6th Global 21cm workshop IFPU, Trieste

ICRAR

International Centre for Radio Astronomy Research

Detecting Global 21-cm Signal using Lunar Occultation with MWA

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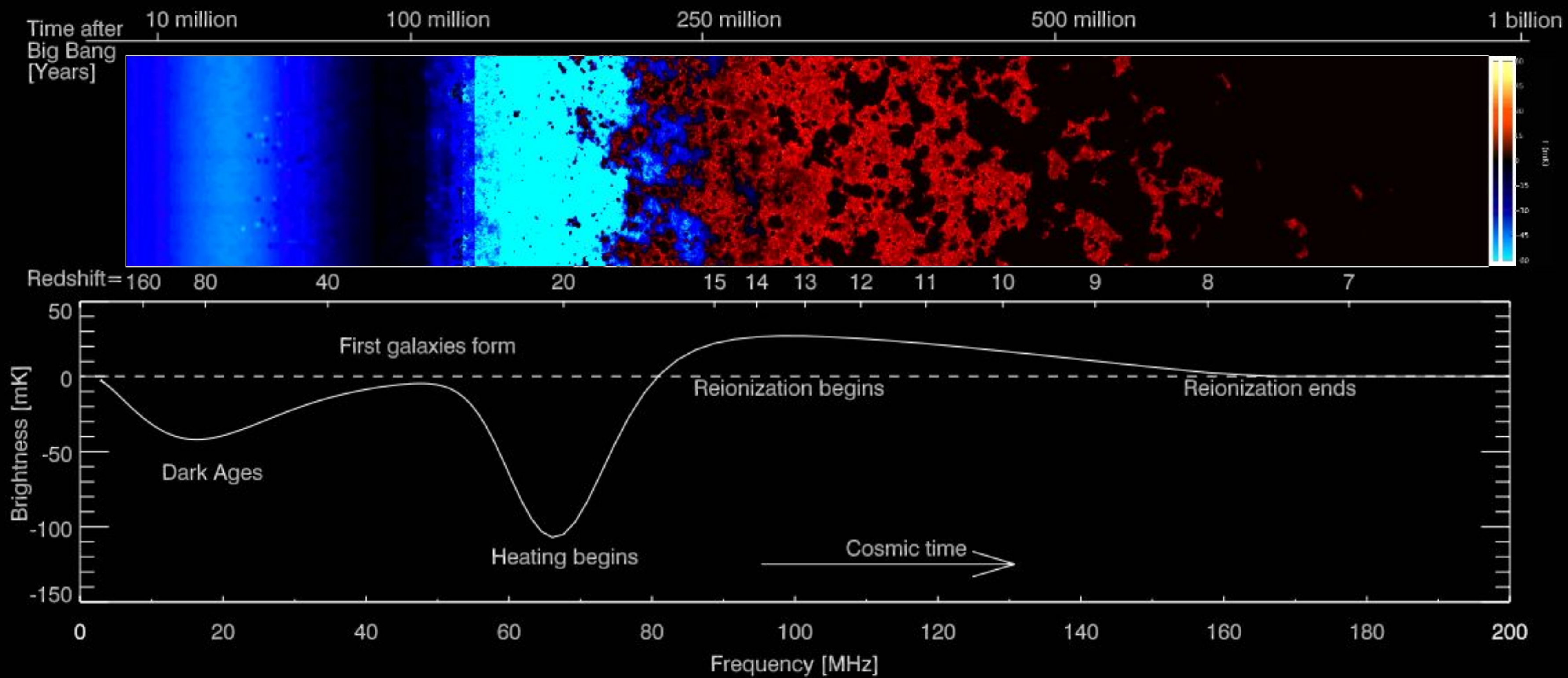
EoR- Global 21-cm Signal



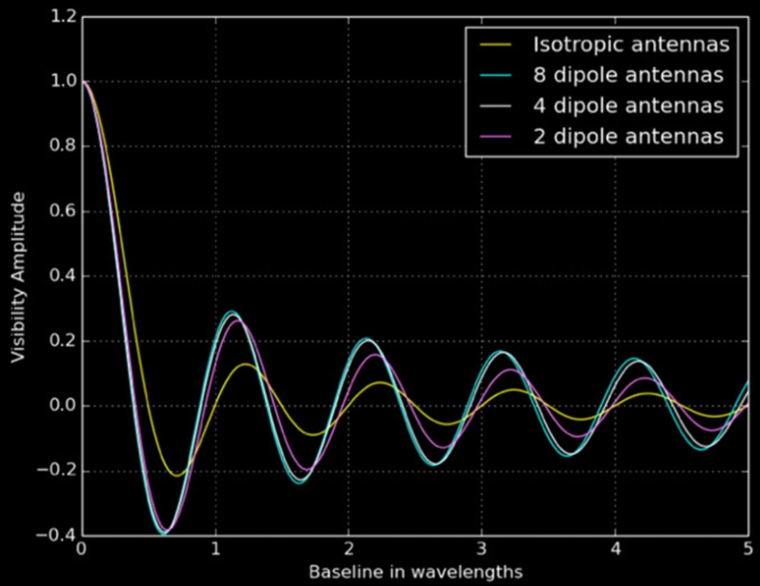
credit: Pritchard, J. R., & Loeb, A. 2012

$$\delta T_b \approx \frac{T_S - T_R}{1+z}\tau$$

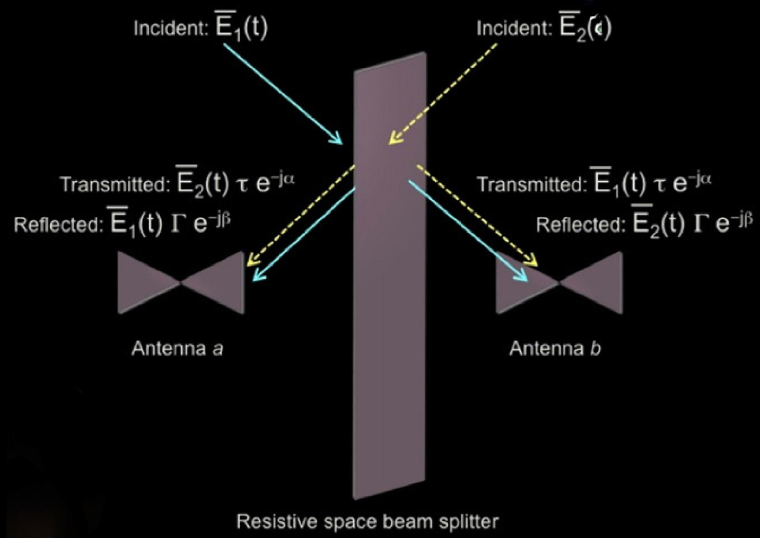
Interferometers to Global 21-cm Signal

Global Experiments are Great!

what about Interferometers?



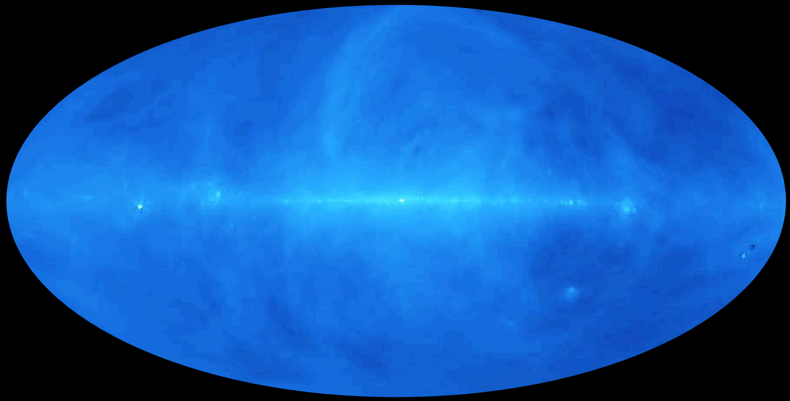
Singh, S. (2015)

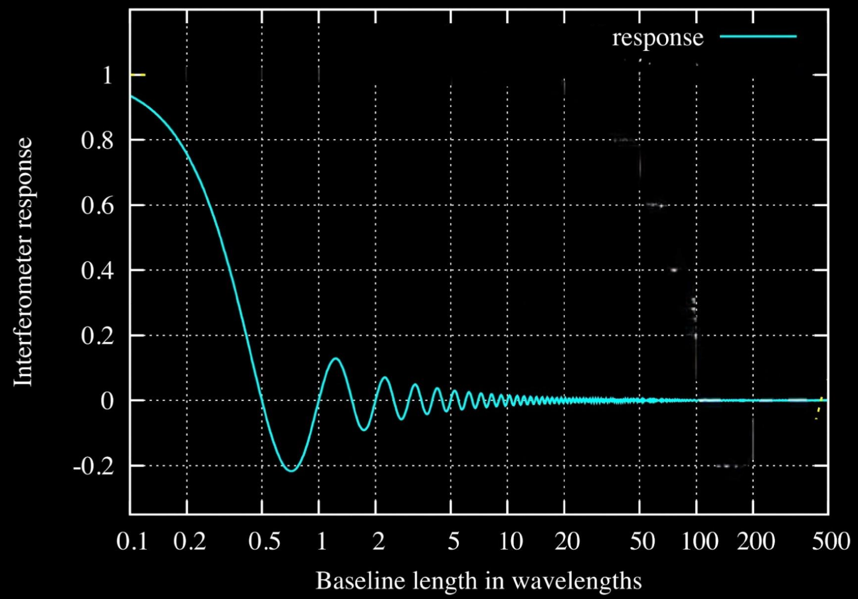


Mahesh, N. (2015)

Theory: Interferometers to Global 21-cm Signal

$$V(\vec{u},\nu) = \frac{1}{4\pi}\int d\Omega\, T_{\rm sky}(\vec{r},\nu)e^{2\pi i\vec{u}.\vec{r}}$$



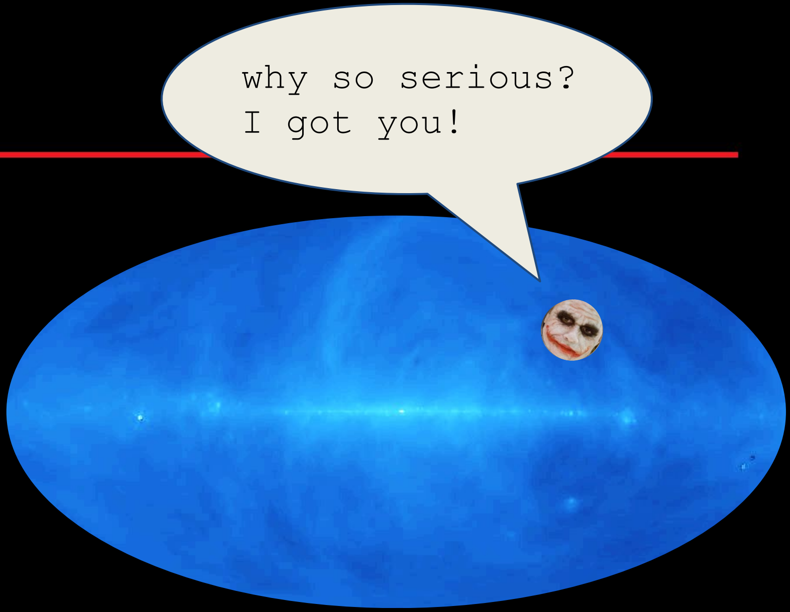


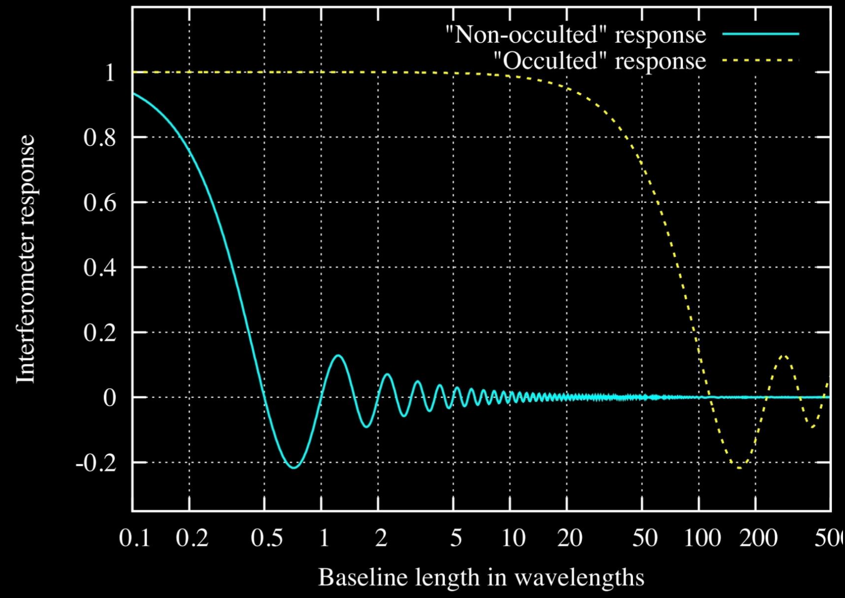
credit: Vedantham et al. [2015]

Lunar Occultation

$$V(\vec{u},\nu) = \frac{1}{4\pi}\int d\Omega\, T_{\rm sky}(\vec{r},\nu)e^{2\pi i\vec{u}.\vec{r}}$$

$$\begin{aligned} T_{\rm sky} &= T_{\rm B}\,(1-M) + T_{\rm M}\,M \\ &= \underbrace{(T_{\rm M}-T_{\rm B})M}_{\text{occulted}} \;+\; \underbrace{T_{\rm B}}_{\text{non-occulted}}\;, \end{aligned}$$





credit: Vedantham et al. [2015]

Lunar Occultation

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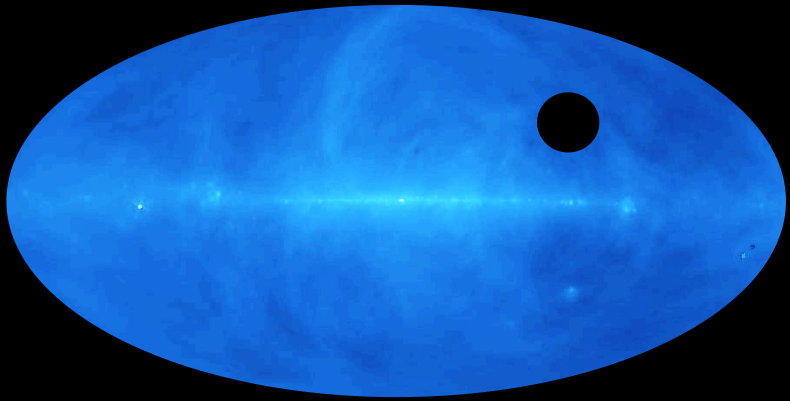
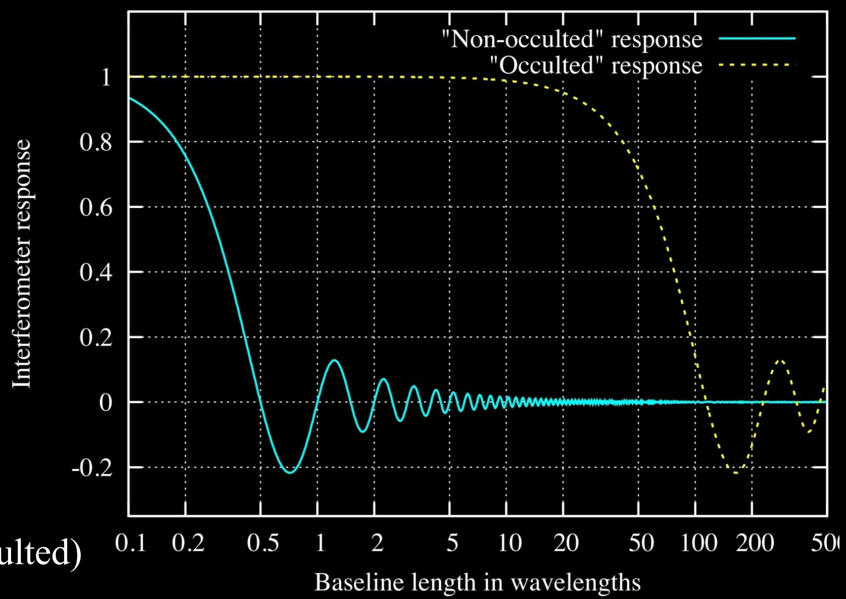
$$\begin{aligned} T_{\rm sky} &= T_{\rm B}\,(1-M) + T_{\rm M}\,M \\ &= \underbrace{(T_{\rm M}-T_{\rm B})M}_{\text{occulted}} + \underbrace{T_{\rm B}}_{\text{non-occulted}}\,, \end{aligned}$$

$$V(\vec{u},\nu) = T_{\rm B}(\nu)\frac{\sin 2\pi|\vec{u}|}{2\pi|\vec{u}|}$$ (Non-occulted)

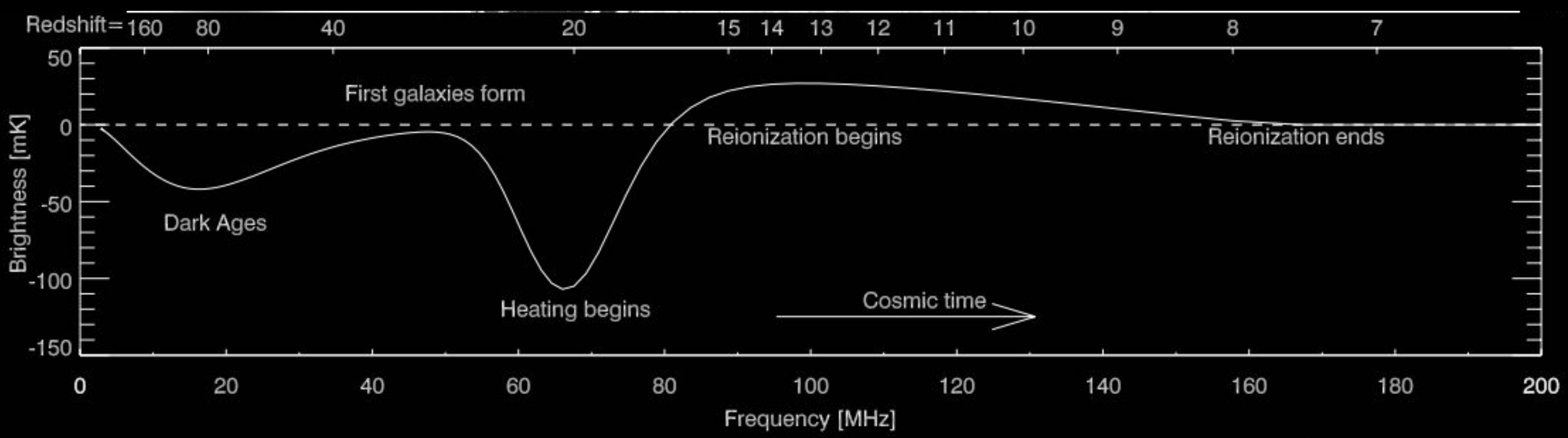
$$V(\vec{u}) \approx (T_{\rm M}-T_{\rm B})\frac{\Omega_a}{4\pi}\frac{2J_1(\pi a|\vec{u}|)}{\pi a|\vec{u}|}$$ (Occulted)





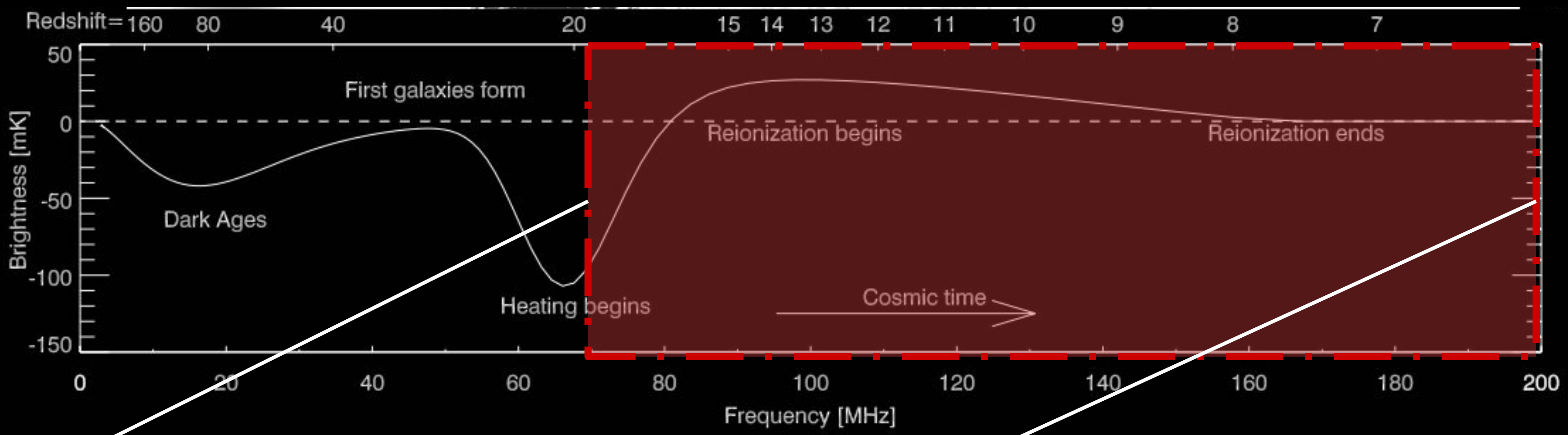
credit: Vedantham et al. [2015]

EoR- Global 21-cm Signal

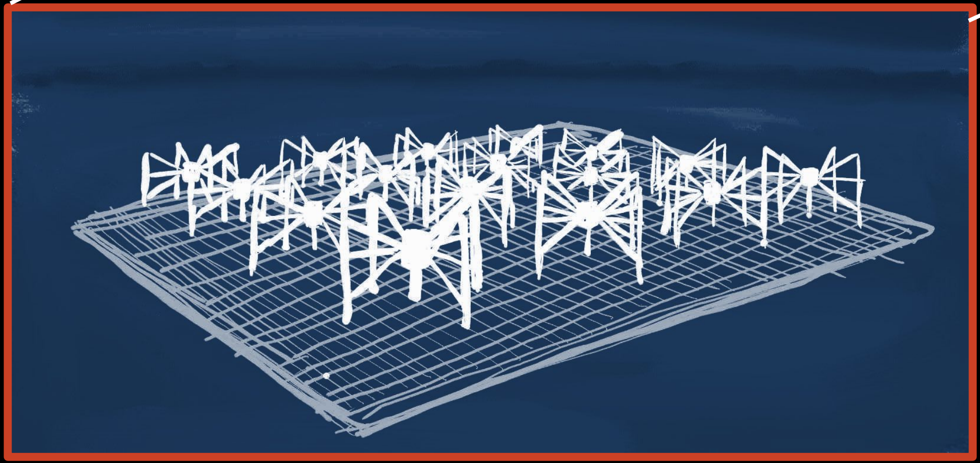


credit: Pritchard, J. R., & Loeb, A. 2012

EoR- Global 21-cm Signal



credit: Pritchard, J. R., & Loeb, A. 2012

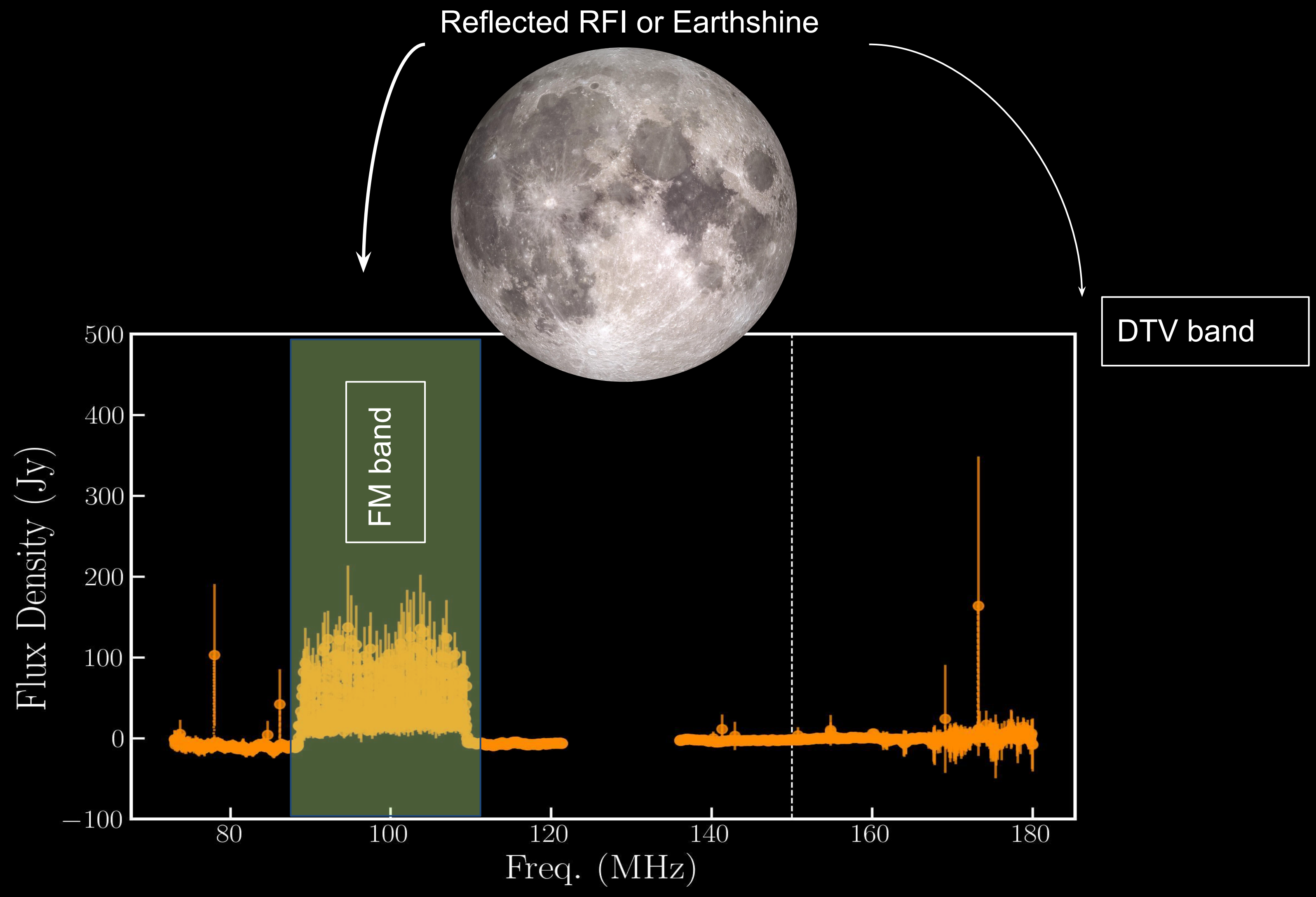


Measurements of the Moon

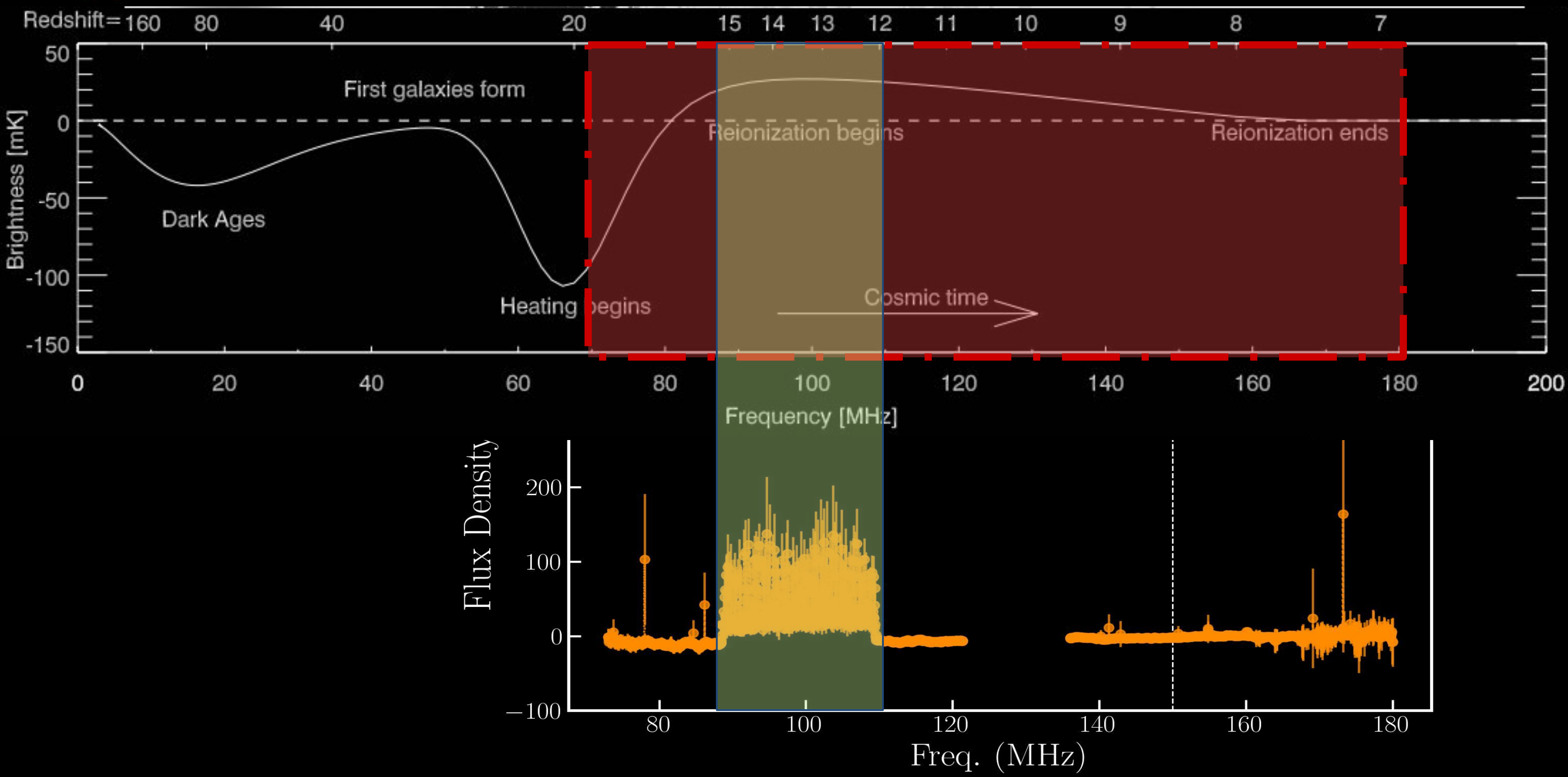
How does the Moon looks like in Radio?

Indeed!

How does the Moon is in Radio?



How does the Moon is in Radio?

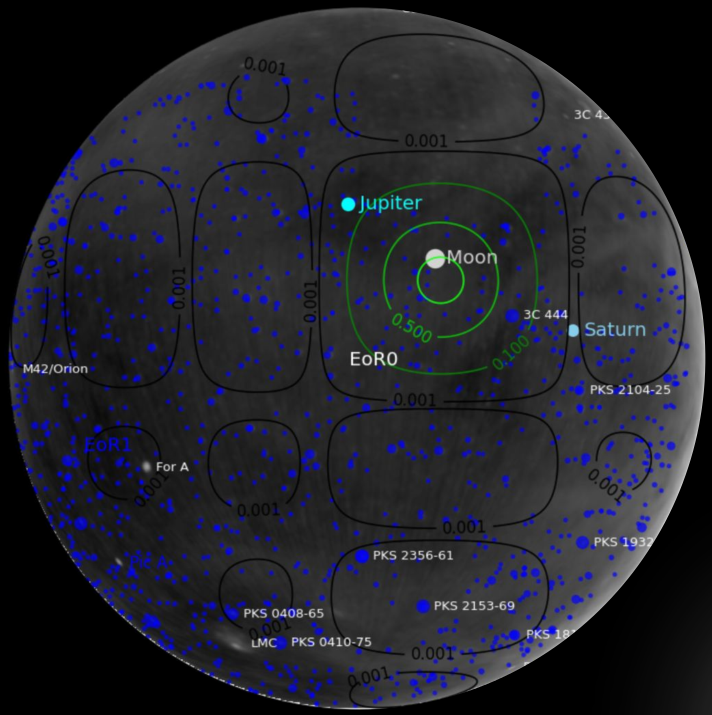



where is EoR?
You humans produce RFI!!

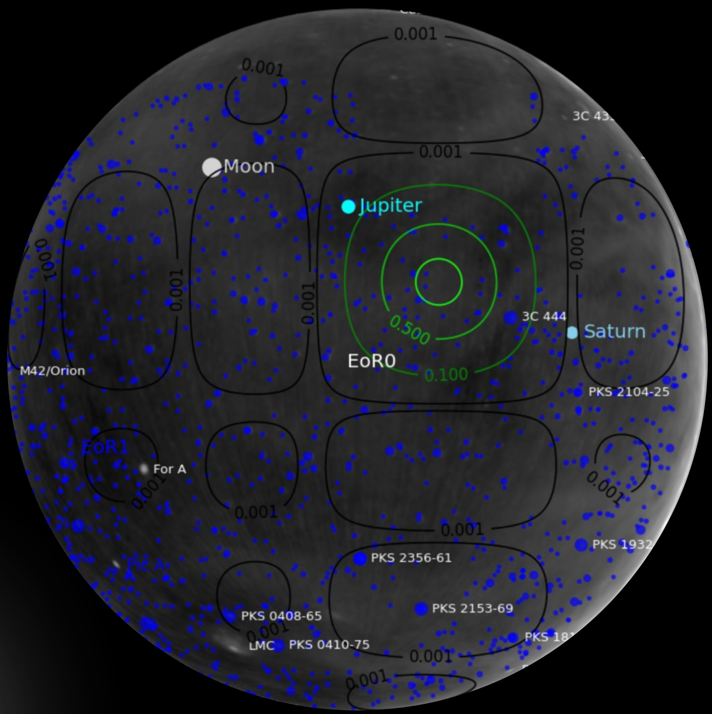
Mitigating Earthshine from the Moon!

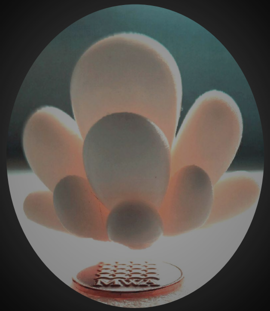
observations

ON-Moon



OFF-Moon

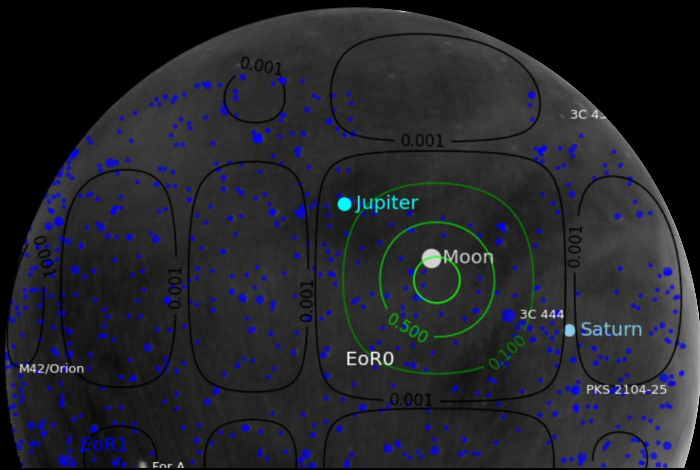




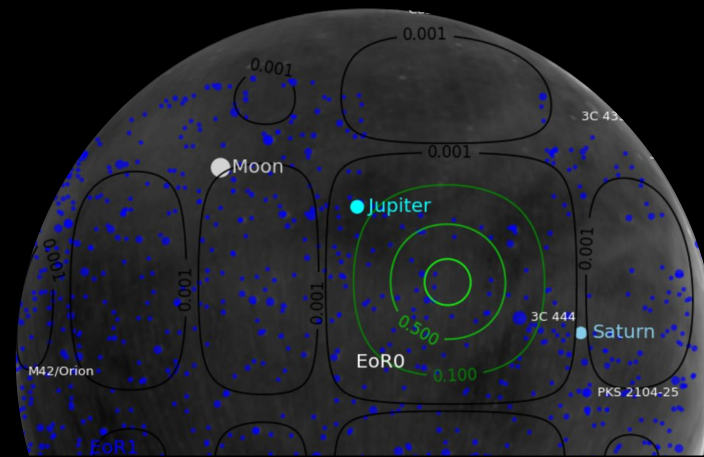
LST locked pair of observation
Data: MWA phase-1
Obs date: Aug 2015, Sept 2015, Dec2015

observations

ON-Moon



OFF-Moon

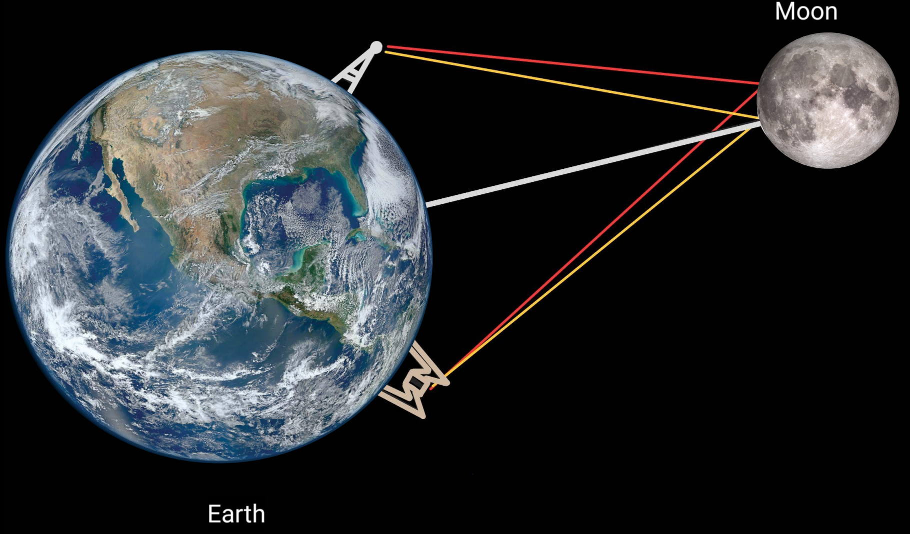


ON – Moon							
Date	N_{obs}	$N_{obs}^{full-band}$	Bandwidth (MHz)	Freq. res. (kHz)	Time res. (sec)	Total Int. time (sec)	Obs. duration (hrs)
30^{th}Aug.2015	60	12	30.76	40	4	236	3.93
26^{th}Sept.2015	55	11	30.76	40	4	236	3.60
21^{th}Dec.2015	55	11	30.76	40	4	236	3.60
OFF – Moon							
2^{nd}Sept.2015	60	12	30.76	40	4	236	3.93
29^{th}Sept.2015	55	11	30.76	40	4	236	3.60
24^{th}Dec.2015	55	11	30.76	40	4	236	3.60
	$N_{total} = 340$	$N_{total}^{full-band} = 68$					$Time_{total}^{ON-Moon} = 11.13$

Modelling Earthshine

Assumed Two component Earthshine, Evans (1969), McKinley (2018)

specular, diffuse

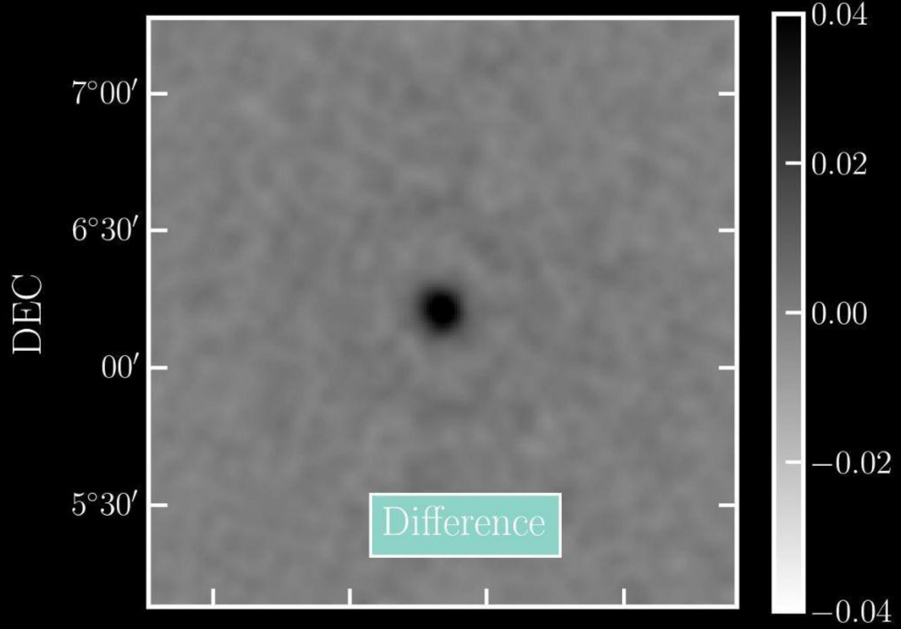


Modelling Earthshine

Assumed Two component Earthshine, Evans (1969), McKinley (2018)

- **step 1: create dirty difference images of the Moon**

$$\mathbf{D} = (s_{\mathrm{disk}}\mathbf{M} + s_{\mathrm{spec}}\mathbf{B}) * \mathbf{P} + \mathbf{N}$$



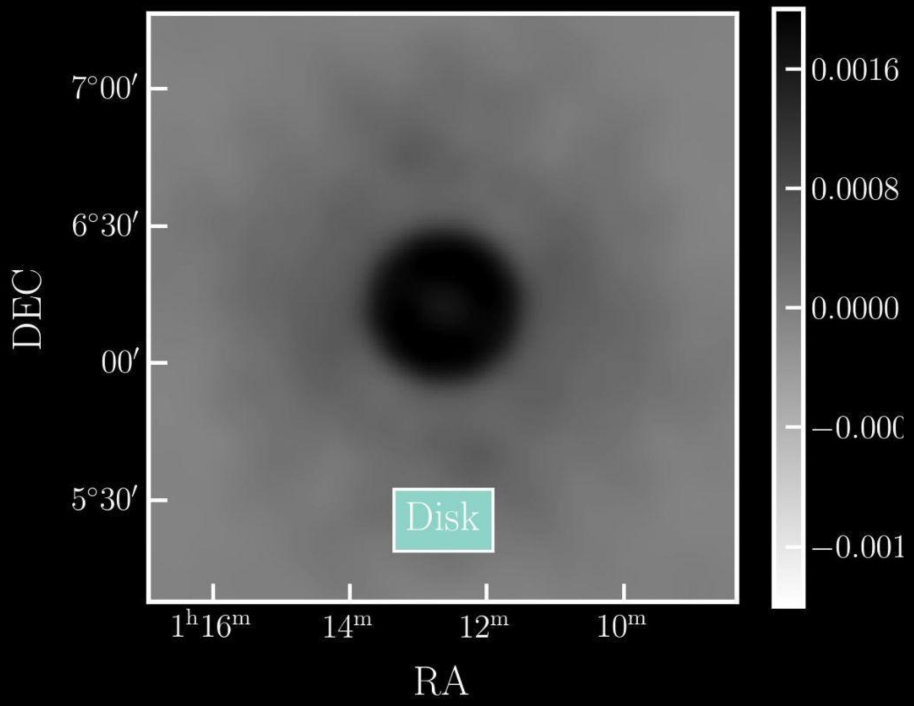
Moon at ~100 MHz

Modelling Earthshine

- **step 1: create dirty difference images of the Moon**
- **Step 2: Create mask**
  - disk M
  - Specular B

$$\mathbf{D} = (s_{\text{disk}}\mathbf{M} + s_{\text{spec}}\mathbf{B}) * \mathbf{P} + \mathbf{N}$$

Moon at ~100 MHz



Modelling Earthshine

- **step 1: create dirty difference images of the Moon**

- **Step 2: Create mask**
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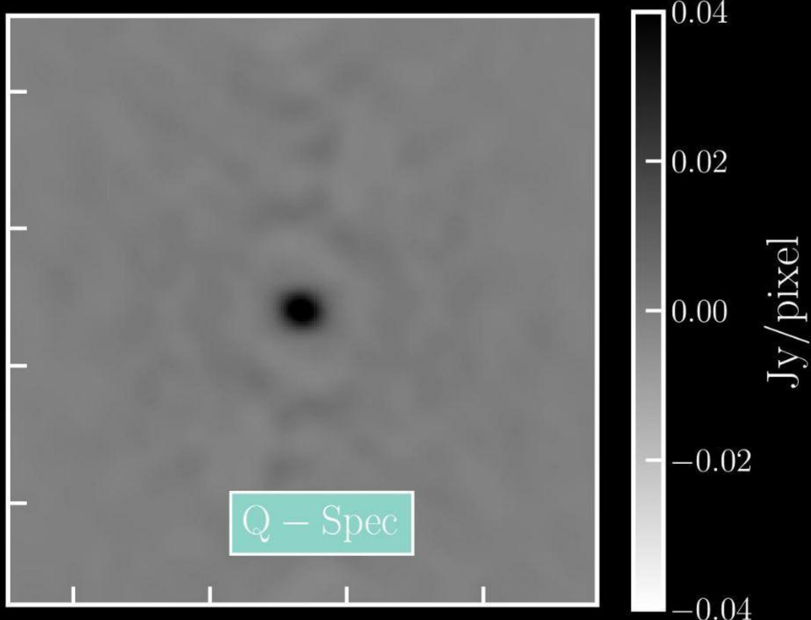
Moon at ~100 MHz



Modelling Earthshine

- **step 1: create dirty difference images of the Moon**
- **Step 2: Create mask**
  - disk M
  - Specular B

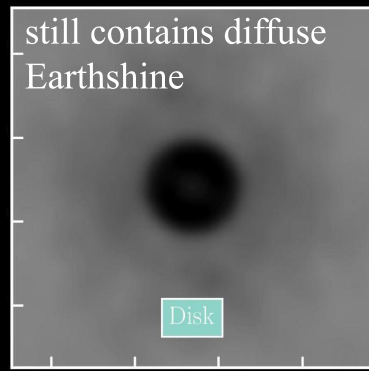
$$\mathbf{D} = (s_{\mathrm{disk}}\mathbf{M} + s_{\mathrm{spec}}\mathbf{B}) * \mathbf{P} + \mathbf{N}$$

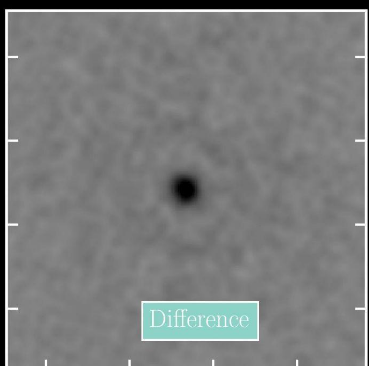
- **Step 3: solve for s_{disk}, s_{spec}**

$$[s_{\mathrm{disk}}, s_{\mathrm{spec}}] = (\mathrm{H}^{\mathrm{T}}\mathrm{H})^{-1}\mathrm{H}^{\mathrm{T}}\mathbf{D}$$

$$\mathrm{H} = [\mathbf{M}*\mathbf{P}, \mathbf{B}*\mathbf{P}]$$

Isolating Earthshine- specular component



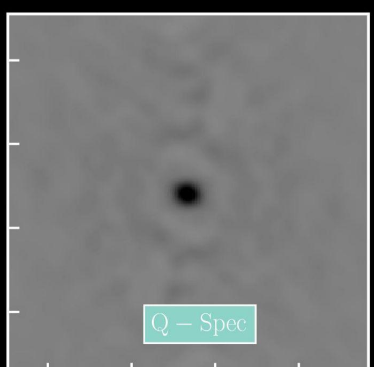


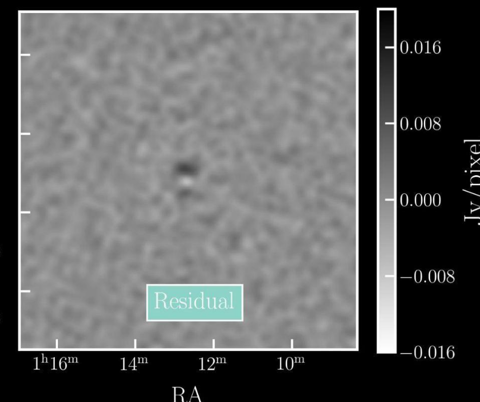
$$S_{\text{disk}} = \sum s_{\text{disk}}.\mathbf{M}$$

Reconstructed Moon's disk

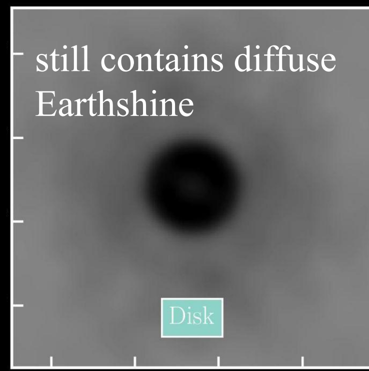
$$S_{\text{spec}} = \sum s_{\text{spec}}.\mathbf{B}$$

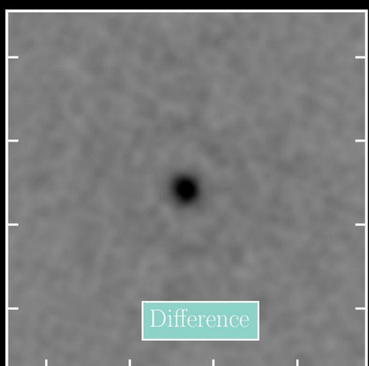
Specular earthshine





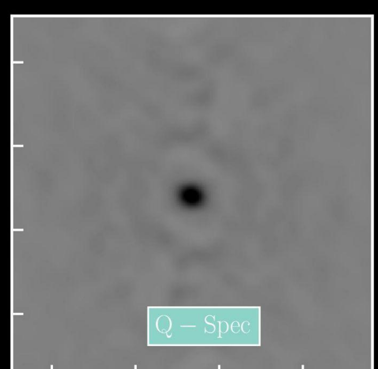
Isolating Earthshine- specular component

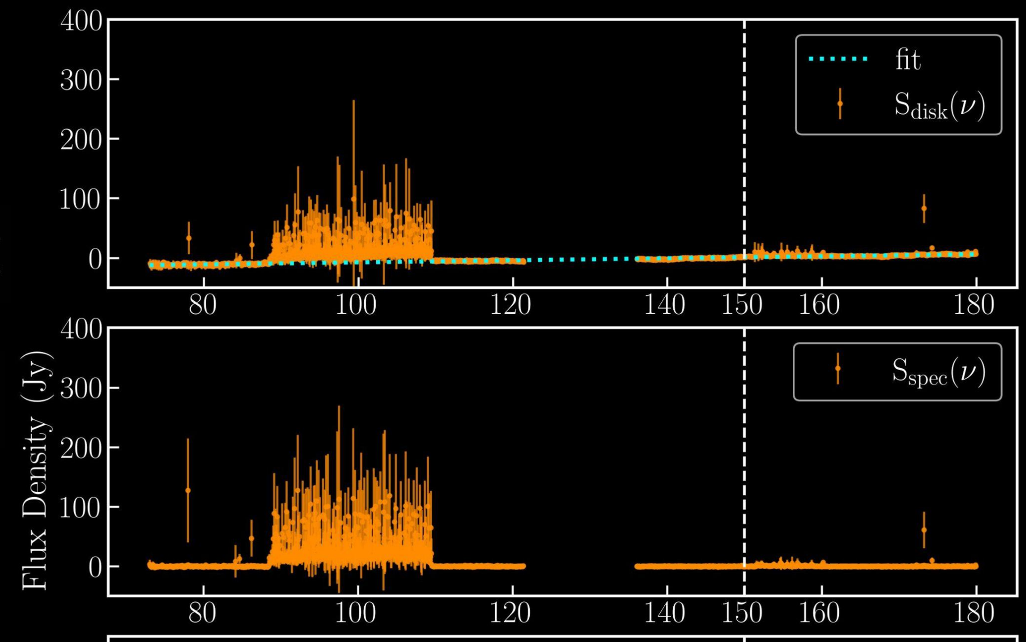




$$S_{\text{disk}} = \sum s_{\text{disk}}.\mathbf{M}$$

$$S_{\text{spec}} = \sum s_{\text{spec}}.\mathbf{B}$$





Isolating Earthshine- diffuse component (method: 1)

Radar studies from Evans (1969)

- **relation between the two Earthshine component**

$$S_{\text{diffuse}}(\nu) = R_e(\nu) S_{\text{spec}}(\nu)$$

$$R_e(\nu) = \left(\frac{S_{\text{diffuse}}(\nu{=}100\text{MHz})}{S_{\text{spec}}(\nu{=}100\text{MHz})}\right)\left(\frac{\nu}{100\text{MHz}}\right)^{0.58}$$

flux-density of the Moon

$$S_{\mathrm{diffuse}}(\nu) = R_e(\nu) S_{\mathrm{spec}}(\nu)$$

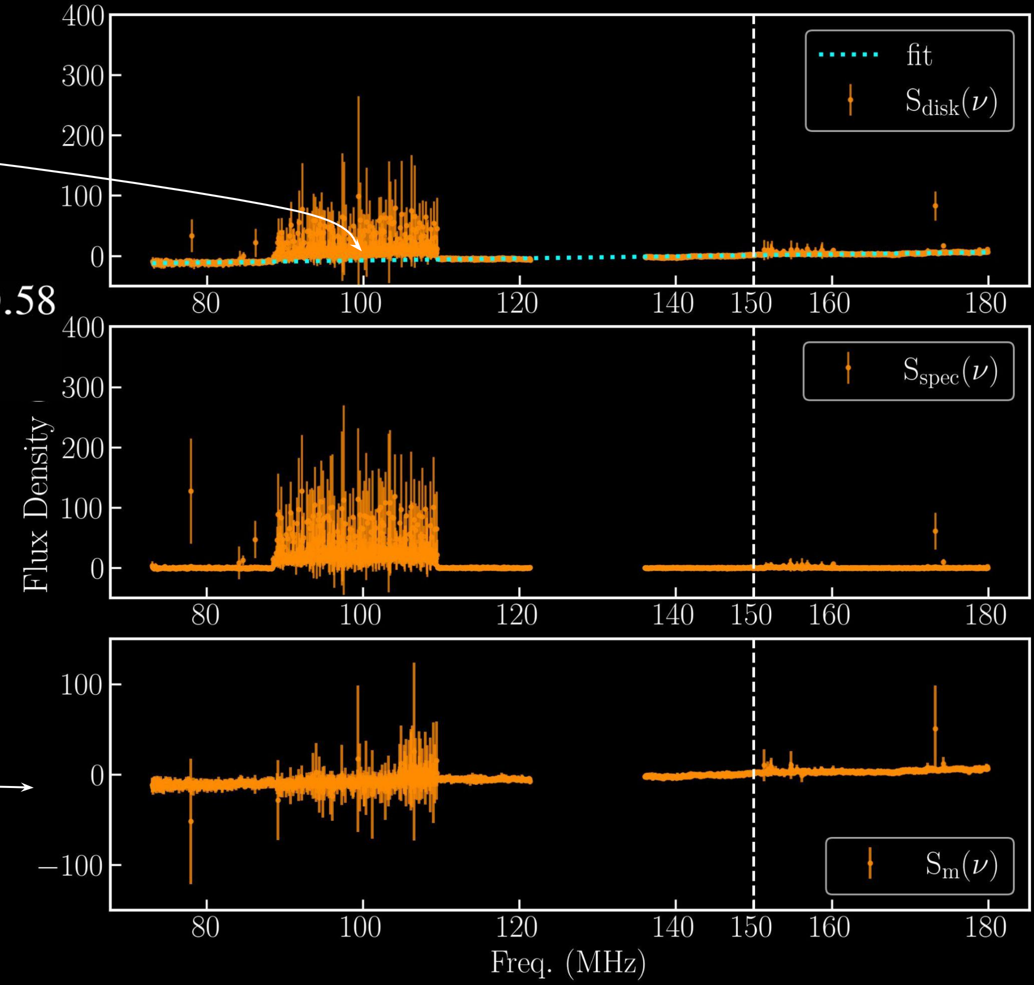
$$R_e(\nu) = \left(\frac{S_{\mathrm{diffuse}}(\nu{=}100\mathrm{MHz})}{S_{\mathrm{spec}}(\nu{=}100\mathrm{MHz})}\right)\left(\frac{\nu}{100\mathrm{MHz}}\right)^{0.58}$$

$$S_m(\nu) = S_{\mathrm{disk}}(\nu) - S_{\mathrm{diffuse}}(\nu)$$

flux-density of the Moon

$$R_e(\nu) = \left(\frac{S_{\text{diffuse}}(\nu{=}100\text{MHz})}{S_{\text{spec}}(\nu{=}100\text{MHz})}\right)\left(\frac{\nu}{100\text{MHz}}\right)^{0.58}$$

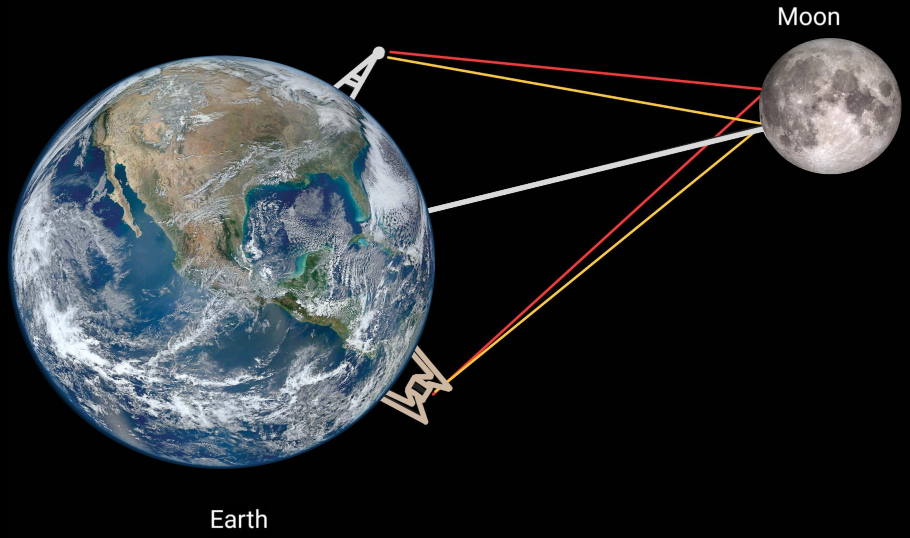
$$S_m(\nu) = S_{\text{disk}}(\nu) - S_{\text{diffuse}}(\nu)$$



Freq res. $\Delta\nu$ = 40 KHz

Isolating Earthshine- diffuse component (method: 2)

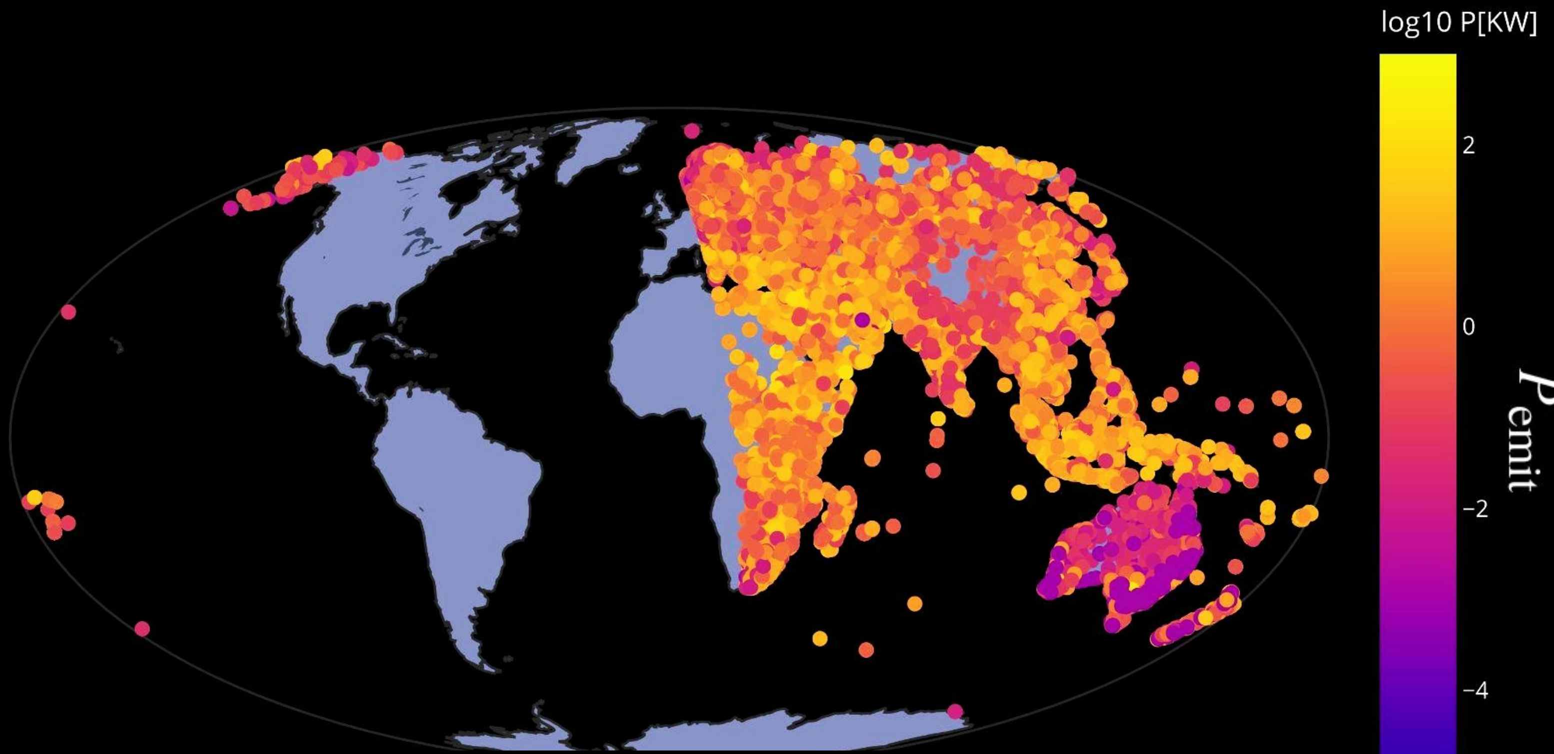
- FM station catalog - fmlist.org
- Estimating power received at MWA during the observations



Assumptions

- All FM stations produce isotropic power, have constant bandwidth
- Reflection from the Moon are diffuse

Reflected Power from the Moon



$$P_{\rm rec}(\nu) = \frac{P_{\rm emit}(\nu)\sigma_{\rm cross}A_{\rm eff}}{(4\pi)^2 D_1^2 D_2^2},$$

$P_{\rm emit}(\nu)$ - Station Power

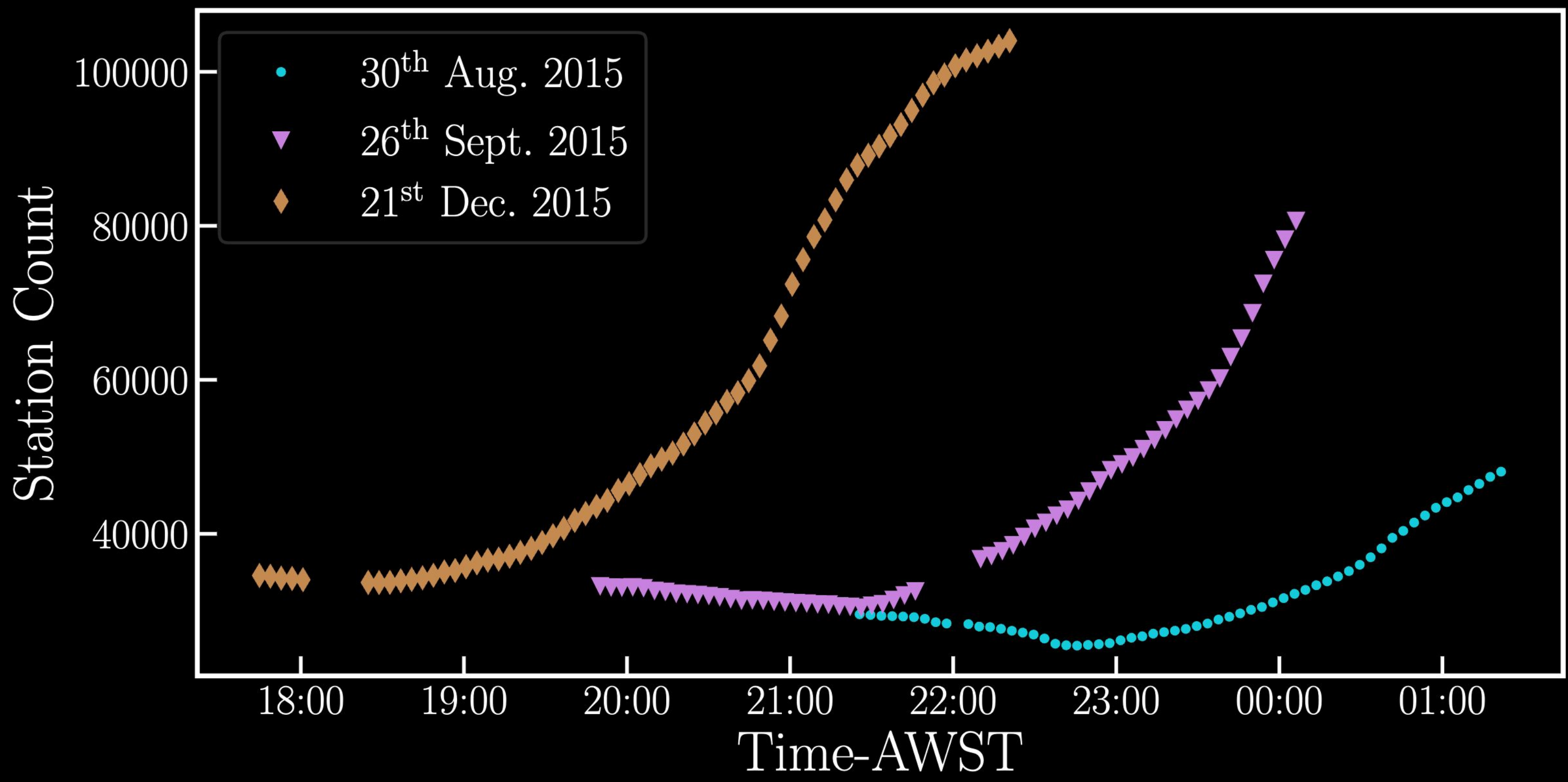
$\sigma_{\rm cross}$ - Radar Cross section (~7% albedo in Radio, Evans (1969))

ΔB - Transmission Bandwidth

$D1, D2$ - Distance between the Moon from MWA, FM station

FM simulations

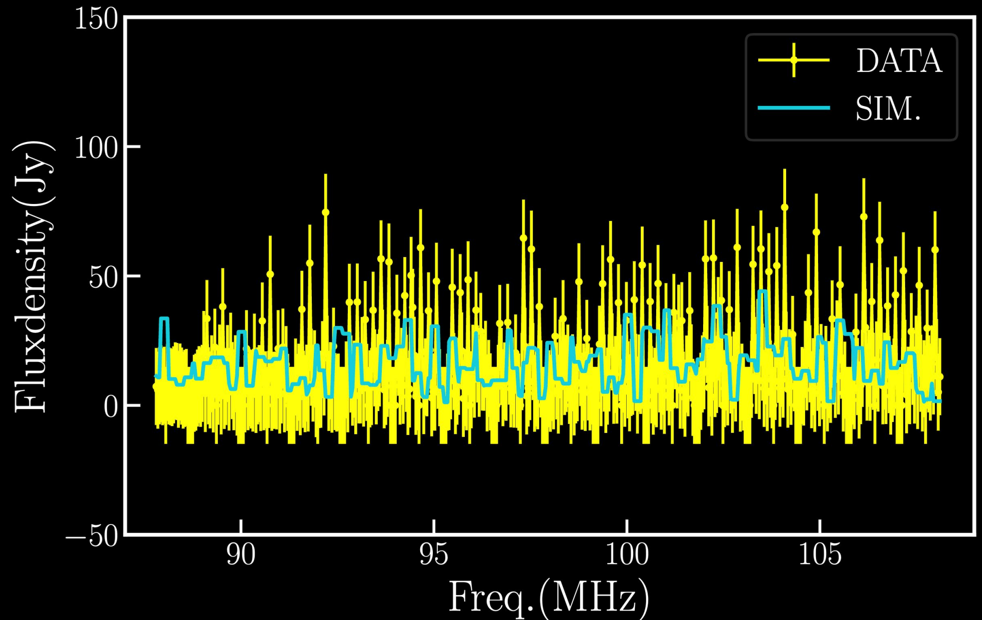
Station count vs. Observing Time



Isolating Earthshine- diffuse component (method: 2)

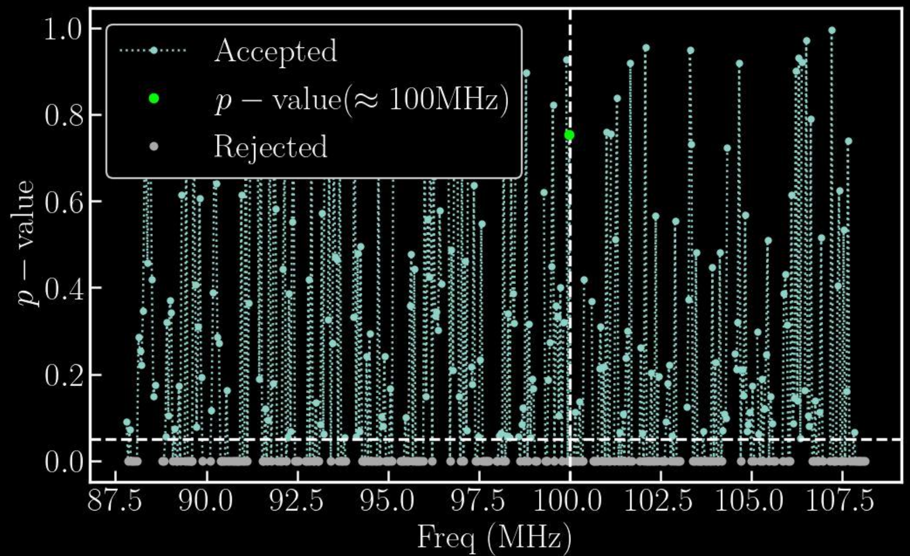
Freq res. $\Delta\nu = 40$ KHz

Diffuse Flux-density
Data and Simulation

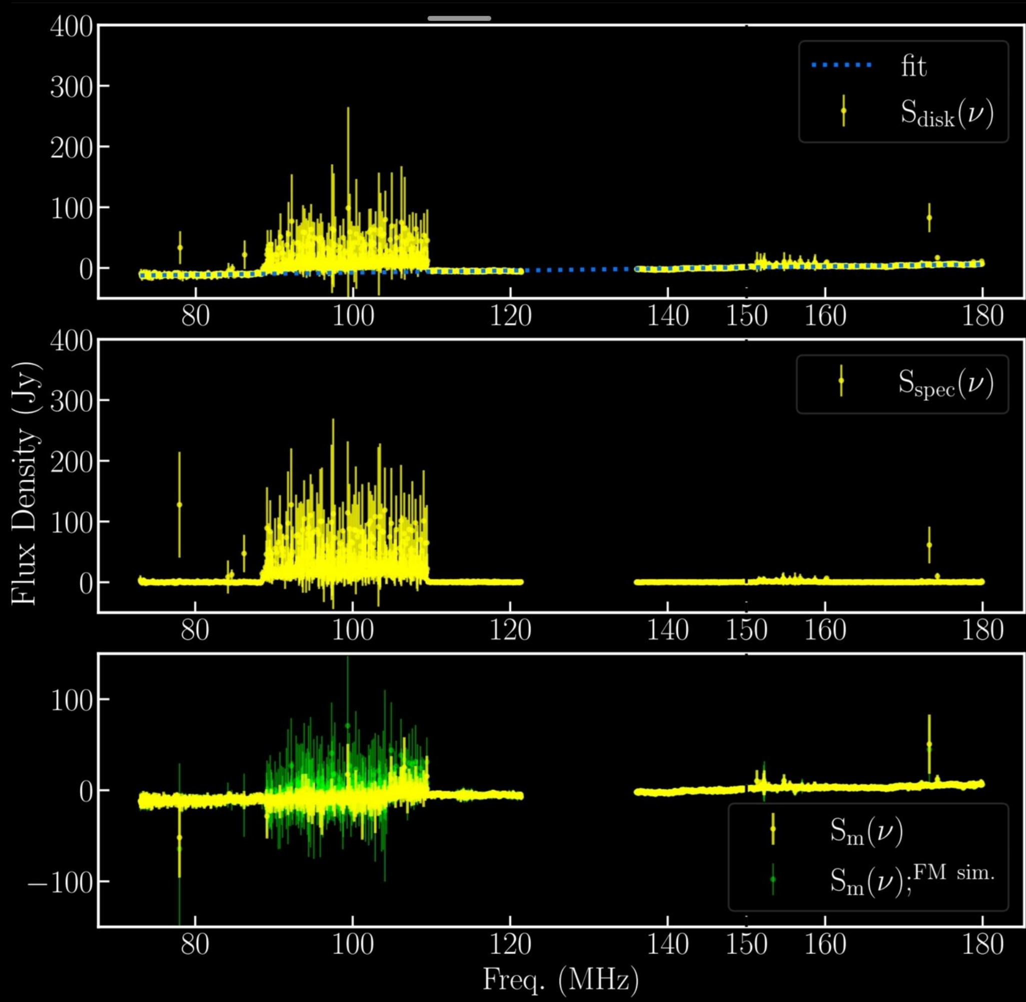


T-test

Epochs	p-value at ($\approx \nu_0$)
Aug.	0.75
Sept.	0.69
Nov.	0.78

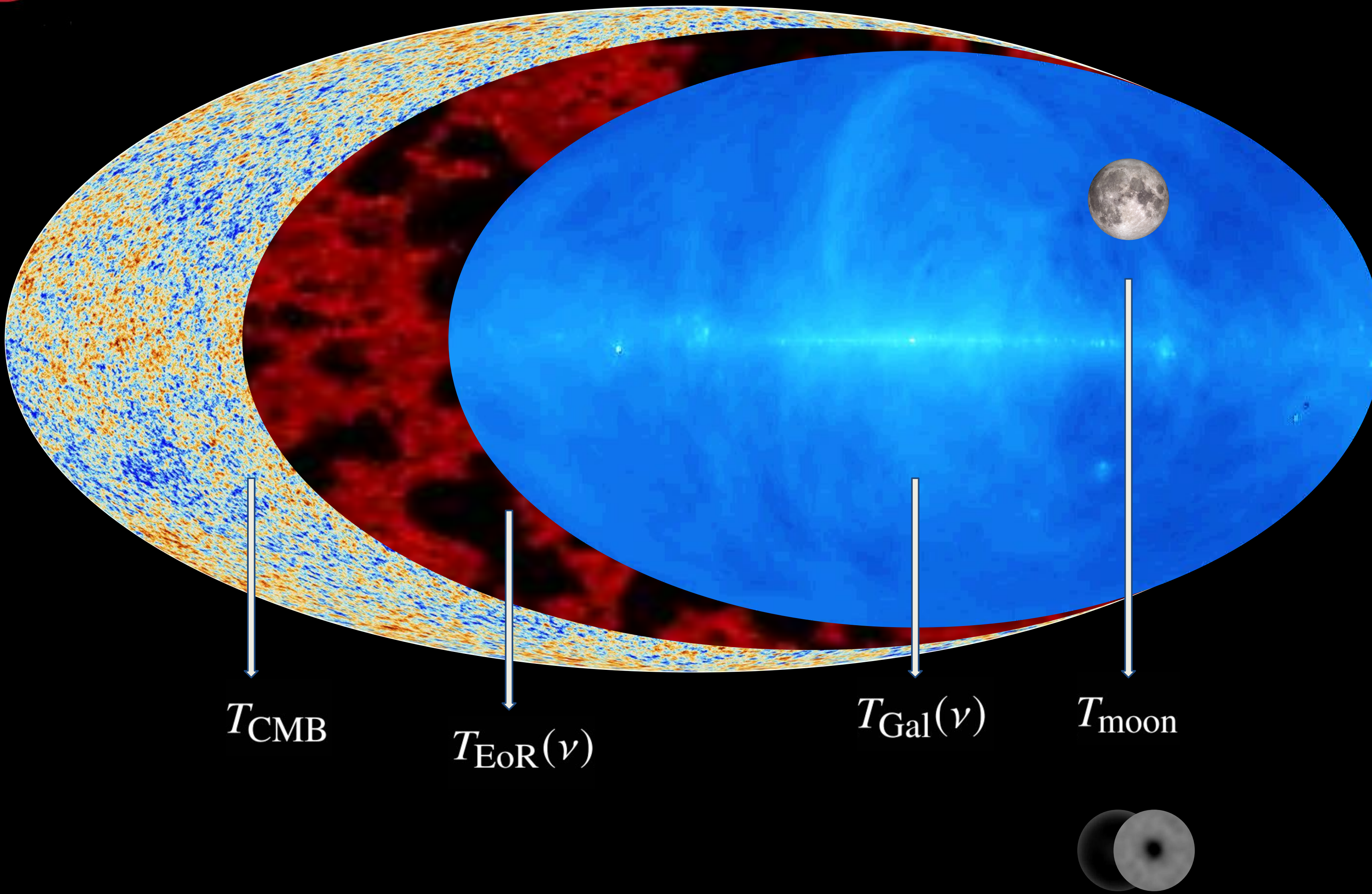


flux-density of the Moon

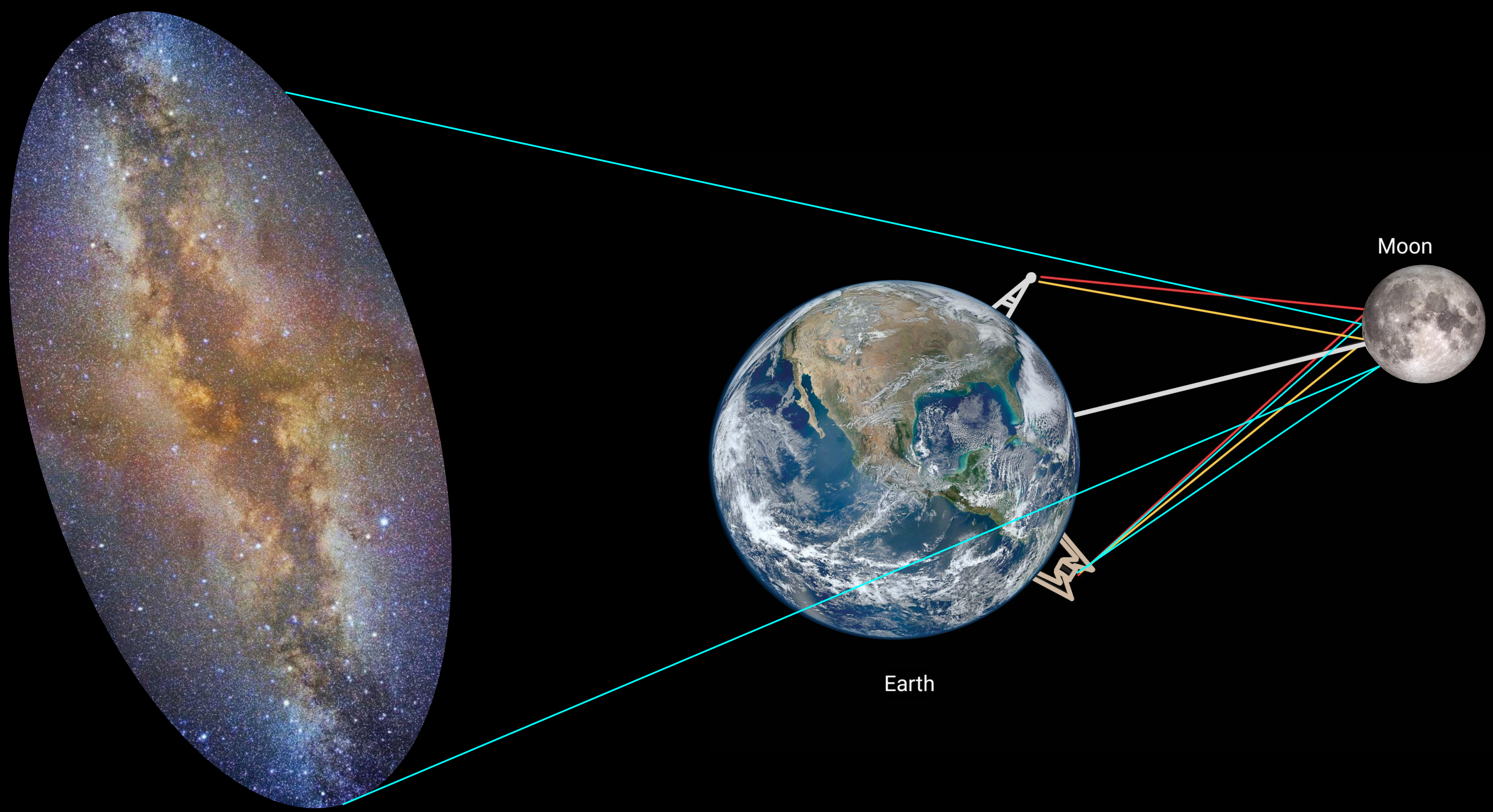


It doesn’t ends here!

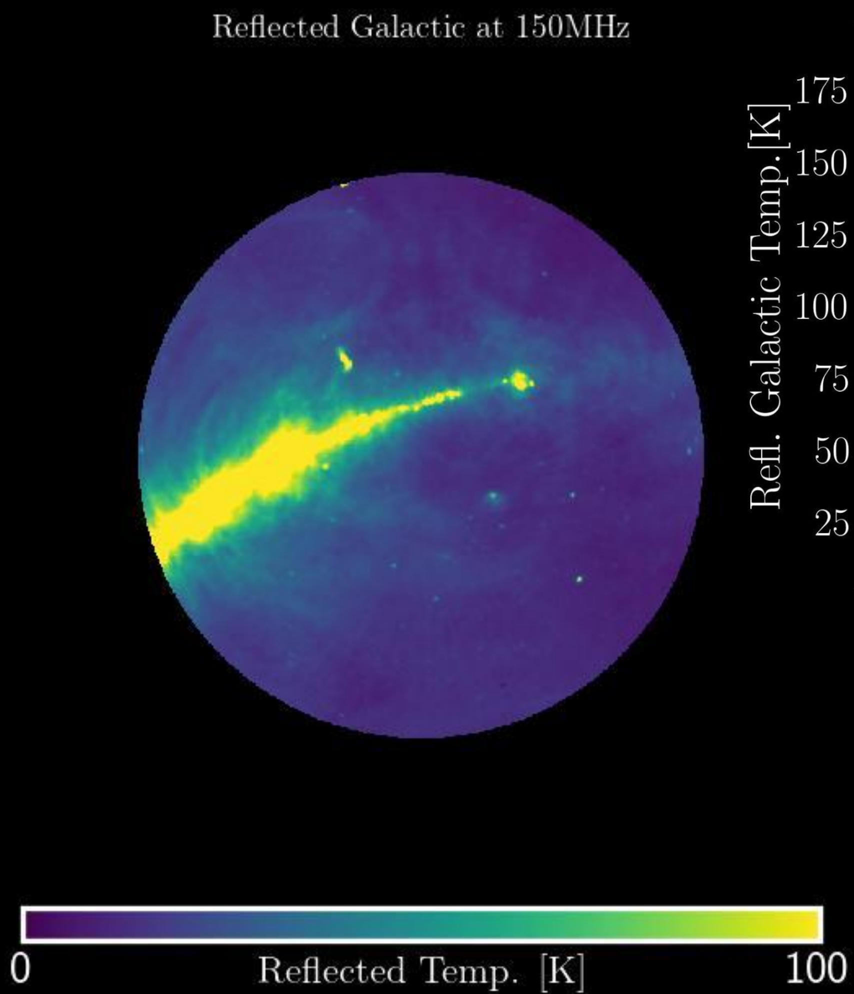
The Universe of Temperatures

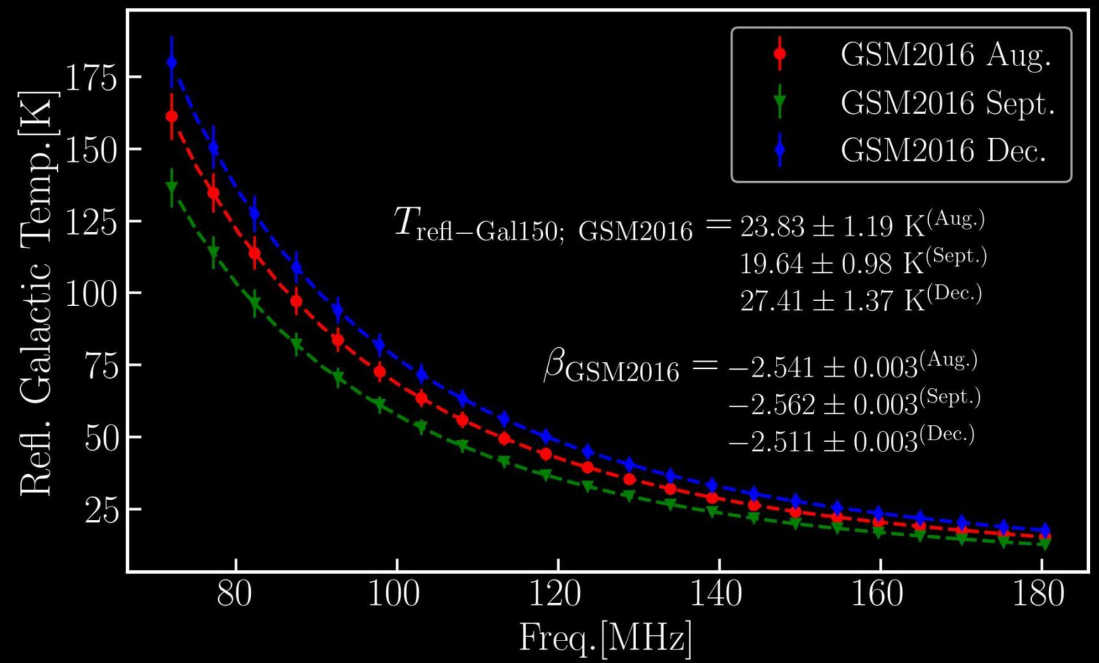


Next Step:



Reflected Galactic Emission $T_{\mathrm{refl-Gal}}(\nu)$

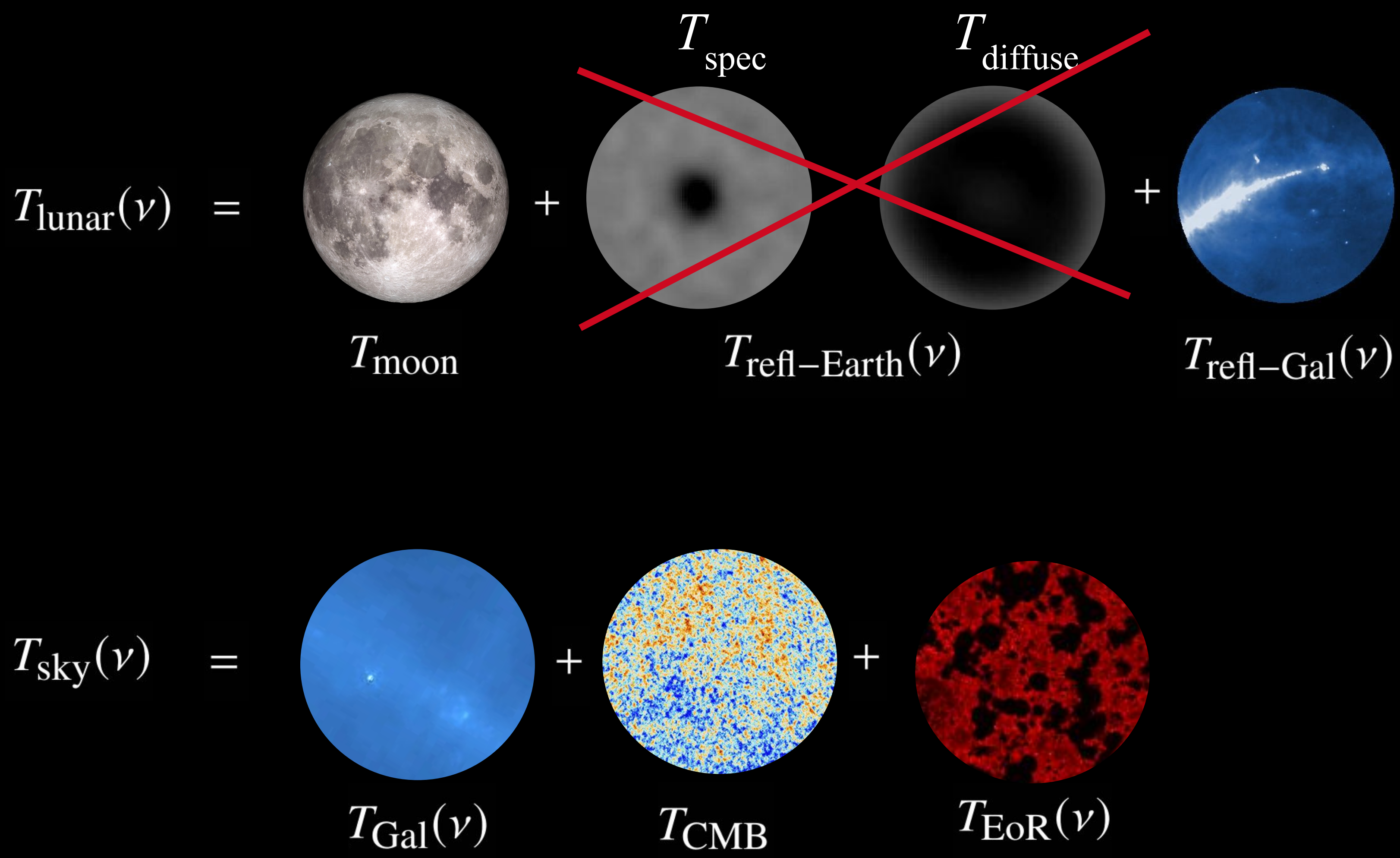




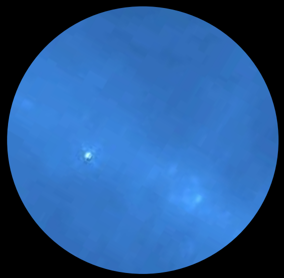
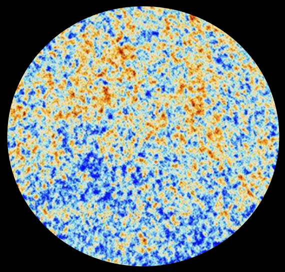
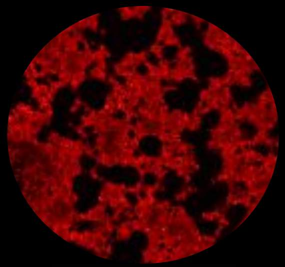
Reflected galactic emission from the Moon

$$T_{\mathrm{Gal}}(\nu) = T_{150}\left(\frac{\nu}{150\mathrm{MHz}}\right)^{\alpha}$$

What MWA sees?



Occulted Sky Temperatures

$T_{\rm sky}(\nu) =$  $+$  $+$ 

$T_{\rm Gal}(\nu)$ $\quad$ $T_{\rm CMB}$ $\quad$ $T_{\rm EoR}(\nu)$

$T_{\rm Gal}(\nu)$ - Temp. of the patch of sky occulted by the Moon

$T_{\rm CMB}$ - 2.735 K

What MWA sees?

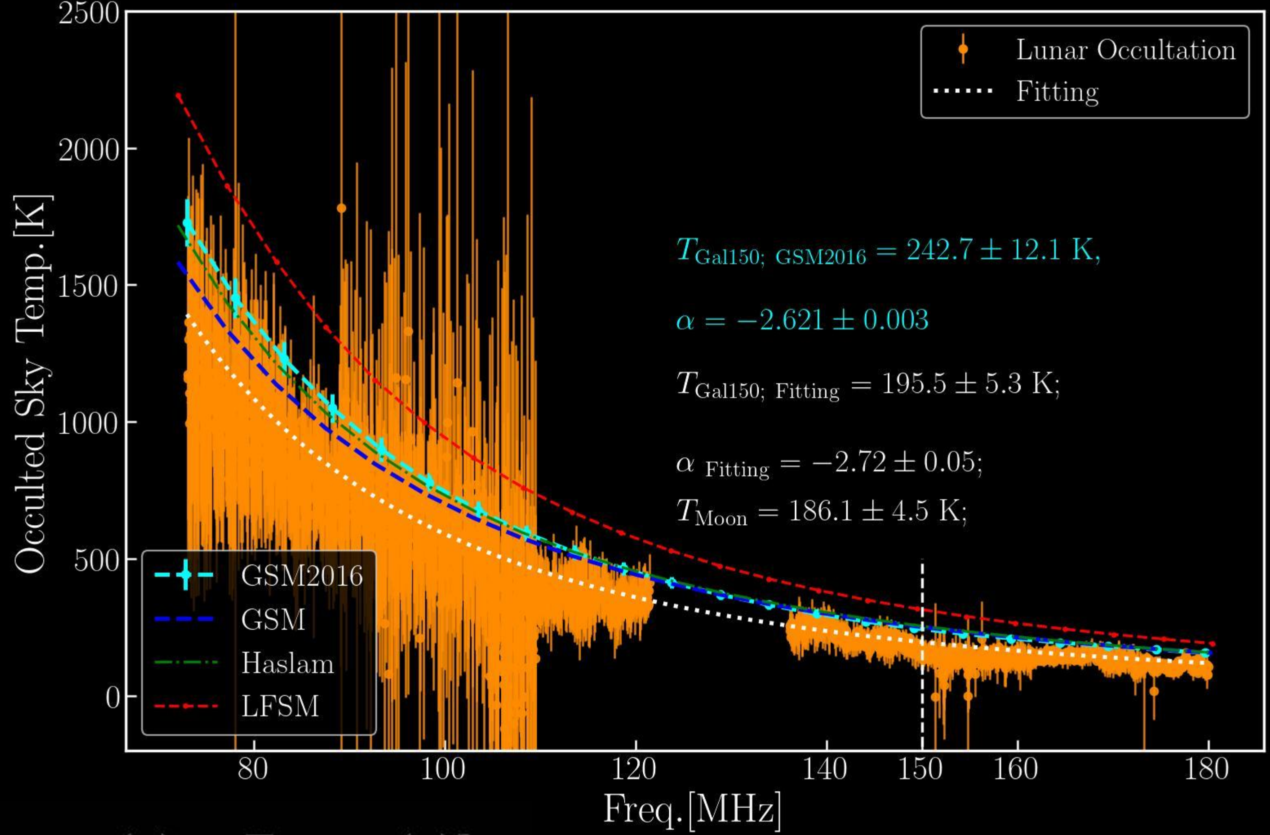
$$\Delta T(\nu) = T_{\rm lunar}(\nu) - T_{\rm sky}(\nu)$$
$$= [T_{\rm moon} + \cancel{T_{\rm refl-Earth}(\nu)} + T_{\rm refl-Gal}(\nu)]$$
$$- [T_{\rm Gal}(\nu) + T_{\rm CMB} + T_{\rm EoR}(\nu)]$$

where, $$\Delta T(\nu) = \frac{10^{-26} c^2 S_m(\nu)}{2k\Omega\nu^2}$$

$S_m(\nu)$: flux density of the Moon

Ω : Solid angle of the Moon

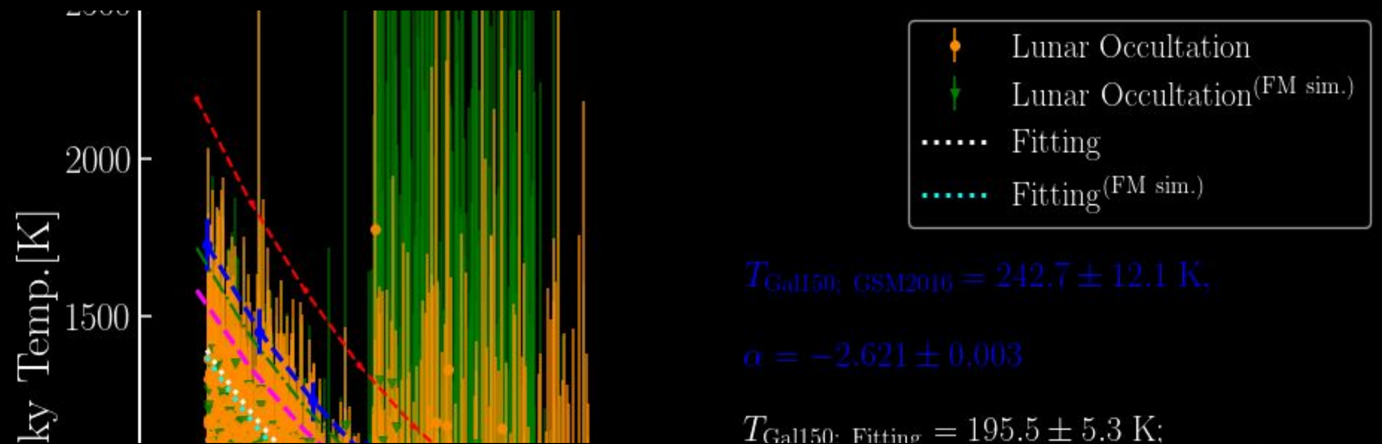
Fitting for Galactic Temp (method: 1)



$$T_{\mathrm{Gal}}(\nu) - T_{\mathrm{moon}} = [T_{\mathrm{refl-Earth}}(\nu) + T_{\mathrm{refl-Gal}}(\nu)] - [\Delta T(\nu) + T_{\mathrm{CMB}} + T_{\mathrm{EoR}}(\nu)]$$

$$T_{\mathrm{Gal}}(\nu) - T_{\mathrm{moon}} = T_{\mathrm{Gal150}} \left(\frac{\nu}{150\,\mathrm{MHz}}\right)^{\alpha} - T_{\mathrm{offset}}$$

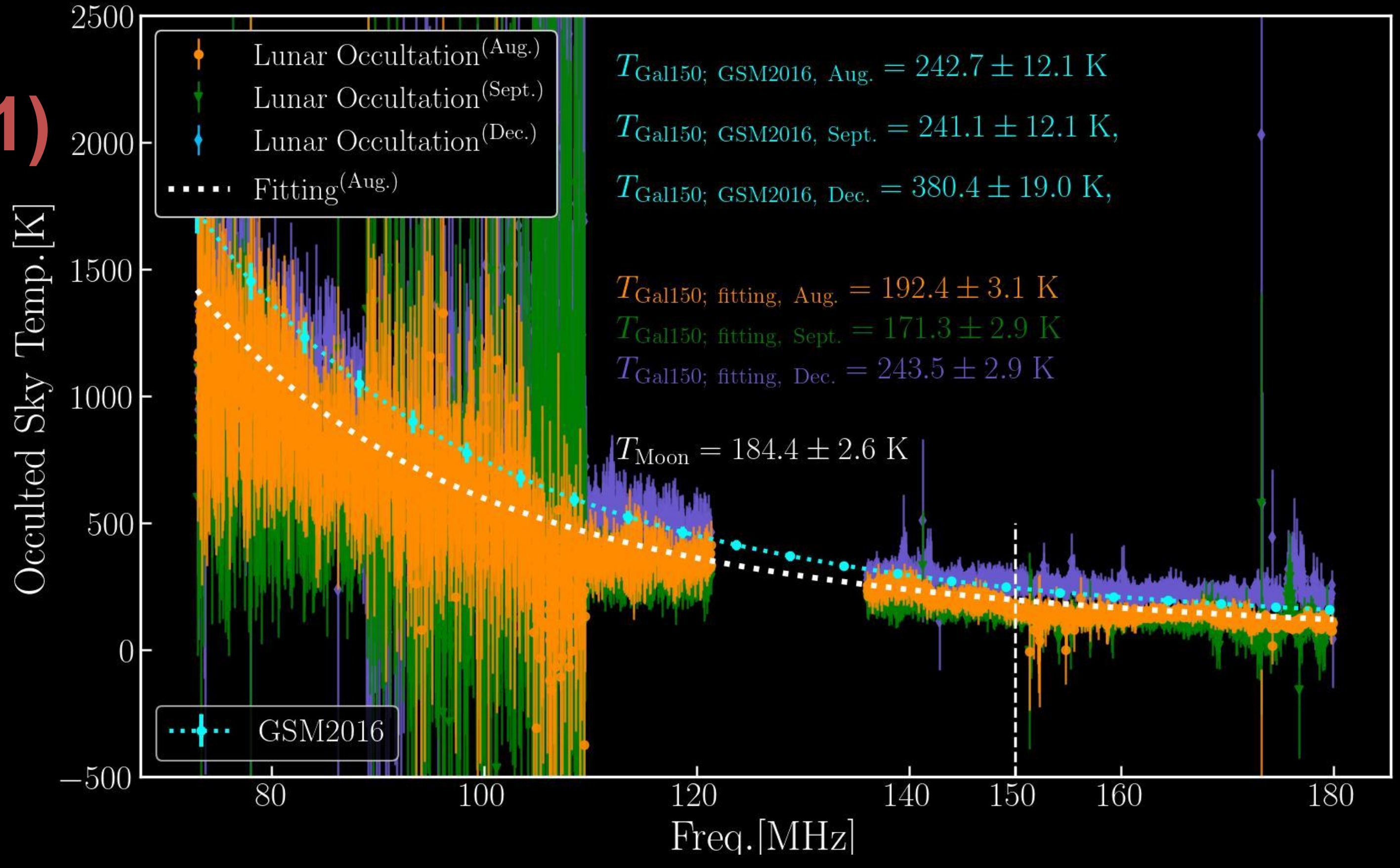
Fitting for Galactic Temp



Epoch	Sky − model	$T_{\{Gal150;\ model\}}$ (K)	α_{model}	Fitting	$T_{\{Gal150;\ fitting\}}$ (K)	$\alpha_{fitting}$	$T_{\{Moon\}}$ (K)
Aug.	GSM	250.4 ± 12.5	-2.540 ± 0.002	Method 1	199.2 ± 5.4	-2.70 ± 0.05	188.3 ± 4.6
				Method 2 $^{(FM\ sim.)}$	183.5 ± 5.1	-2.79 ± 0.05	174.2 ± 4.4
	GSM2016	242.7 ± 12.1	-2.621 ± 0.003	.	195.5 ± 5.3	-2.72 ± 0.05	186.1 ± 4.5
				..	179.2 ± 5.0	-2.82 ± 0.05	171.4 ± 4.3
	LFSM	313.9 ± 15.7	-2.689 ± 0.003	.	202.8 ± 5.3	-2.70 ± 0.05	188.5 ± 4.5
				..	189.0 ± 5.1	-2.78 ± 0.05	176.2 ± 4.4
	Haslam	253.7 ± 12.7	-2.603 ± 0.003	.	199.2 ± 5.3	-2.71 ± 0.05	187.9 ± 4.6
				..	183.7 ± 5.1	-2.80 ± 0.05	174.0 ± 4.3
Sept.	GSM	253.4 ± 12.7	-2.540 ± 0.002	.	177.6 ± 4.4	-2.54 ± 0.04	189.4 ± 4.2
				..	185.6 ± 5.1	-2.43 ± 0.05	198.5 ± 4.9
	GSM2016	241.0 ± 12.0	-2.585 ± 0.003	.	174.4 ± 4.3	-2.56 ± 0.04	187.4 ± 4.4
				..	182.2 ± 5.0	-2.47 ± 0.05	196.0 ± 4.8
	LFSM	295.3 ± 14.8	-2.689 ± 0.003	.	180.8 ± 4.4	-2.56 ± 0.04	189.2 ± 4.2
				..	188.6 ± 5.0	-2.46 ± 0.04	198.0 ± 4.8
	Haslam	250.7 ± 12.5	-2.603 ± 0.003	.	177.4 ± 4.4	-2.56 ± 0.04	188.9 ± 4.2

Jointly fitting for the Galactic Temp

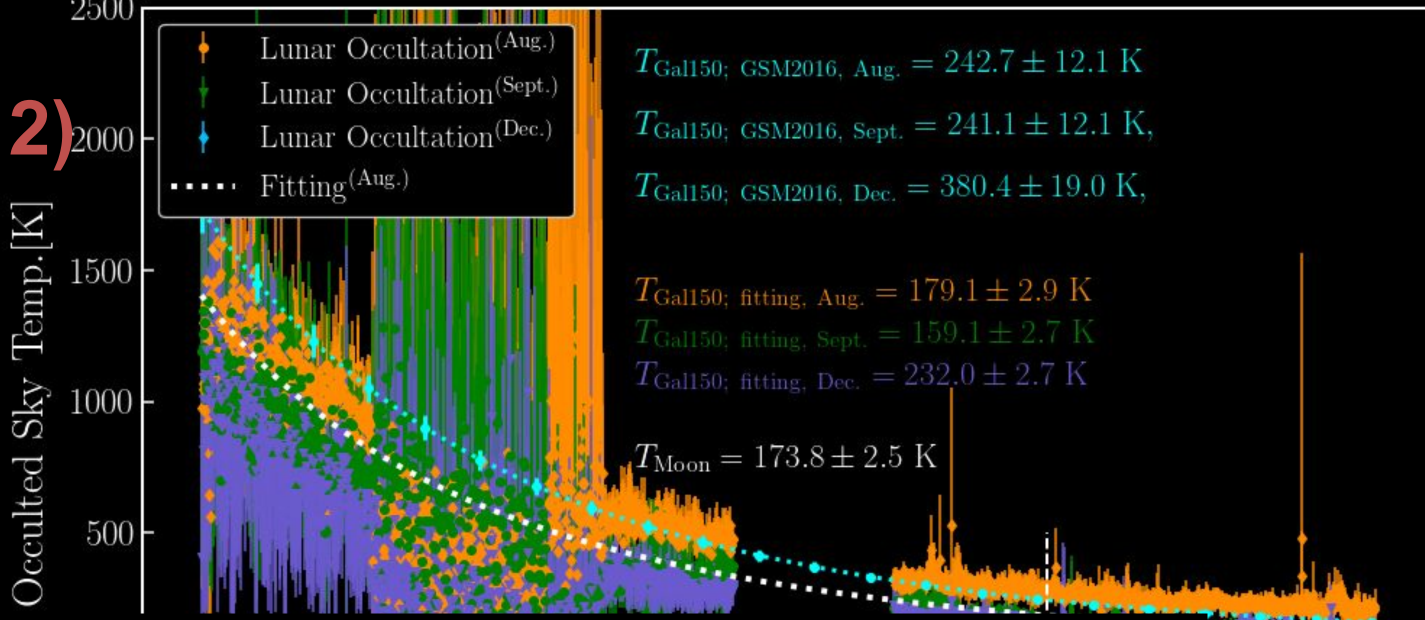
(method: 1)



assumption: T_Moon is constant through all the epochs

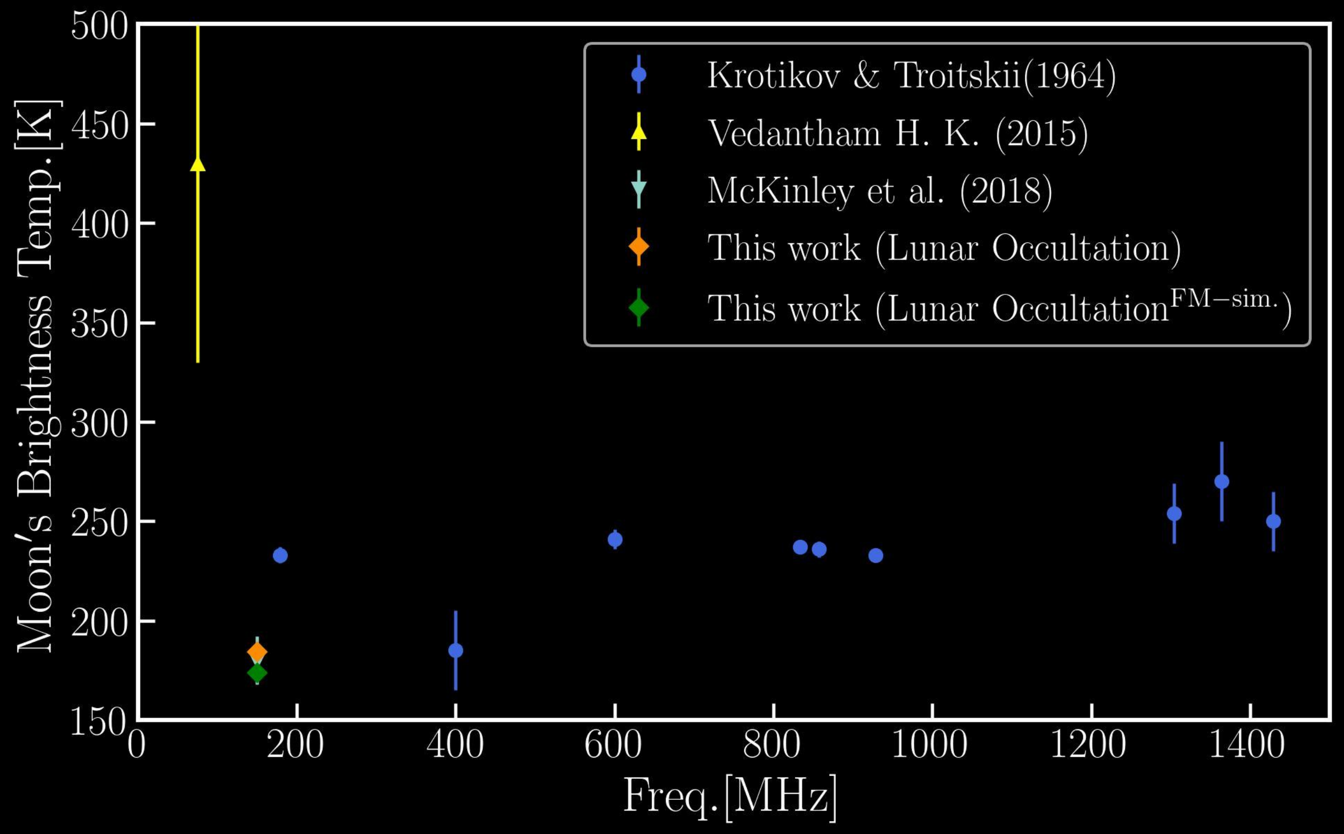
Fitting with Galactic Temp

(method: 2)



Epochs	$T_{\{Gal150;\ GSM2016\}}$ (K)	$\alpha_{GSM2016}$	$T_{\{Gal150;\ fitting\}}$ (K)	$\alpha_{fitting}$	$T_{\{Moon\}}$ (K)
Method 1					
Aug.	242.7 ± 12.1	−2.621 ± 0.003	192.4 ± 3.1	−2.745 ± 0.031	
Sept.	241.0 ± 12.0	−2.585 ± 0.002	171.3 ± 2.8	−2.598 ± 0.033	184.4 ± 2.6
Dec.	380.4 ± 19.0	−2.497 ± 0.002	243.5 ± 2.9	−2.612 ± 0.022	
Method 2 $^{(FM\ sim.)}$					
Aug.	242.7 ± 12.1	−2.621 ± 0.003	179.1 ± 2.9	−2.798 ± 0.033	
Sept.	241.0 ± 12.0	−2.585 ± 0.002	159.1 ± 2.7	−2.640 ± 0.034	173.8 ± 2.5
Dec.	380.4 ± 19.0	−2.497 ± 0.002	232.0 ± 2.7	−2.661 ± 0.021	

Previous Moon measurements



Moon temperature is consistent with the previous work from McKinley, B. (2018)

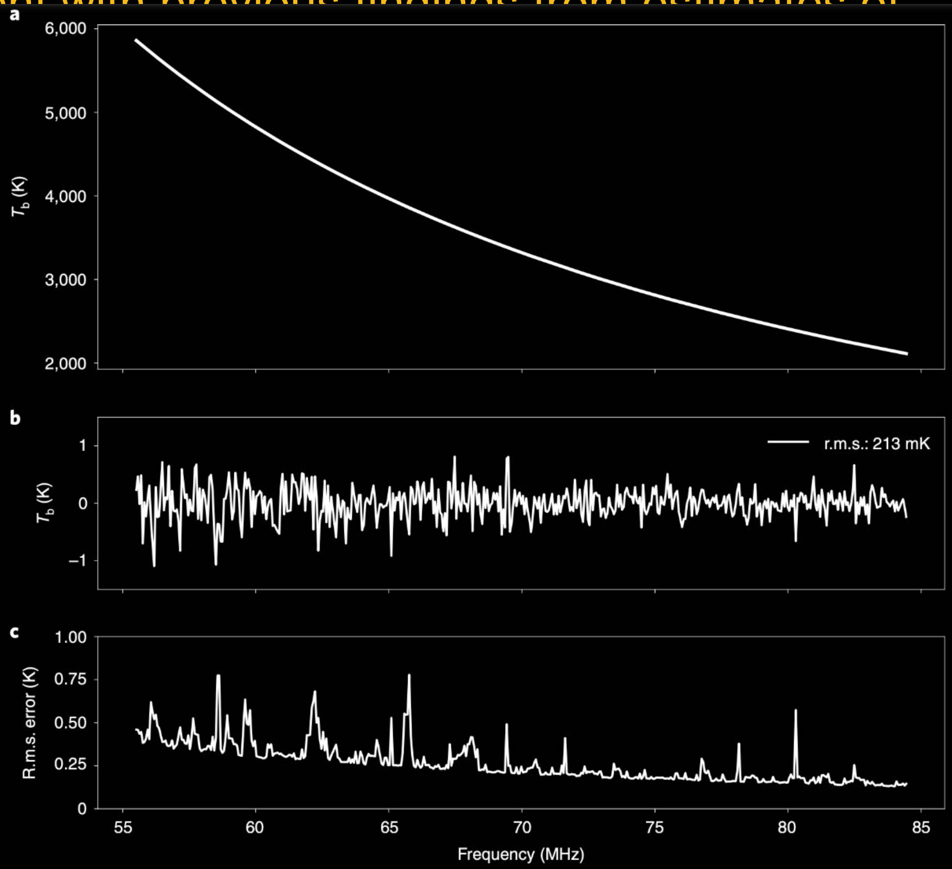
Summary

- We used 6 Nights of MWA-I observations to test Lunar Occultation.
- FM RFI mitigation technique
    - using RADAR studies of Moon’s reflections Evans (1969).
    - with simple FM flux-density estimator.
- Moon’s temperature is consistent with previous findings from estimates of McKinley (2018).
- The jointly fitted occulted bac due to data and partly due to

EARTHSHINE mitigation is really

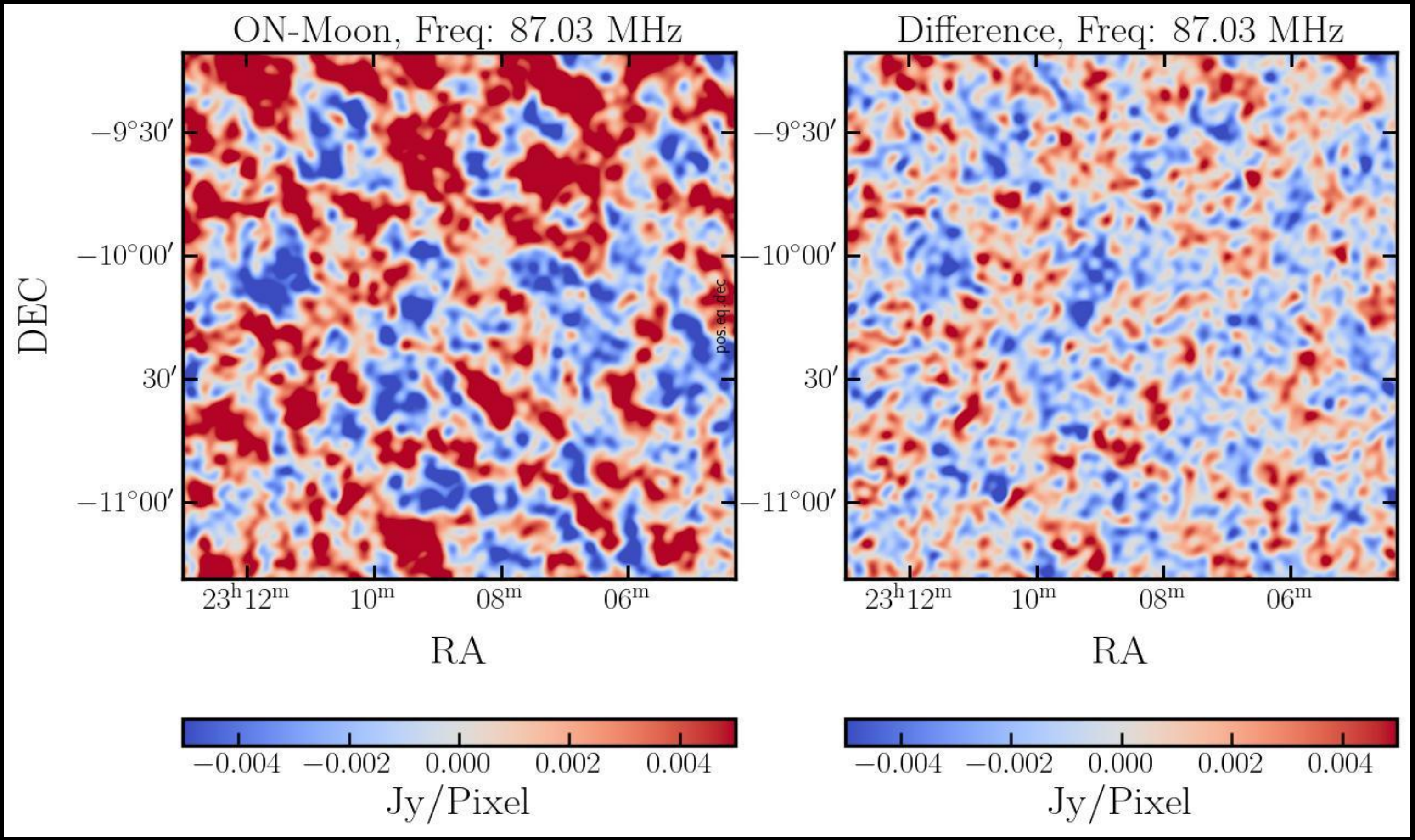
Future hopes?

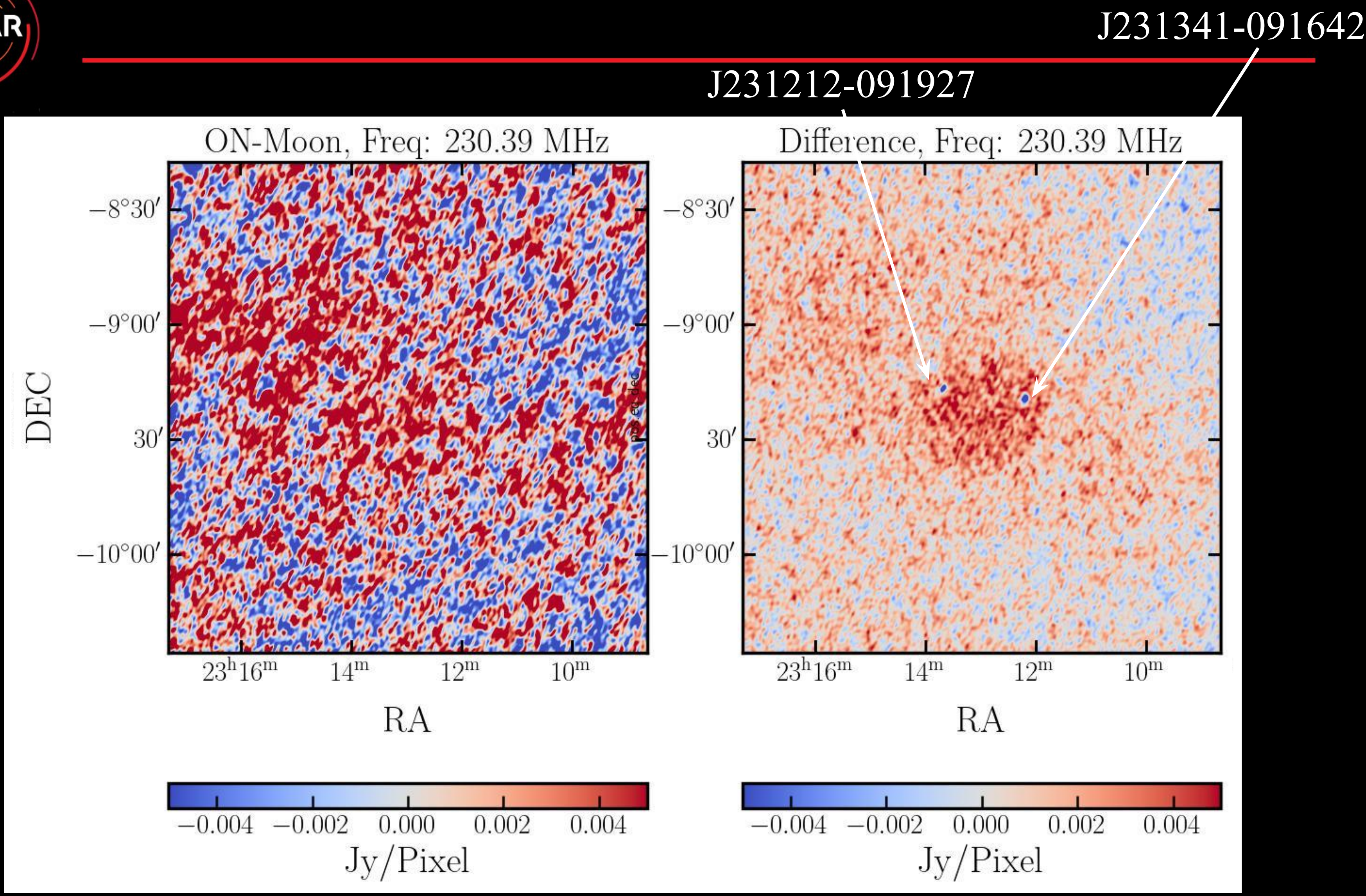
- Independent constraints on T such as EDA2.
- Hope to reach a RMS level as
- Check for the systematics intr
- Check if Occulted Sky Tempe similar tests as Global Experi

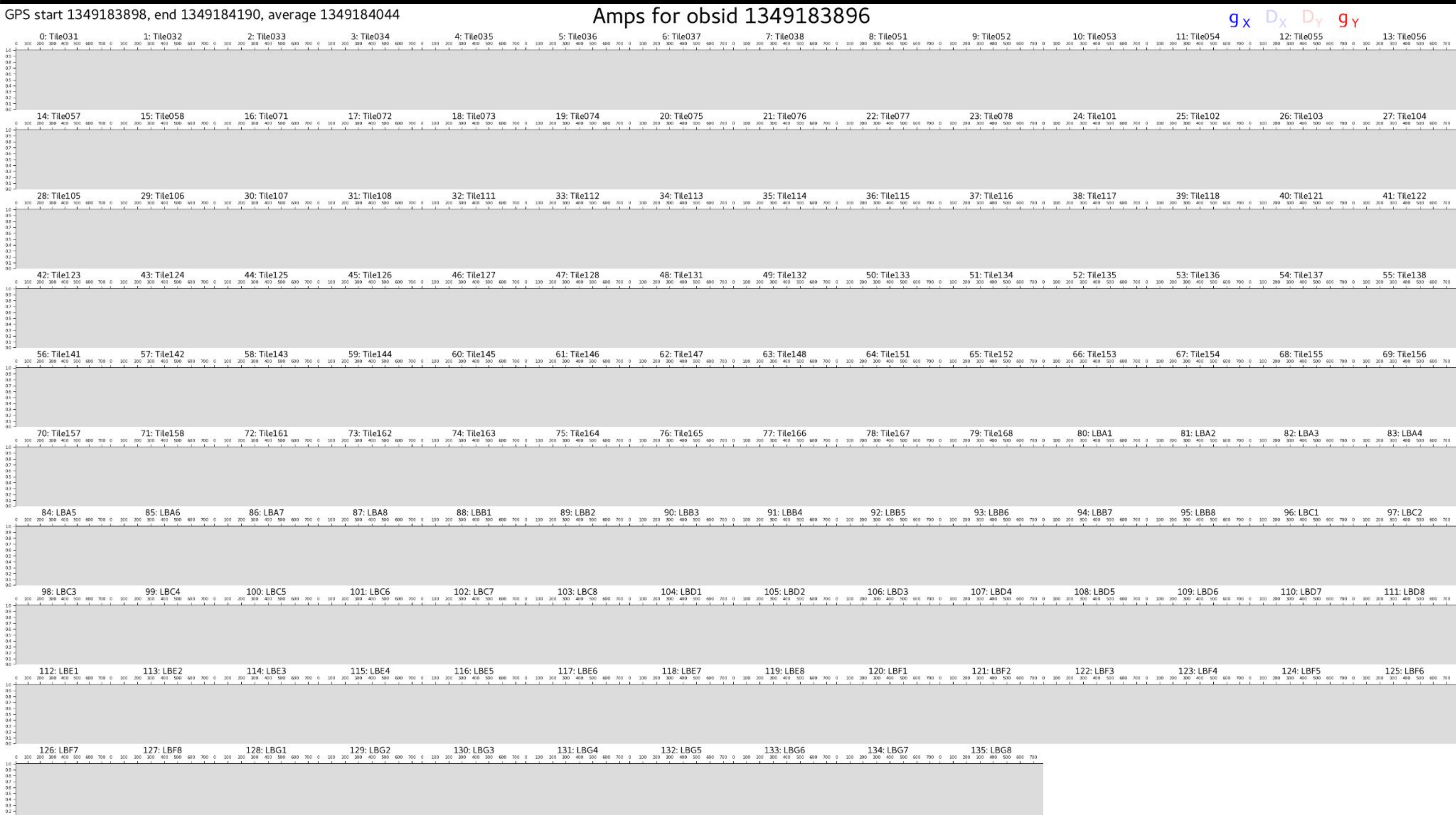


My feelings at present :(

Some MWA-phase II (extended) images




J231341-091642
J231212-091927
ON-Moon, Freq: 230.39 MHz
Difference, Freq: 230.39 MHz
DEC
−8°30′
−9°00′
30′
−10°00′
23h16m
14m
12m
10m
RA
−0.004
−0.002
0.000
0.002
0.004
Jy/Pixel


GPS start 1349183898, end 1349184190, average 1349184044
Amps for obsid 1349183896
gX DX DY gY
0: Tile031
1: Tile032
2: Tile033
3: Tile034
4: Tile035
5: Tile036
6: Tile037
7: Tile038
8: Tile051
9: Tile052
10: Tile053
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14: Tile057
15: Tile058
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19: Tile074
20: Tile075
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22: Tile077
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77: Tile166
78: Tile167
79: Tile168
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81: LBA2
82: LBA3
83: LBA4
84: LBA5
85: LBA6
86: LBA7
87: LBA8
88: LBB1
89: LBB2
90: LBB3
91: LBB4
92: LBB5
93: LBB6
94: LBB7
95: LBB8
96: LBC1
97: LBC2
98: LBC3
99: LBC4
100: LBC5
101: LBC6
102: LBC7
103: LBC8
104: LBD1
105: LBD2
106: LBD3
107: LBD4
108: LBD5
109: LBD6
110: LBD7
111: LBD8
112: LBE1
113: LBE2
114: LBE3
115: LBE4
116: LBE5
117: LBE6
118: LBE7
119: LBE8
120: LBF1
121: LBF2
122: LBF3
123: LBF4
124: LBF5
125: LBF6
126: LBF7
127: LBF8
128: LBG1
129: LBG2
130: LBG3
131: LBG4
132: LBG5
133: LBG6
134: LBG7
135: LBG8

Maybe the future