The LOfar COsmic-dawn Search (LOCOS)
Chasing the lunar shadow

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Overview

Science case – cosmic dawn

Observational challenge – what is stopping us currently ?

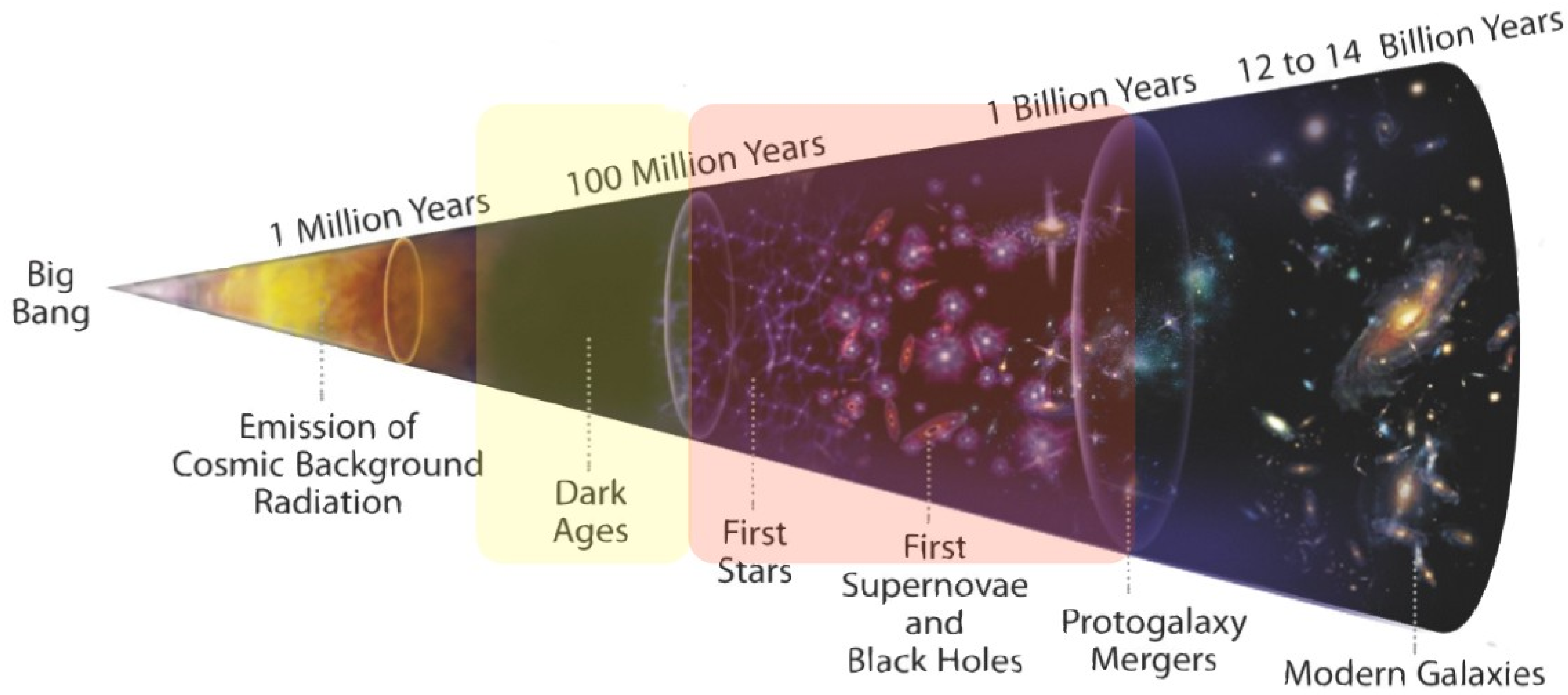
A novel observational technique – lunar occultation

A novel telescope - LOFAR

Pilot results – very encouraging

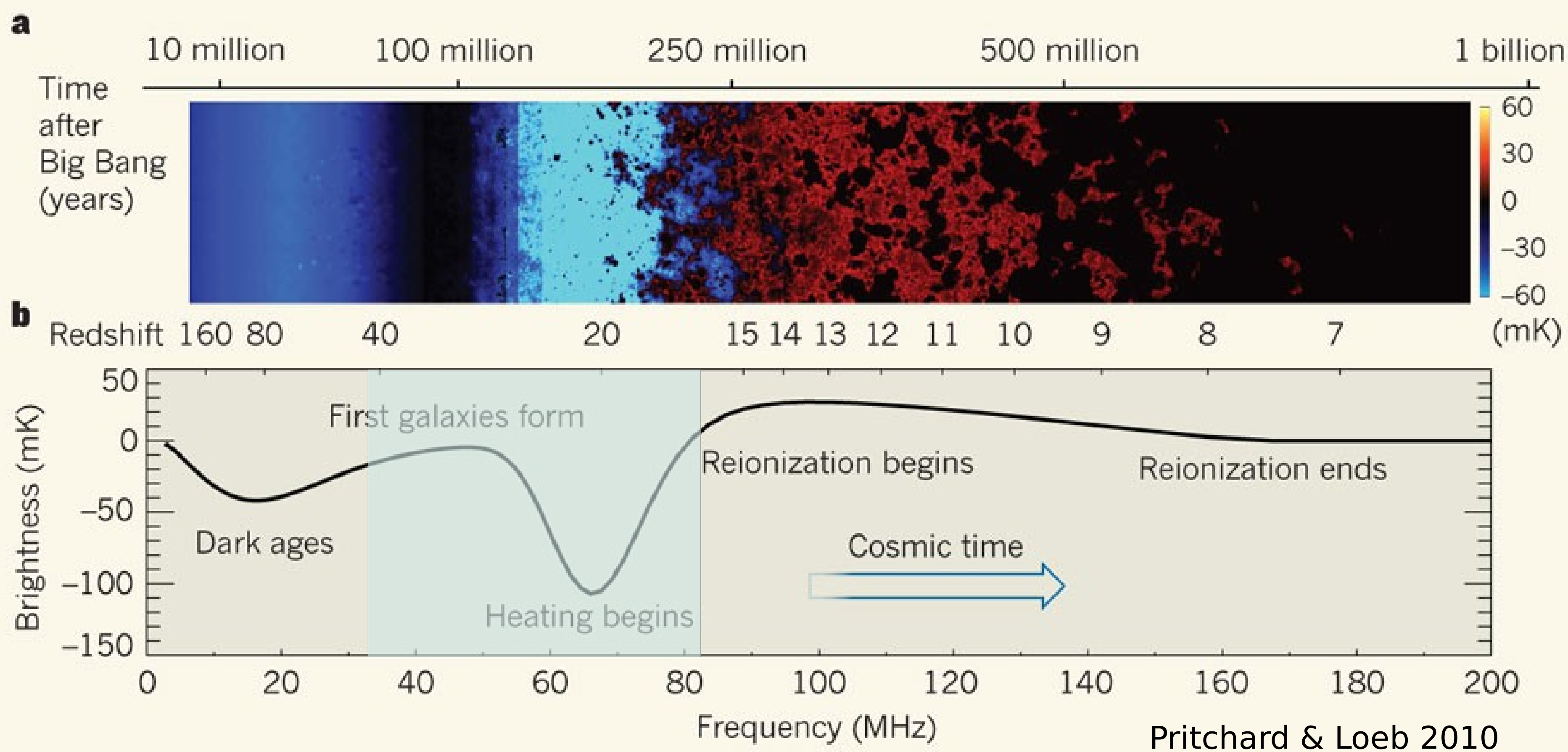
Challenges and prospects

The cosmic dawn



21-cm line of neutral hydrogen can probe the nature of the first stars and black-holes

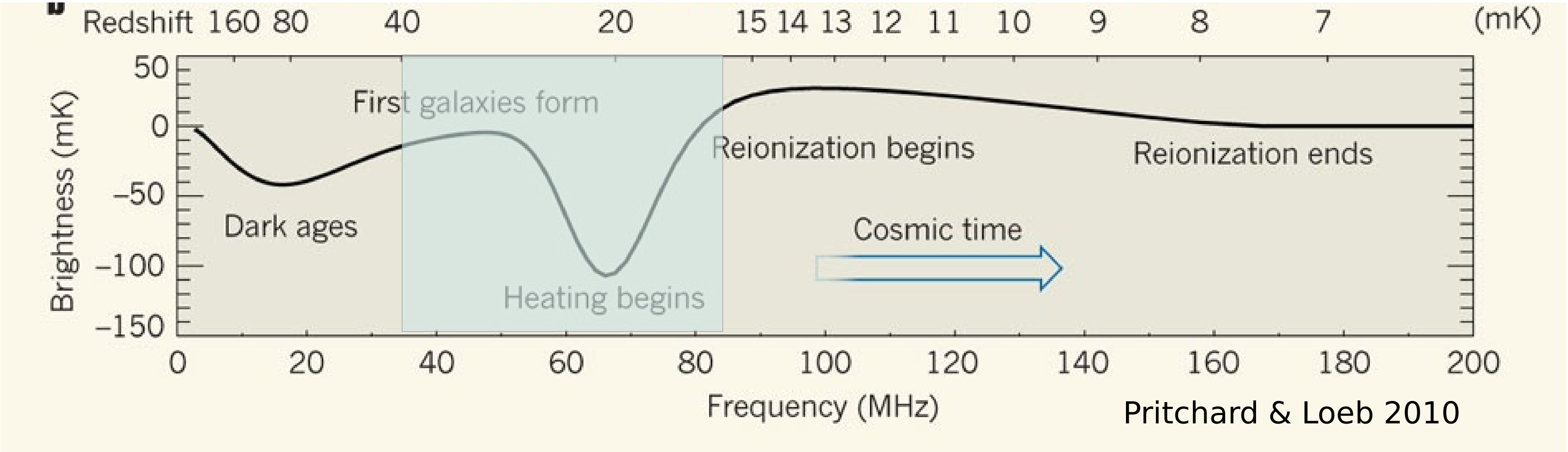
The 21-cm global signal



Pritchard & Loeb 2010

Position depth and width of the absorption feature is a tracer of Lyα and X-ray flux from the first stars

Its not a sensitivity issue



T_{sky} = 3000 K @ 60 MHz

ΔT_{rms} = 35 mK in 1 MHz channel after 1 hour integration
(with a single dipole !)

Its a calibration issue. Required dynamic range is 10^5

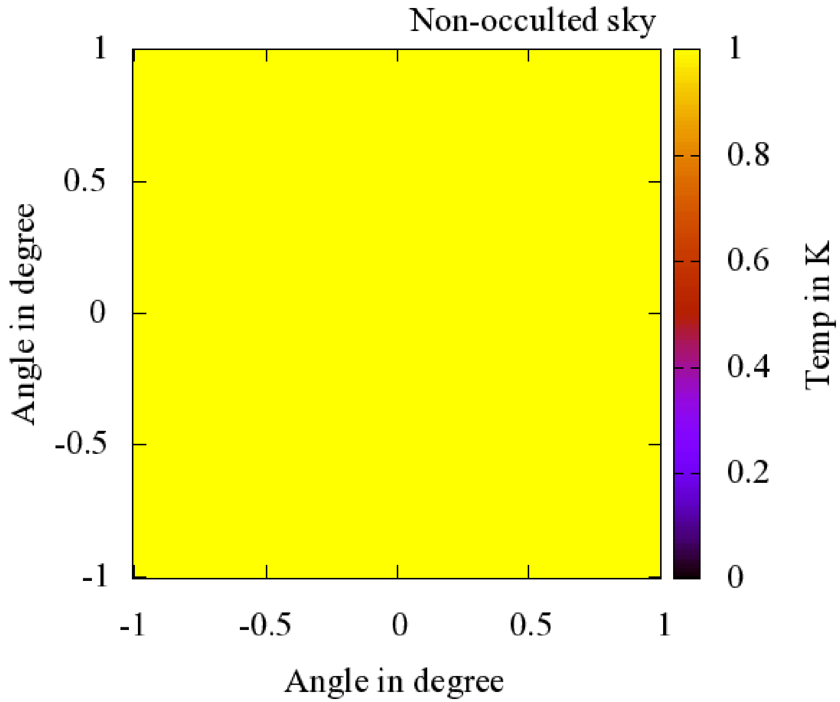
The two approaches

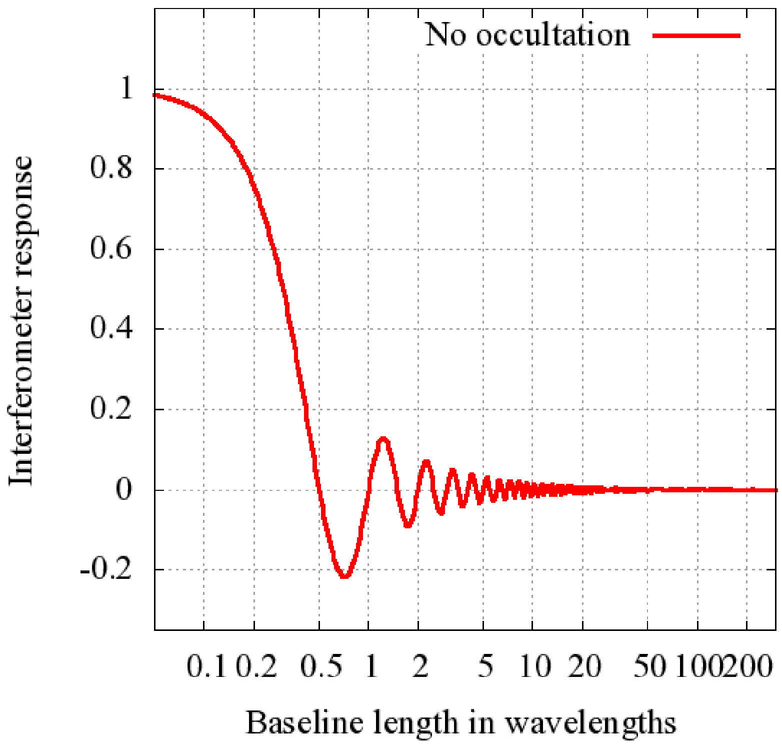
Shaver et al 1999

Single dipole total power	**Interferometric with occultation**
Simple experiment	Complex experiment
Calibration is very difficult	Easier to calibrate (compact astrophysical sources)
Difficult to identify and mitigate systematics (chromatic)	Many checks and balances to identify & mitigate systematics
Examples: LOCOS, EDGES, CoRE, SARAS, BIGHORNS, DARE, SCI-HI	Examples: (i) LOCOS (ii) McKinley et al 2012 ?

The interferometric route has not been explored in good detail
Need a proof of concept project

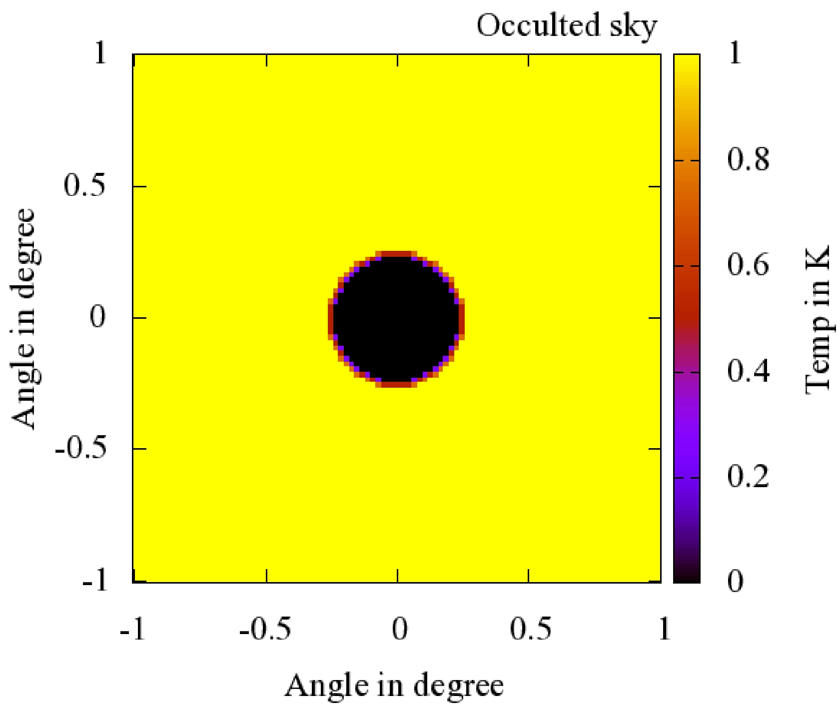
Global signal as seen by an interferometer

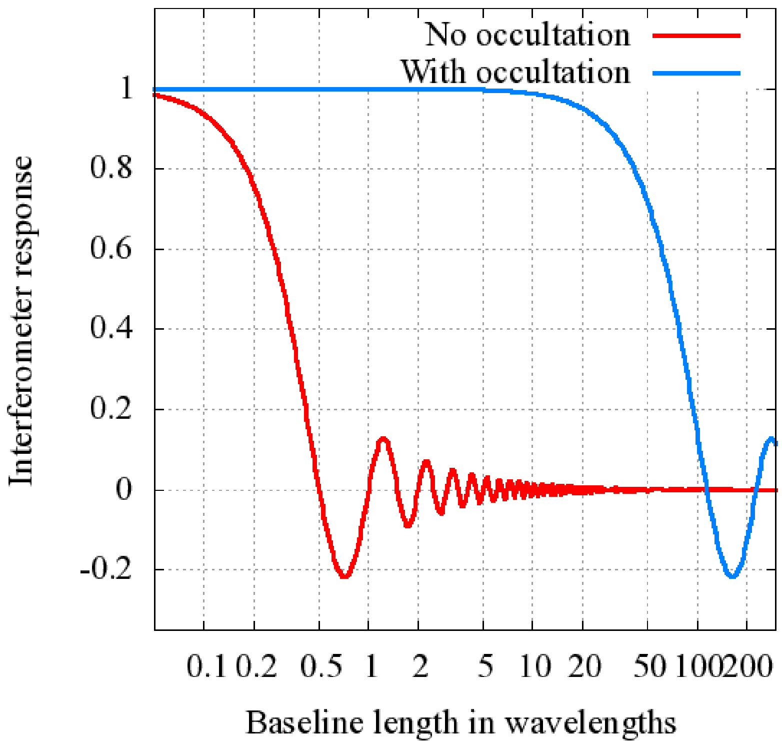




Hence the adage: A radio interferometer cannot measure a global signal

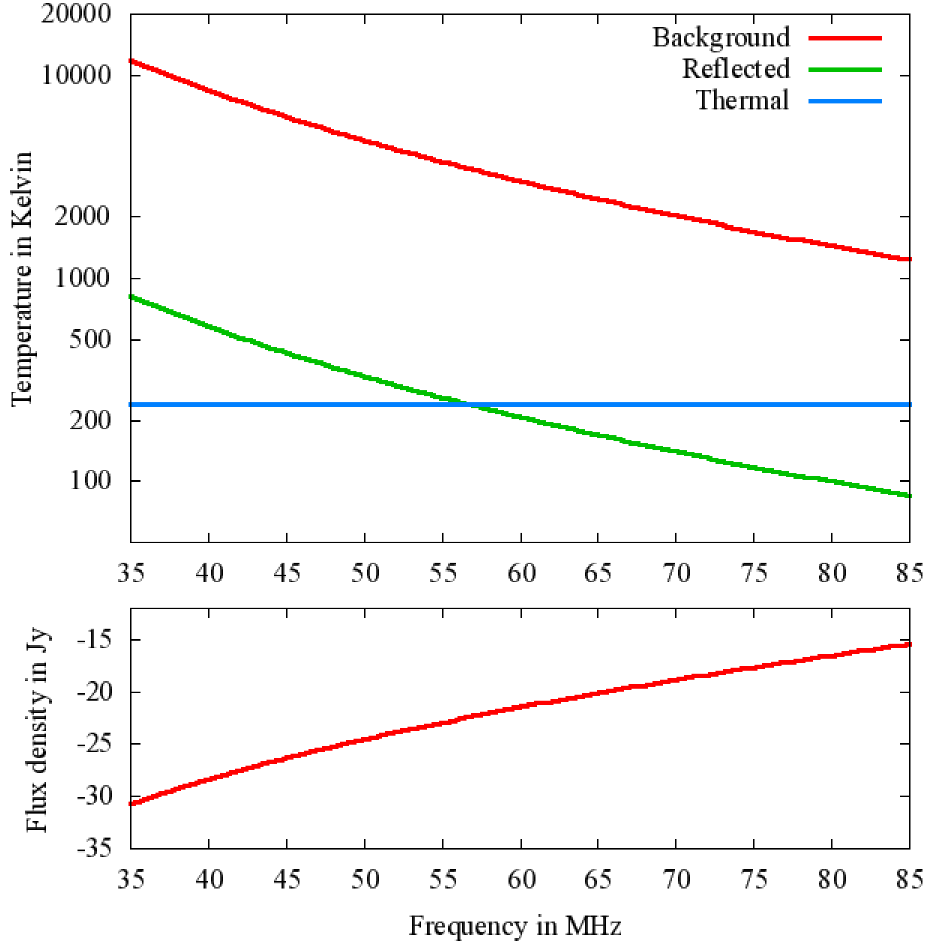
Occultation as seen by an interferometer





But .... interferometers measure the brightness difference between the occulting object T_M and the background T_B

Expected values of T_B and T_M

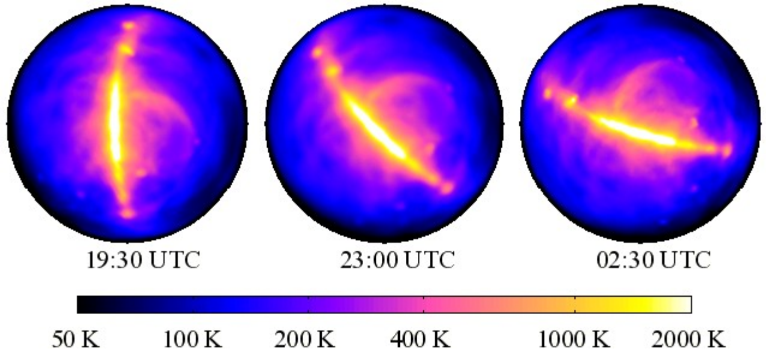


T_B = (Extra) Galactic (3000 K @ 60 MHz)

+ 21-cm signal (10s of mK)

T_M = Intrinsic 240 K blackbody (Heiles & Drake 1963)

+ Reflected Galactic (~200 K @ 60 MHz)

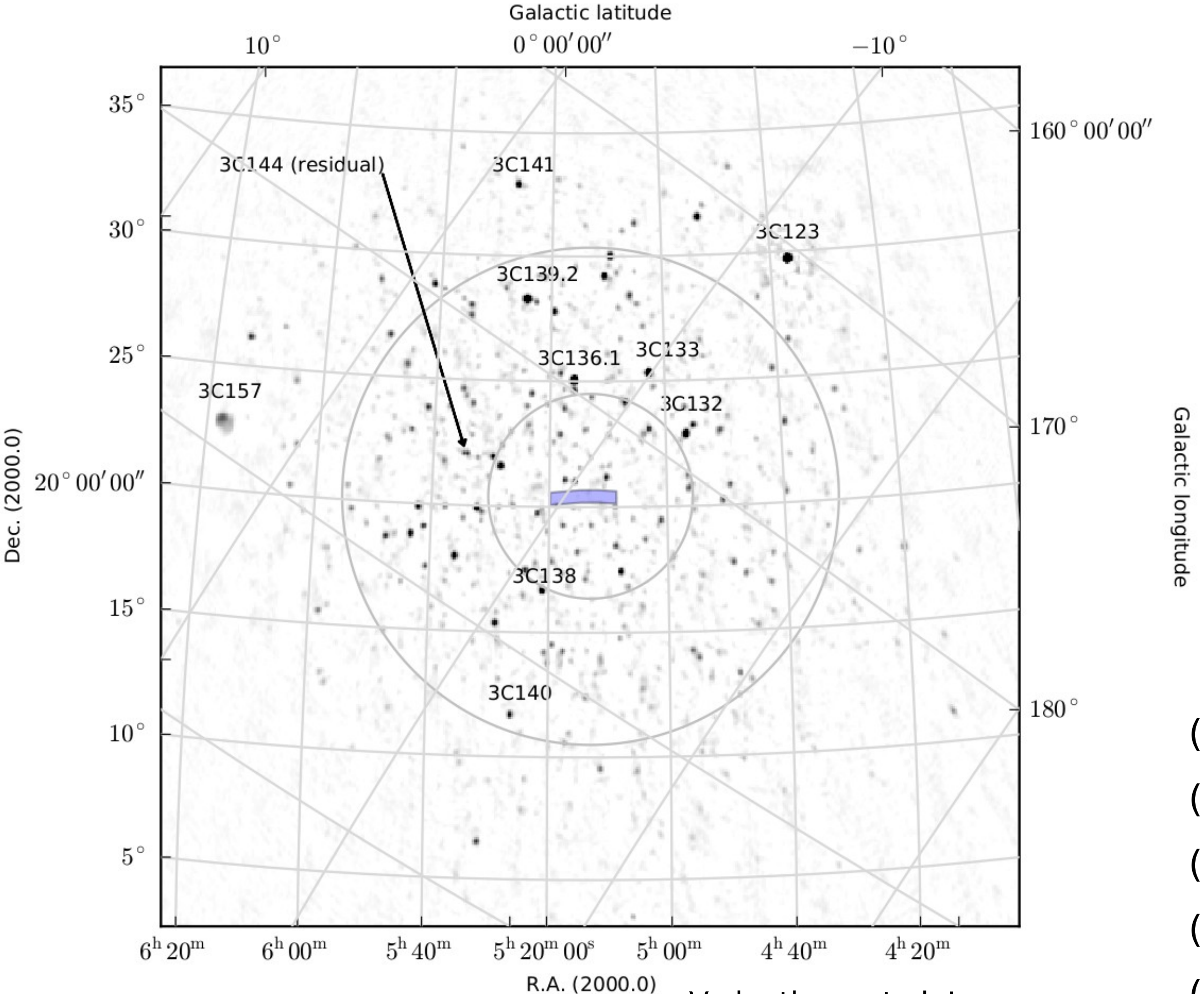


+ Reflected solar (~ 1 K @ 60 MHz)

+ Reflected RFI ? (limiting factor in McKinley et al 2013 ?)

The moon should appear as a negative flux source (-25 Jy) at 60 MHz

LOFAR commissioning data



Vedantham et al. In prep

OBSERVATIONS

Freq range	: 35 to 85 MHz
Date	: 2012-12-26
Exposure	: 7 hours
Beams	: 2 (simultaneous)
Beam1	: Lunar transit point
Beam 2	: 3C123 (cal)
# stations	: 24 core (~ 3 km) + 9 remote (~ 50 km)

PRIMARY PROCESSING

(1) Bandpass calibration (3C123)

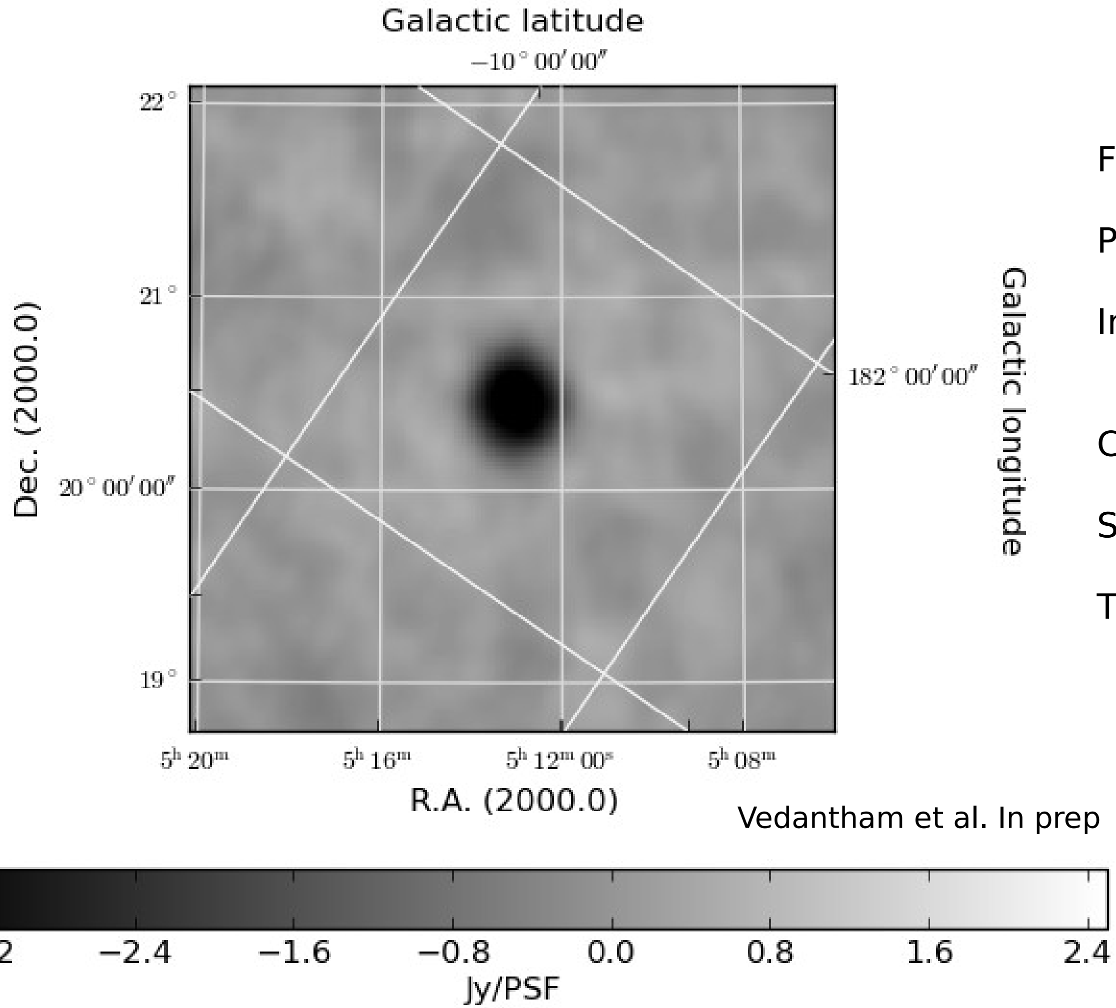
(2) Bright source subtraction (CasA, Crab)

(3) Imaging + faint source extraction

(4) Faint source subtraction (SAGECAL)

(5) Lunar fringe stopping + imaging

A hole in the sky !



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Freq range = 35 to 50 MHz (continuum)

PSF = 10 arcmin

Image plane noise = 140 mJy/beam

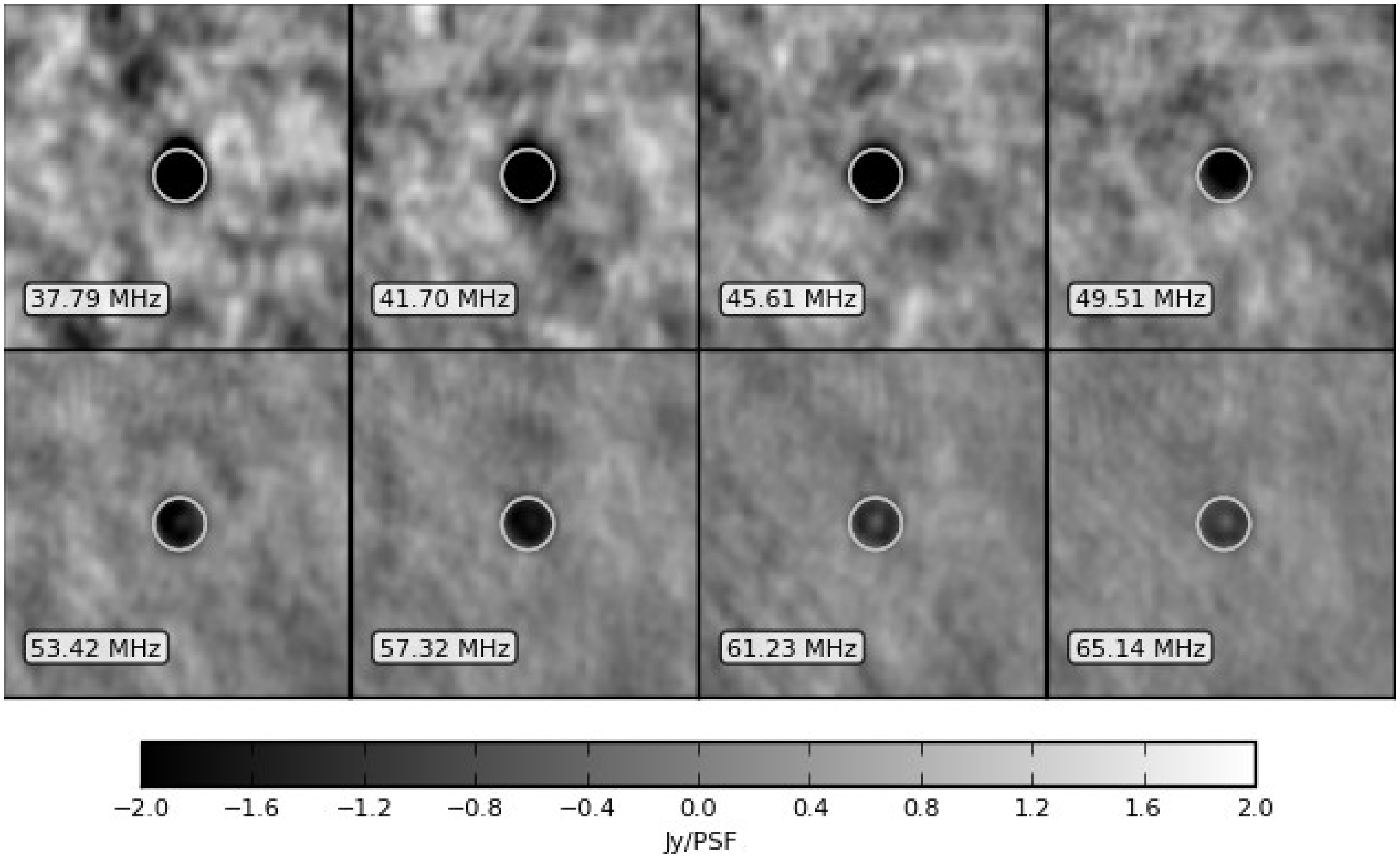
Confusion limit = 25 mJy

Sidelobe confusion = 100 mJy

Thermal noise = 10 mJy

We have made the first detection of diffuse galactic emission by observing its occultation by the moon.

A hole in the sky



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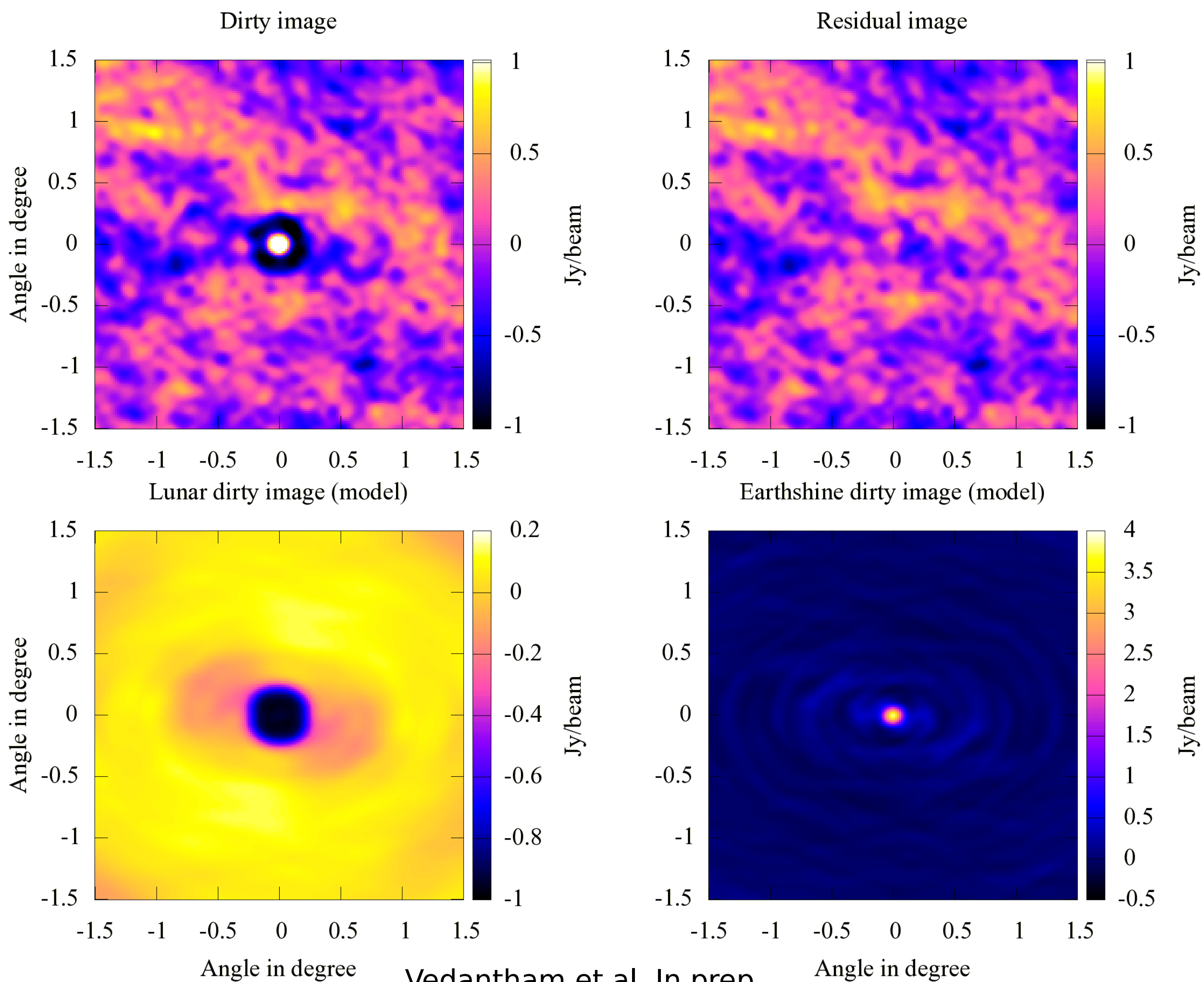
Reflected RFI (Earthshine) images to the center of the lunar disc, due to specular nature of reflection

Removing Earthshine



Vedantham et al. In prep

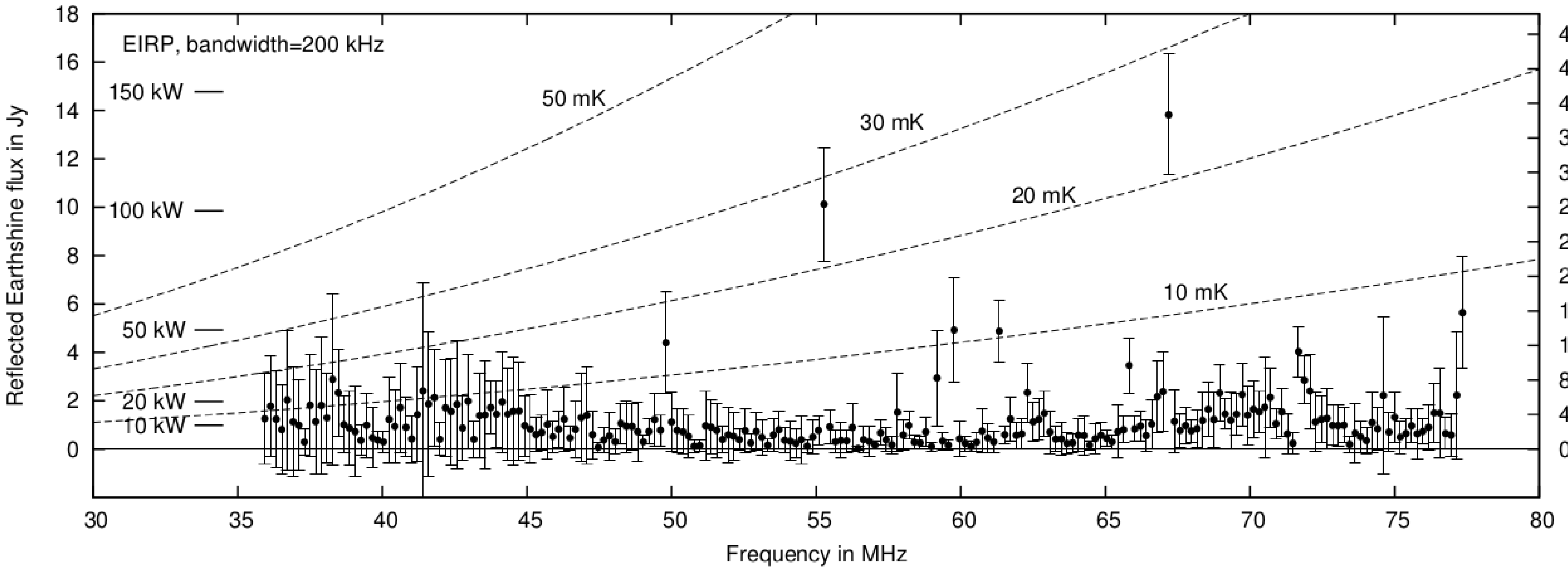
Moon flux   RFI flux

$$\mathbf{d} = (\theta_1 \mathbf{m} + \theta_2) * \mathbf{p}$$

Dirty image   Unit disc   PSF

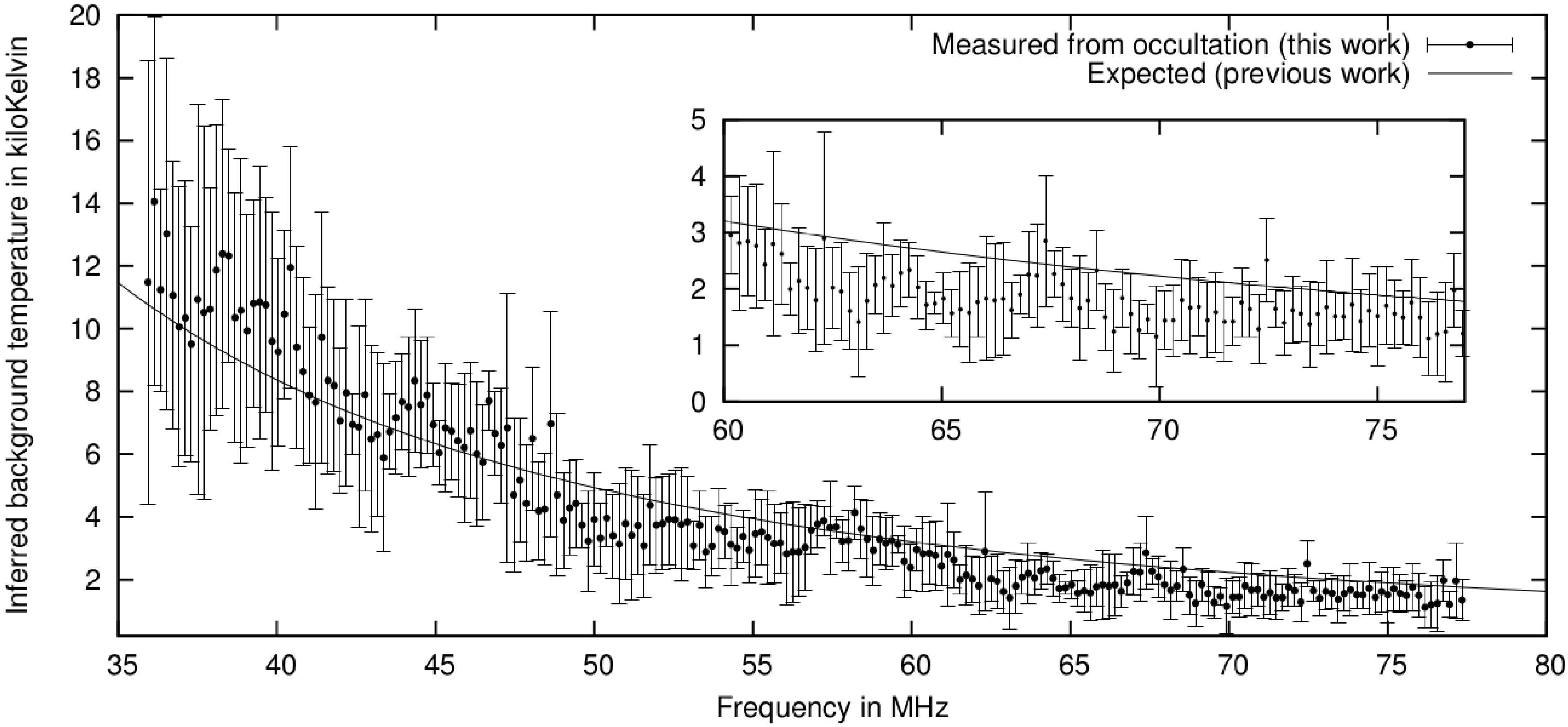
Reflected earthshine can me mitigated using information in longer baselines (not a show stopper for now)

Spectrum of Earthshine (preliminary)



Moon based dark-ages experiment will require > 60 dB of isolation from Earthshine

Spectrum of occulted Galactic emission



Sidelobe confusion at ~ 10% level is currently the dominant systematic --- need for (i) better field, (ii) inter-night differencing

Conclusions and outlook

Interferometers can measure an (occulted) global signal

- Alternative observational route for 21-cm experiments?

First detection of diffuse emission via lunar occultation

- No surprises (to first order) in lunar brightness temperature
- The moon is a good noise reference

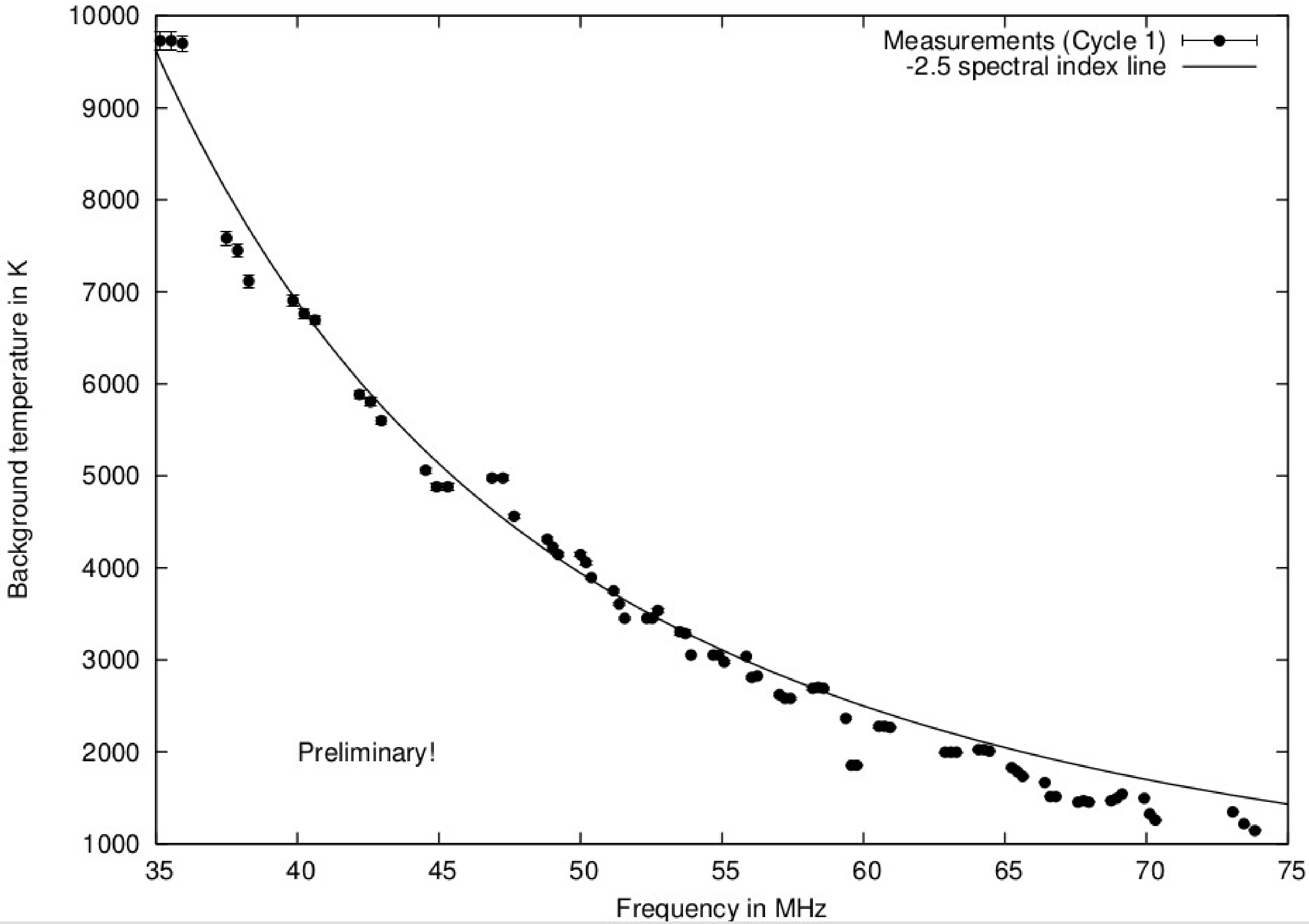
Earthshine can me modeled and removed using long baselines

- Moon based experiments will need > 60 dB isolation from Earthshsine

10% systematic ripple in background spectrum due to 3C144 and the Galactic plane

- Inter-day differencing ? (Now processing data from LOFAR cycle 1)

Cycle1 inter-night differencing: First look



Should be able to place constraints on diffuse Galactic spectra and lunar regolith soon !!!

Questions ?