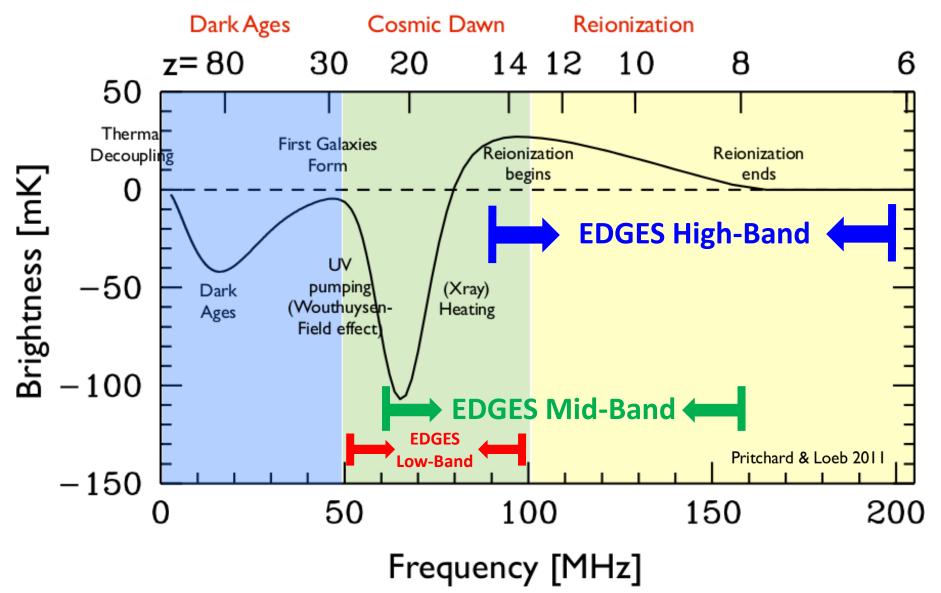
Error source	Estimated	Modelled	Recovered
	uncertainty	error level	amplitude (K)
LNA S11 magnitude	0.1 dB	1.0 dB	0.51
LNA S11 phase (delay)	20 ps	100 ps	0.48
Antenna S11 magnitude	0.02 dB	0.2 dB	0.50
Antenna S11 phase (delay)	20 ps	100 ps	0.48
No loss correction	N/A	N/A	0.51
No beam correction	N/A	N/A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

## Hardware and Processing Cases

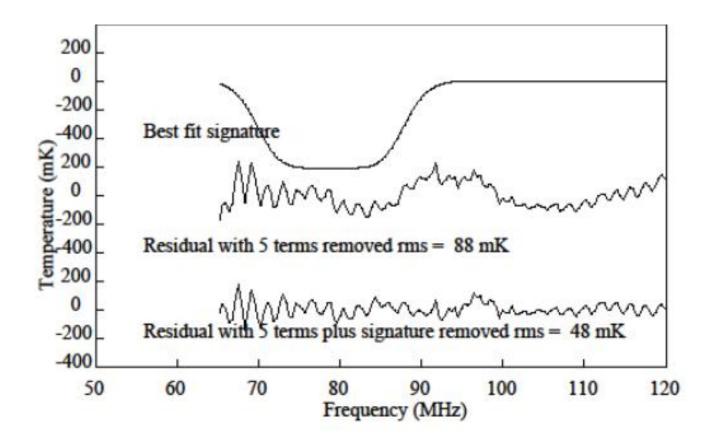
Configuration	Sky Time (hours)	SNR	Centre Frequency (MHz)	Width (MHz)	Amplitude (K)	
Hardware configurations (all P6)			$\widehat{}$	$\frown$	$\wedge$	
H1 – low-1 10x10 ground plane	528	30	78.1	20.4	0.48	
H2 – Iow-1 30x30 ground plane	428	52	78.1	18.8	0.54	
H3 – low-1 30x30 ground plane and recalibrated receiver	64	13	77.4	19.3	0.43	
H4 – Iow-2 NS	228	33	78.5	18.0	0.52	
H5 – Iow-2 EW	68	19	77.4	17.0	0.57	
H6 – Iow-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	

Bowman, Rogers, Monsalve, Mozdzen, Mahesh 2018, Nature, 555, 67

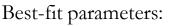
#### **EDGES** Instruments



#### Preliminary Mid-Band Results with Imperfect Data

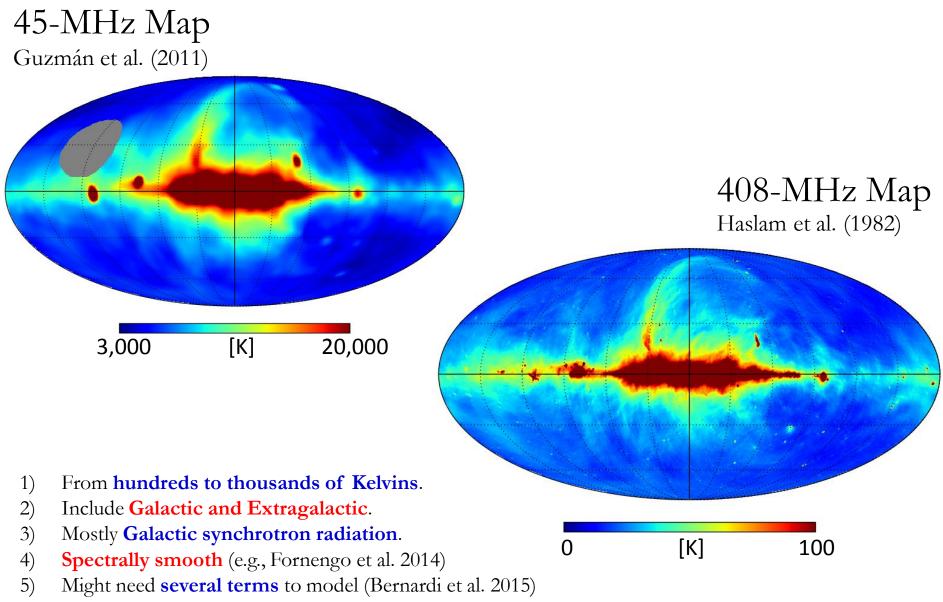


- 1) Data from November 2017-February 2018.
- 2) **Imperfect calibration** (noise source level too low).
- 3) Frequency range **65-120 MHz**.
- 4) **5-term linear "physical" foreground model**.



- **A**: 0.61 K
- ν ν<sub>0</sub>: 78.9 MHz
- *w*: 18.2 MHz
- **t**: 7

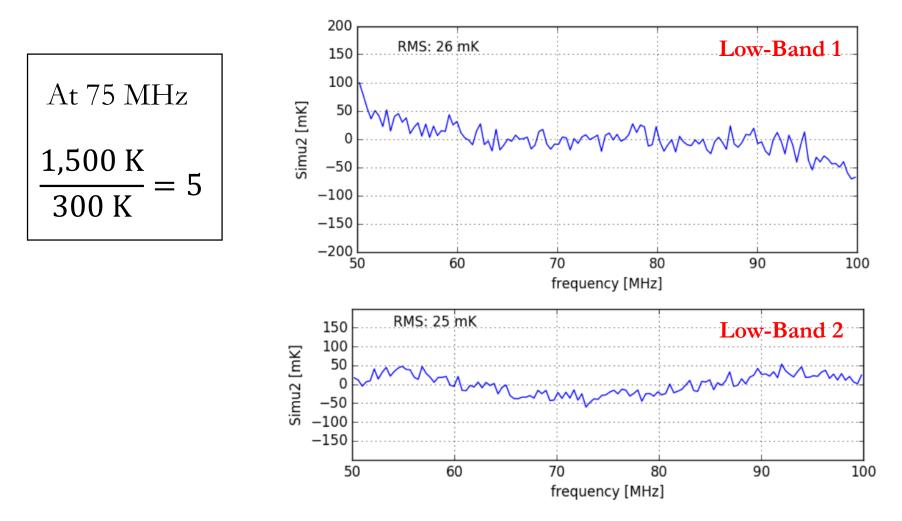
## Diffuse Foregrounds



6) Large **spatial gradients**.

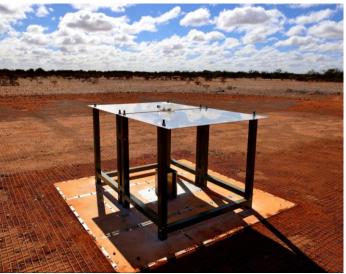
#### Verification Using ~300K Antenna Simulators

Residuals After Removing a Constant



#### **EDGES Mid-Band**

#### Low-Band



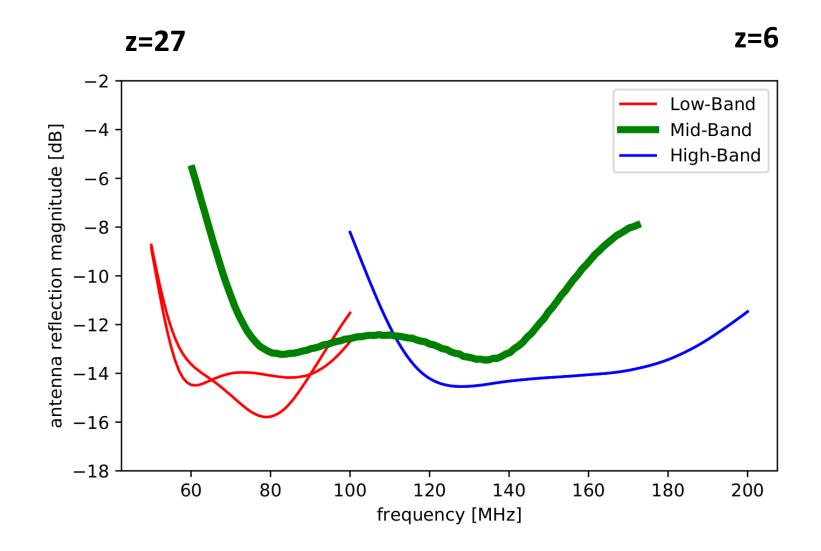
#### **High-Band**



**Mid-Band** 



#### Antenna Reflection Coefficients



Preliminarily .....