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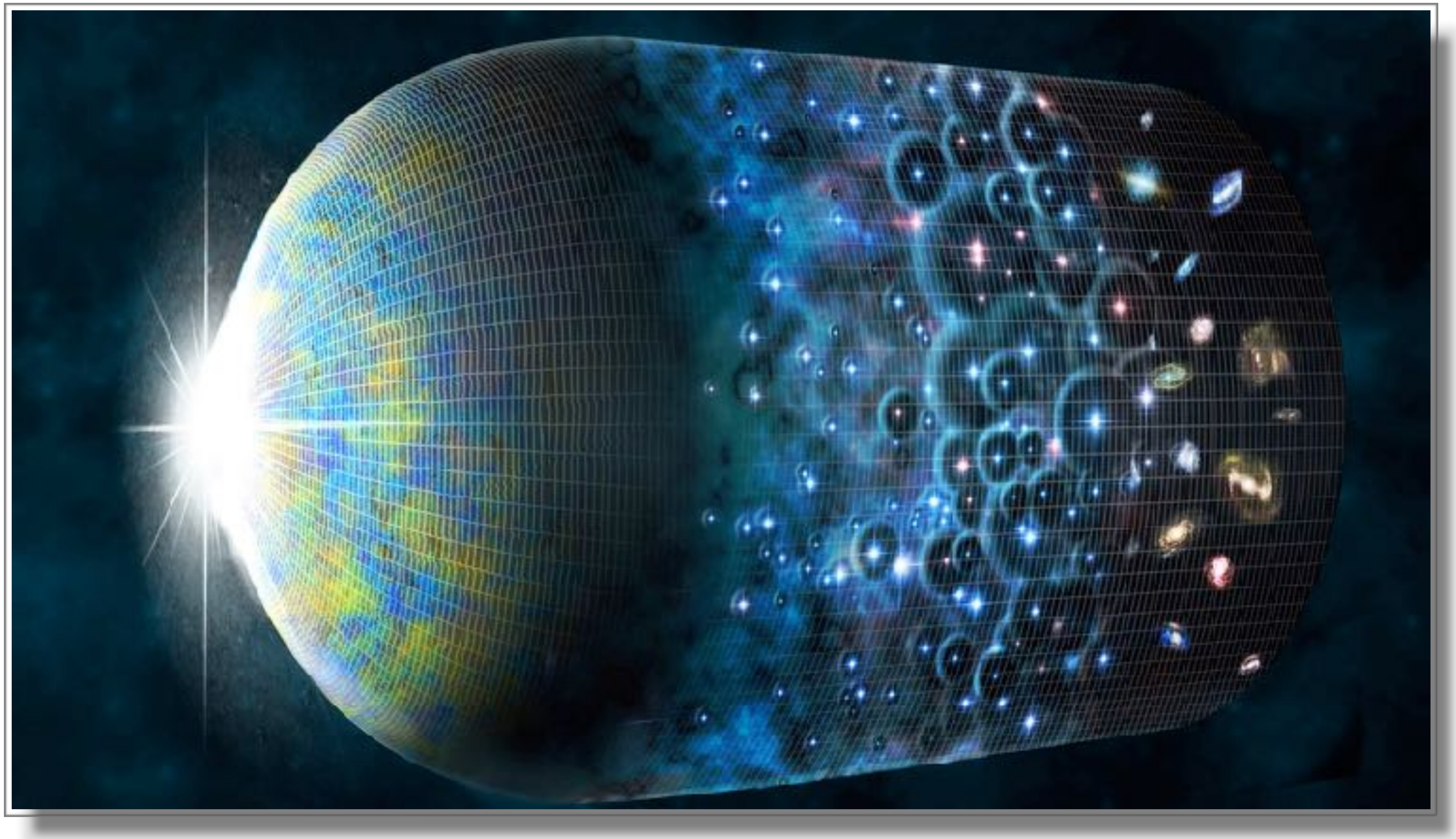
Dark Ages

From the ~~Cosmic Dawn~~ to the Epoch of Reionization

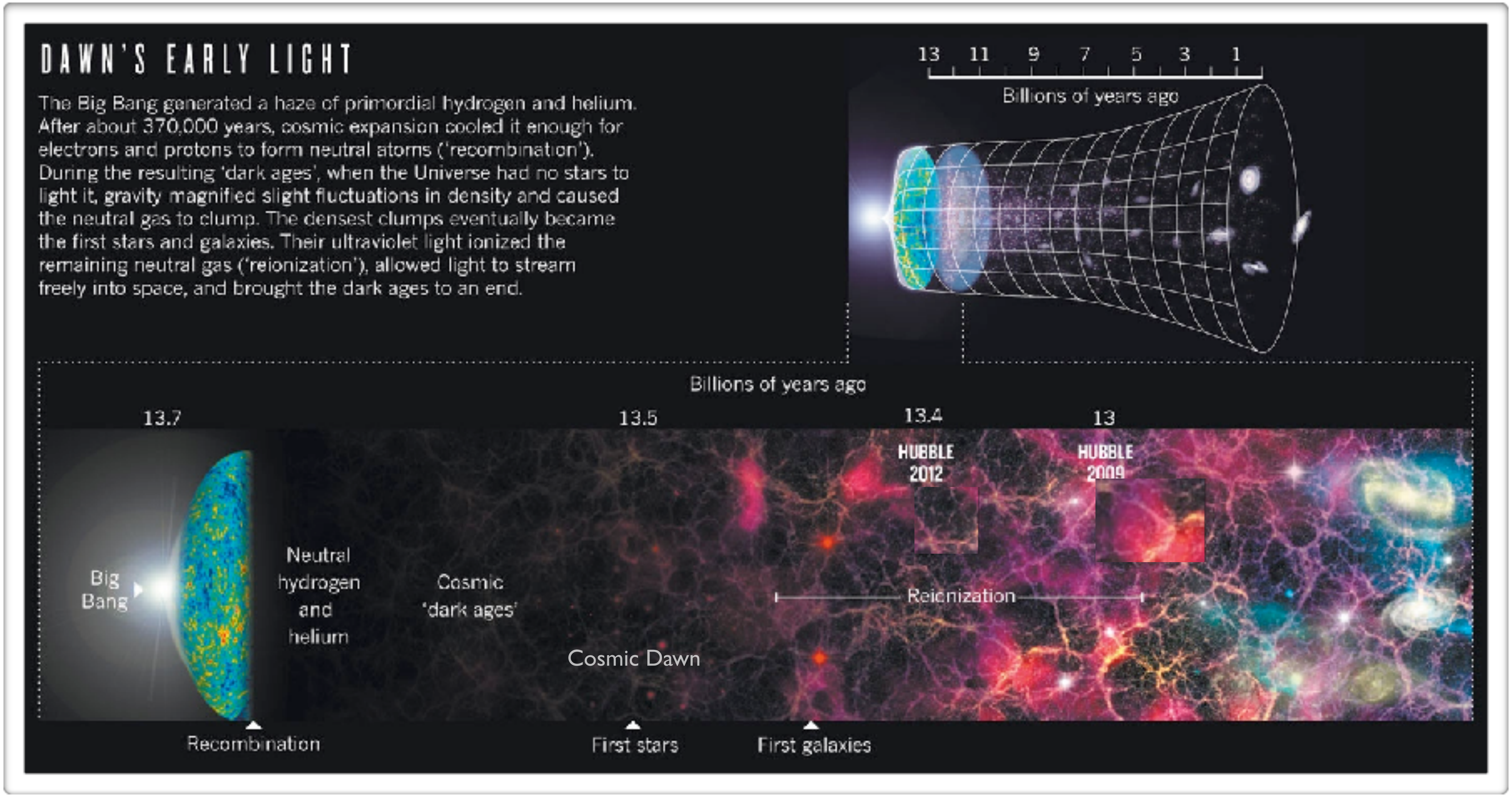
a Radio Quest for Neutral Hydrogen in the Infant Universe



Léon V.E. Koopmans (Kapteyn Astronomical Institute)

Dark Ages, Cosmic Dawn & EoR

The Universe is nearly uncharted between the CMB and the first galaxies that we can observed (0.0004 -1 Gyr after the Big Bang)



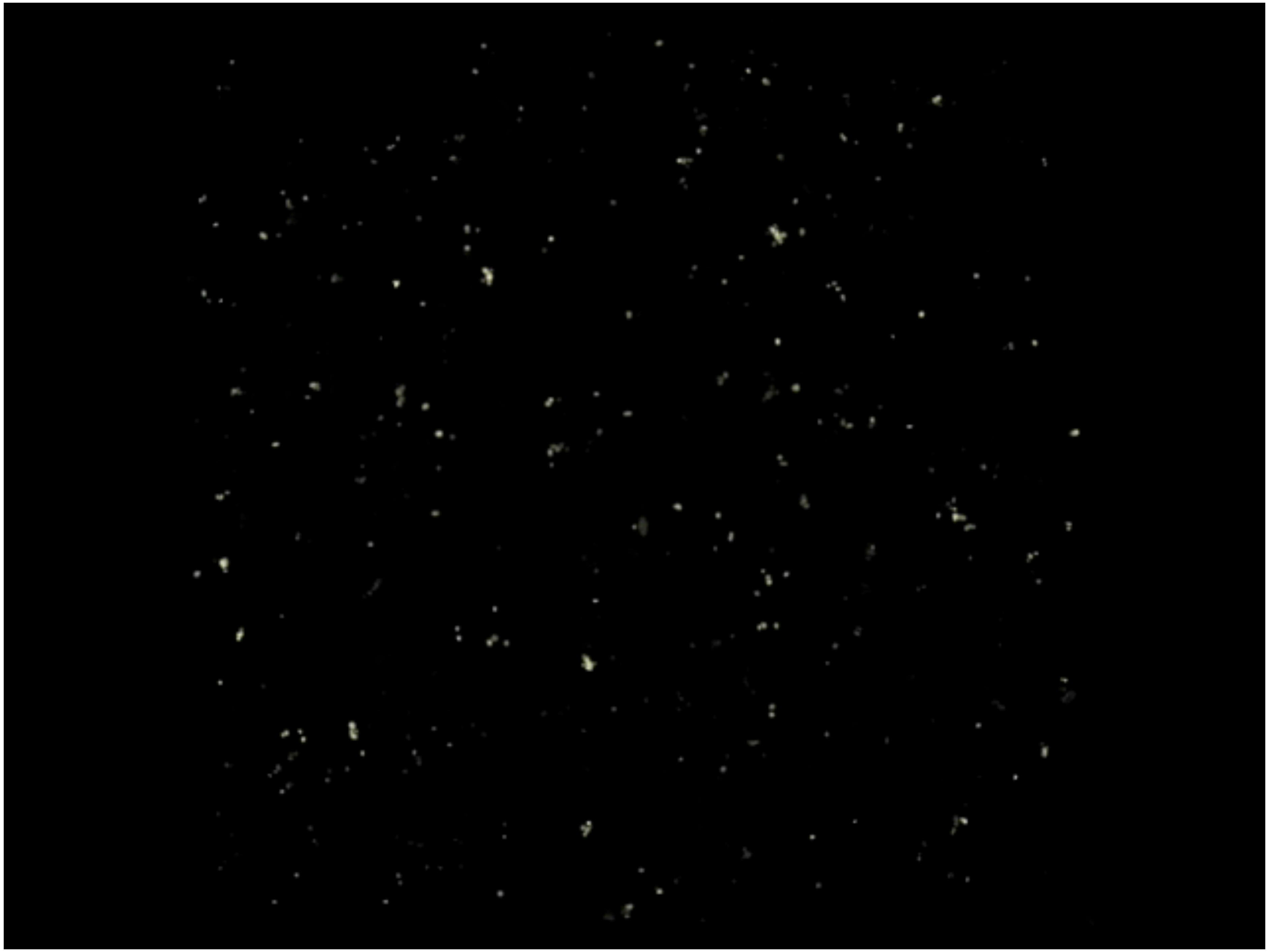
DAWN'S EARLY LIGHT

The Big Bang generated a haze of primordial hydrogen and helium. After about 370,000 years, cosmic expansion cooled it enough for electrons and protons to form neutral atoms ('recombination'). During the resulting 'dark ages', when the Universe had no stars to light it, gravity magnified slight fluctuations in density and caused the neutral gas to clump. The densest clumps eventually became the first stars and galaxies. Their ultraviolet light ionized the remaining neutral gas ('reionization'), allowed light to stream freely into space, and brought the dark ages to an end.

"We know more about recombination than about reionization, even though it forms the foundation of the present-day Universe."

The 21-cm signal of Neutral Hydrogen is a powerful probe of the Universe’s first Gyr

The first radiating sources (stars/remnants/quasars) heat/ionise neutral hydrogen



Alvarez et al. 2009

Combining structure formation in the ΛCDM paradigm with baryonic physics (hydro-dynamics), feedback, heavy-element enrichment and radiative transfer allows us model the evolution of neutral hydrogen, but …

… many processes are poorly known…

The 21-cm signal of Neutral Hydrogen is a powerful probe of the Universe's first Gyr

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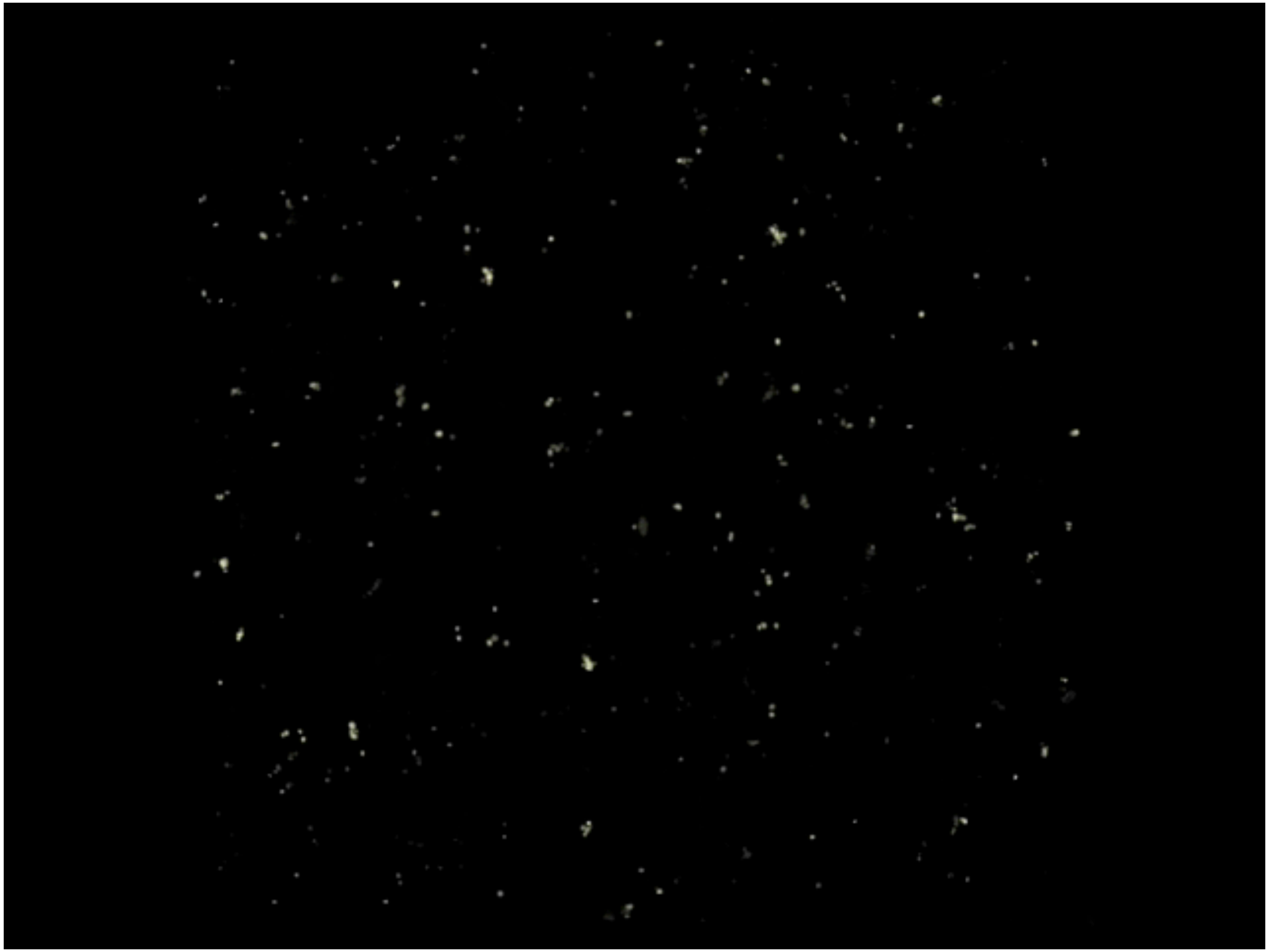

Alvarez et al. 2009

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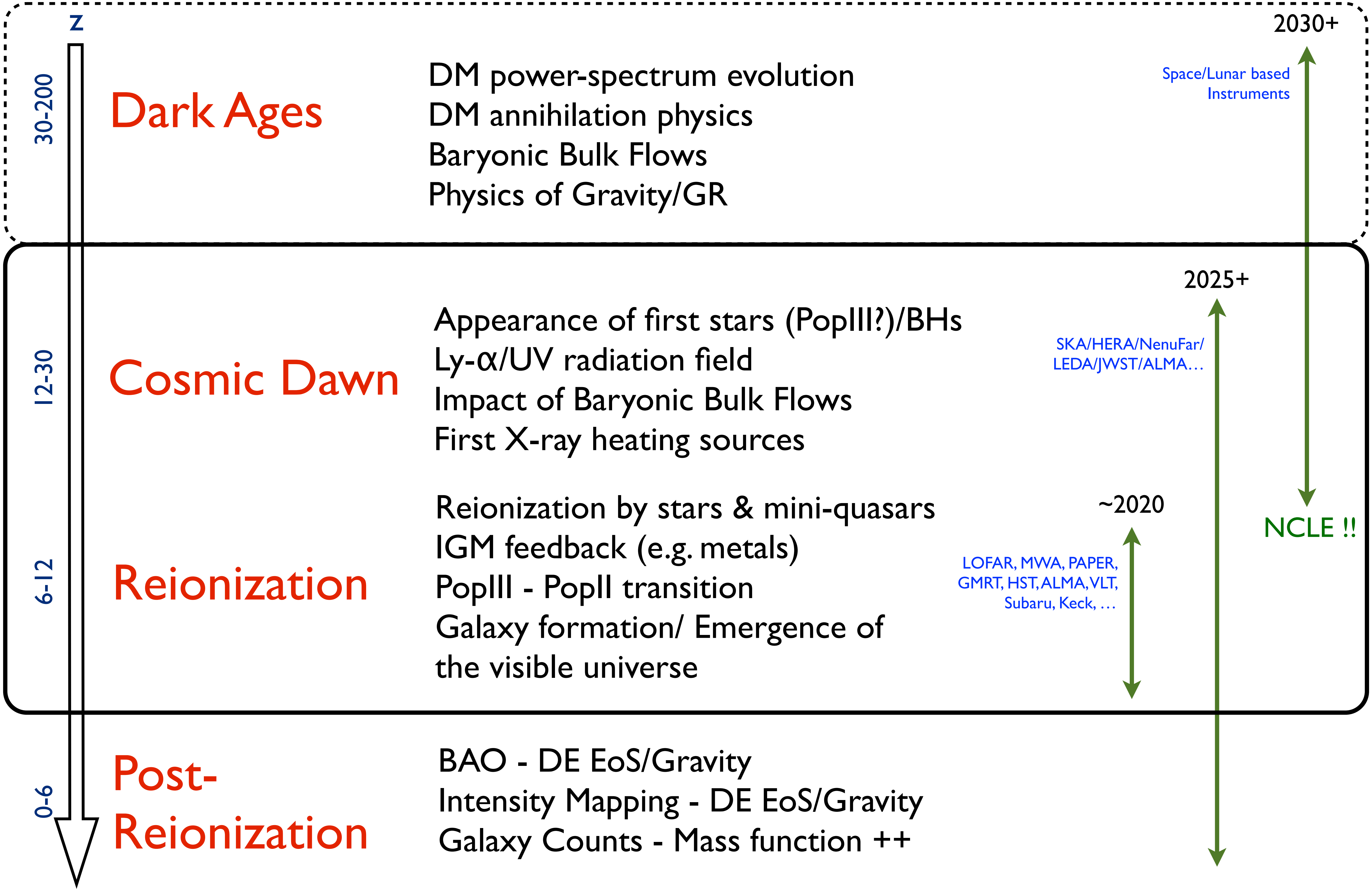
What can this "21-cm Cosmology" tell us?



30-200 **Dark Ages**

DM power-spectrum evolution
DM annihilation physics
Baryonic Bulk Flows
Physics of Gravity/GR

12-30 **Cosmic Dawn**

Appearance of first stars (PopIII?)/BHs
Ly-α/UV radiation field
Impact of Baryonic Bulk Flows
First X-ray heating sources

6-12 **Reionization**

Reionization by stars & mini-quasars
IGM feedback (e.g. metals)
PopIII - PopII transition
Galaxy formation/ Emergence of the visible universe

0-6 **Post-Reionization**

BAO - DE EoS/Gravity
Intensity Mapping - DE EoS/Gravity
Galaxy Counts - Mass function ++

2030+
Space/Lunar based Instruments

2025+
SKA/HERA/NenuFar/LEDA/JWST/ALMA…

~2020
LOFAR, MWA, PAPER, GMRT, HST, ALMA, VLT, Subaru, Keck, …

NCLE !!

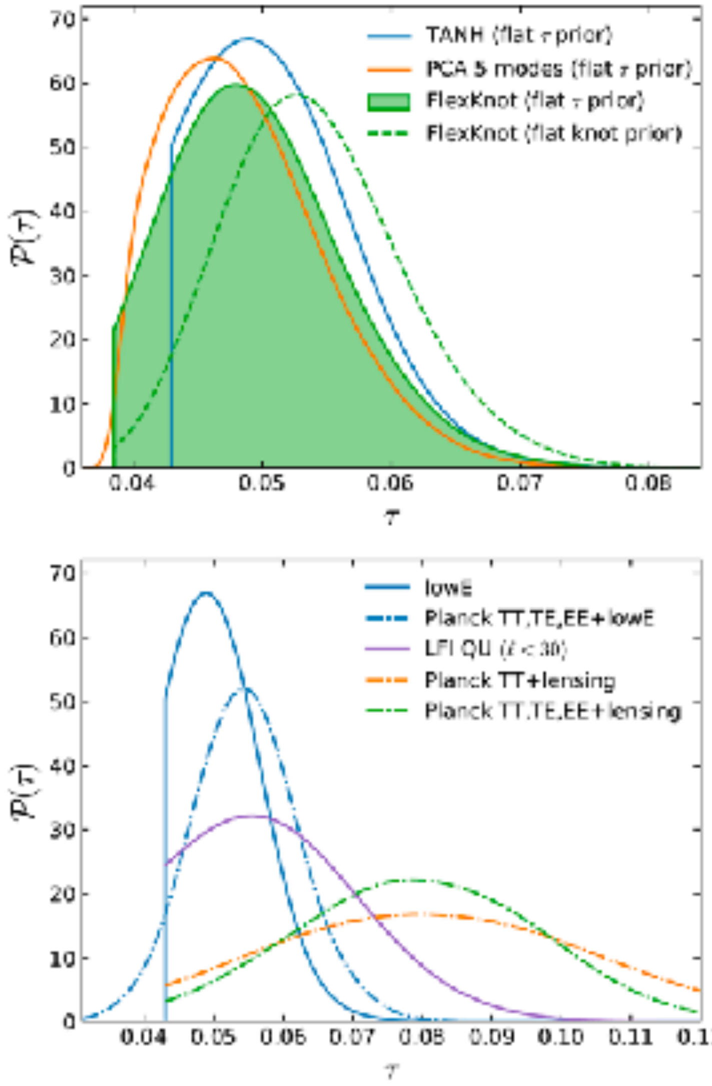
Reionization: Mounting Evidence for Neutral Hydrogen being ionized

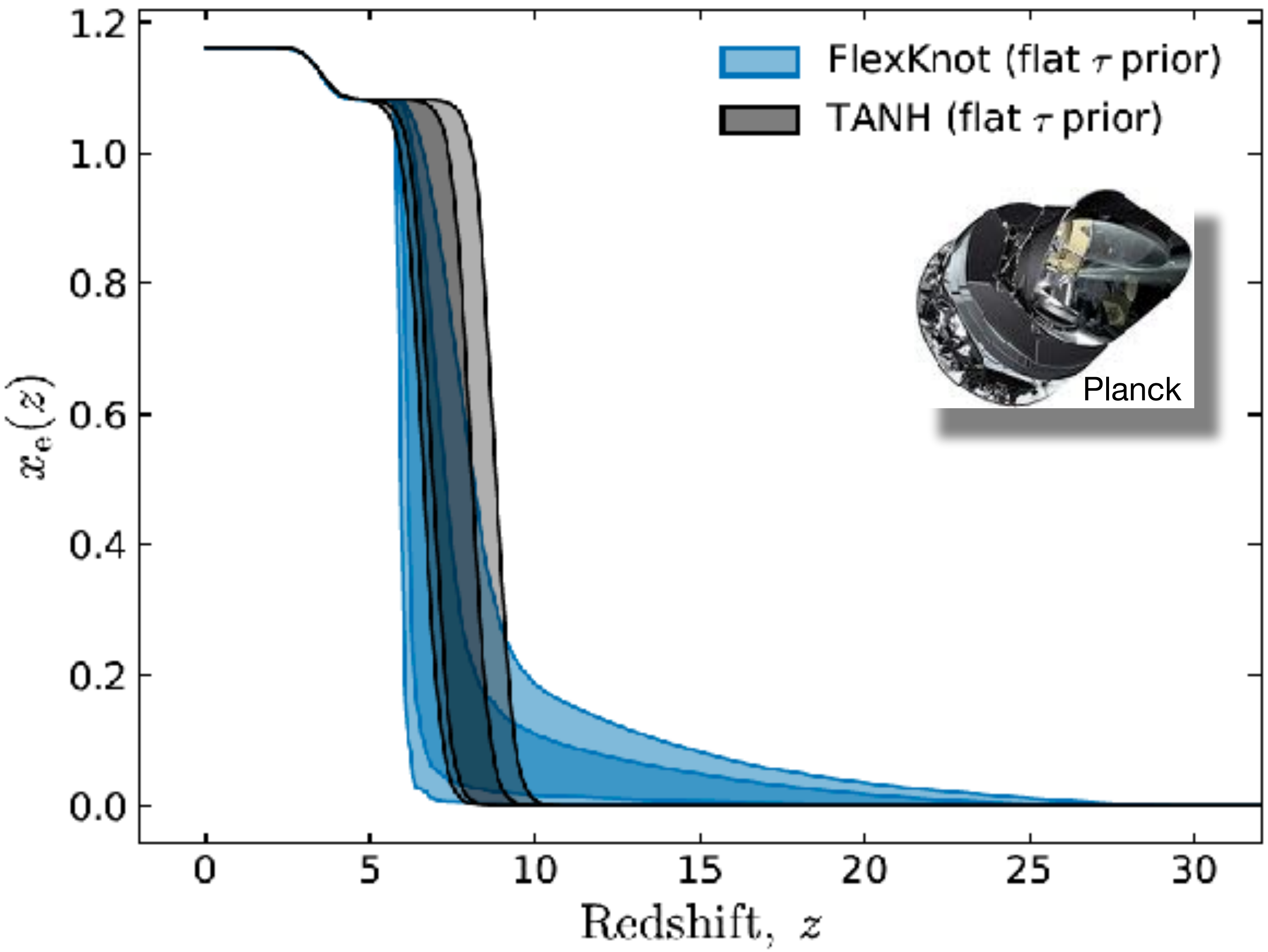
The last decade has witnessed an enormous growth in observational evidence for reionization happening rapidly at relatively low redshifts (z<10)

Joint Colloquium, Bologna, Feb. 14, 2019

Some Selected Observations of the CD/EoR

CMBR observations suggest a low Thomson scattering optical depth and hence a low electron density: i.e. the bulk of reionization occurs at low redshifts (z~8) when the volume of the Universe was already larger.



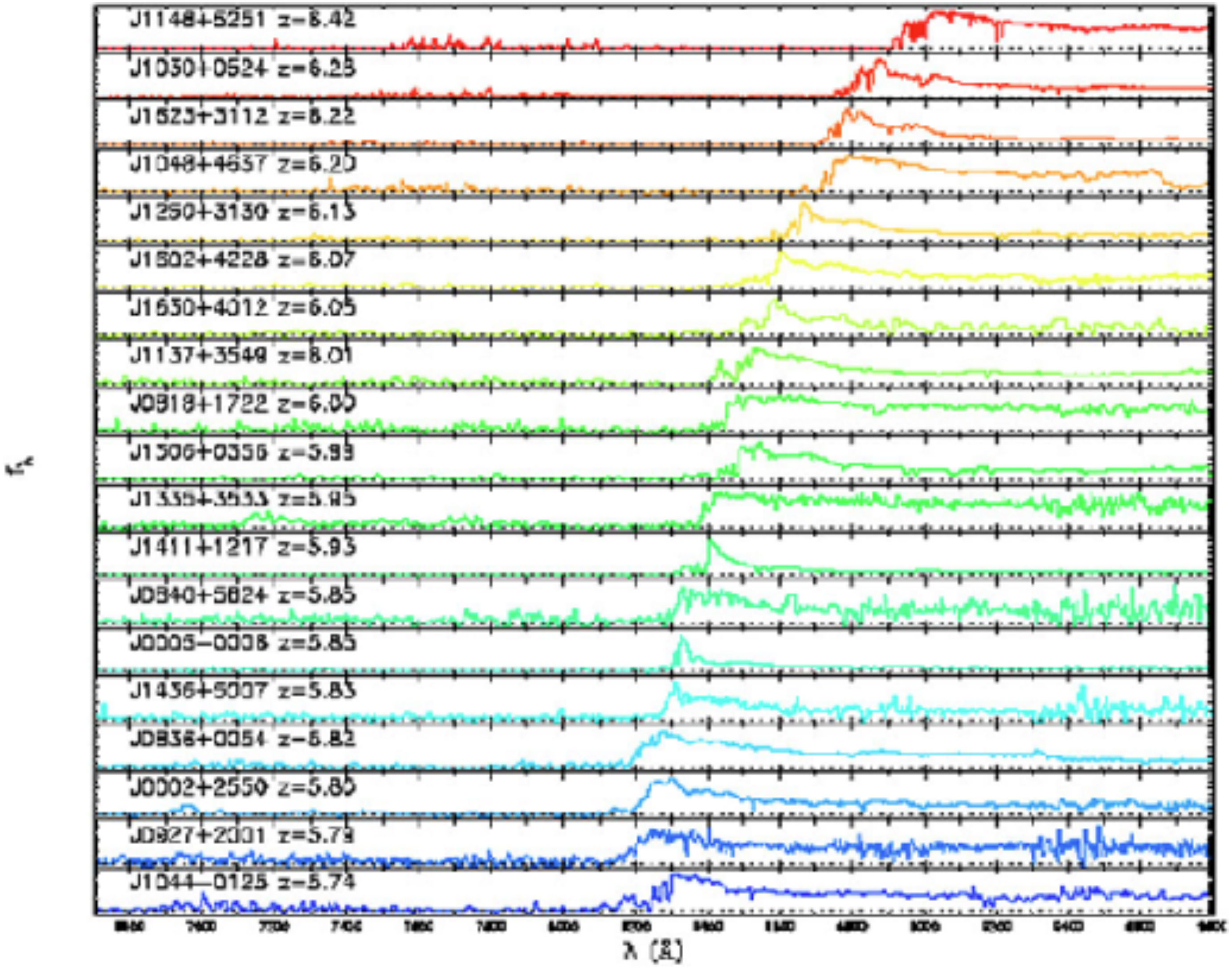


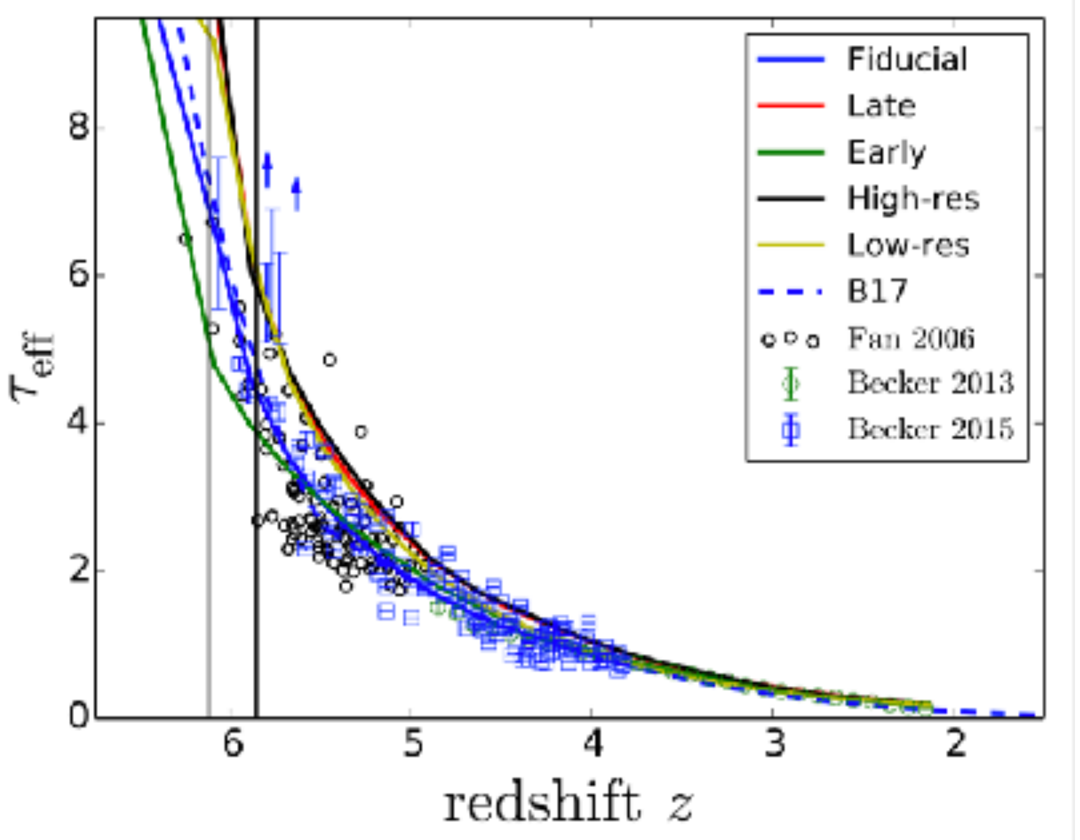
Planck+18

Some Selected Observations of the CD/EoR

Observations of low-z quasars show a clear Gunn-Peterson effects, suggesting that reionization ended around z~6 (rapid increase in optical depth at z>6).

Around z~6 large dark gaps appear in the spectrum



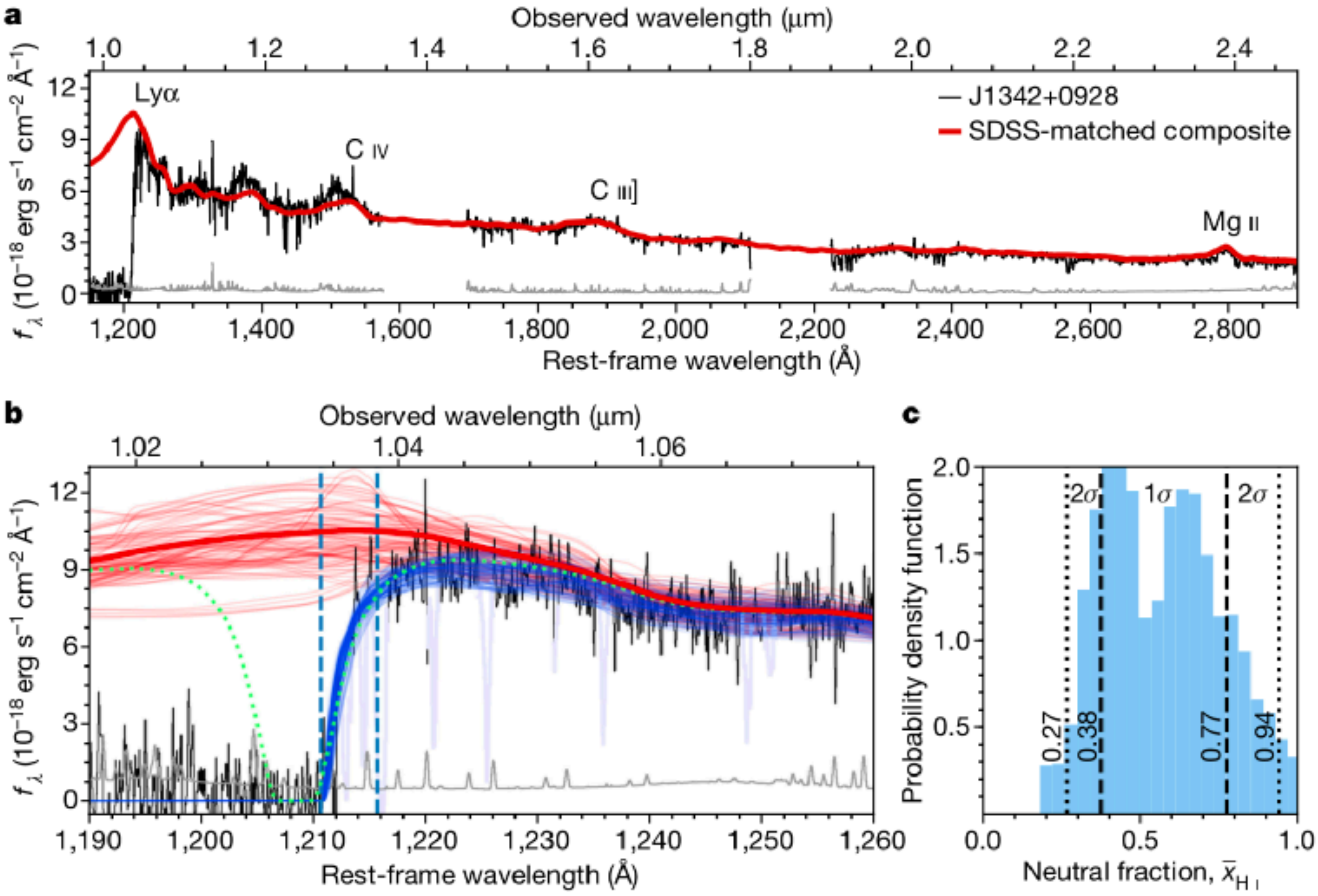


Barnett et al. 2017

Fan et al. 2006

Some Selected Observations of the CD/EoR

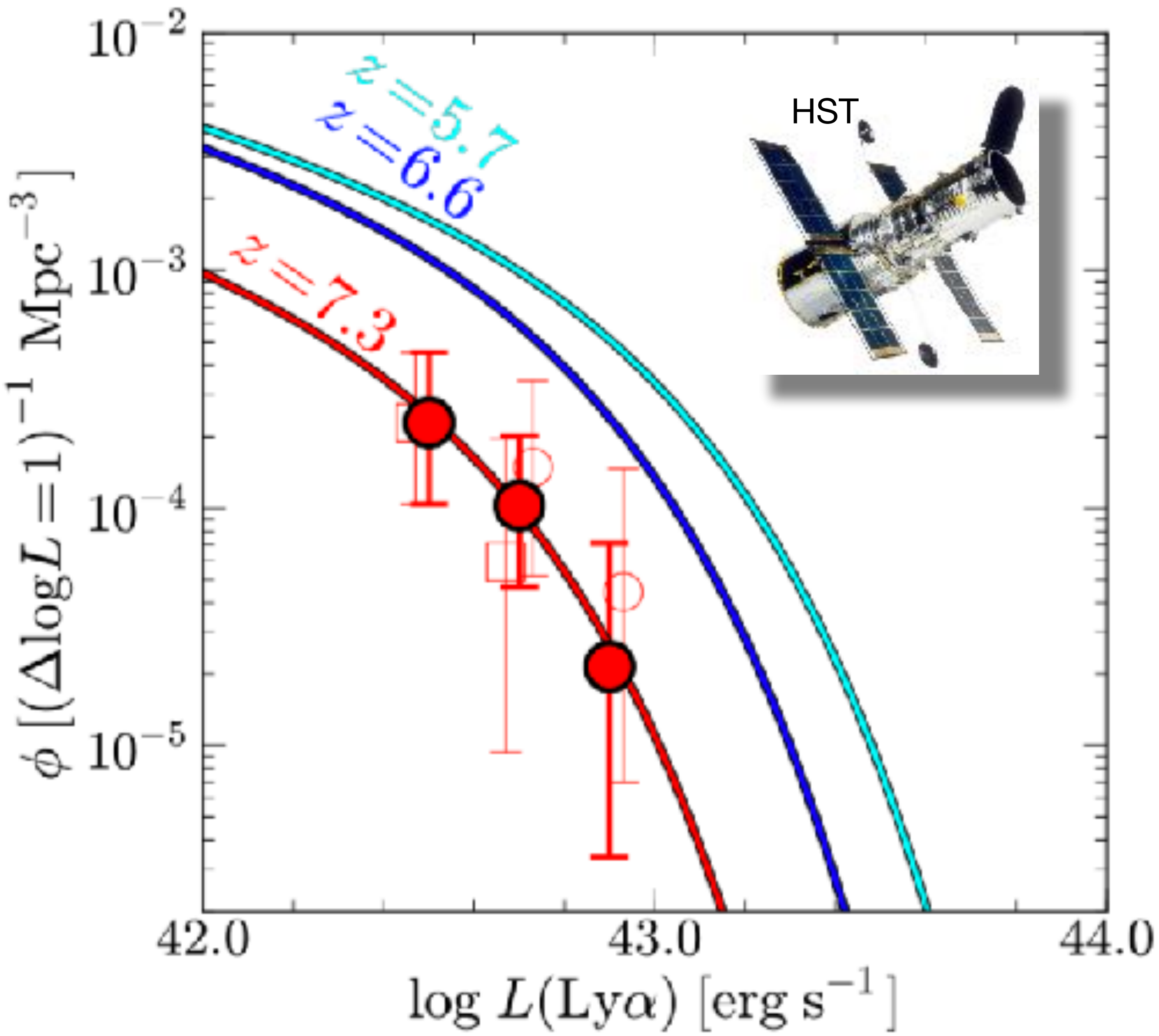
High redshift quasars (rare!) also suggest a high neutral fraction >0.27 (2-sigma) at z=7.5 due to Gunn-Peterson effect.

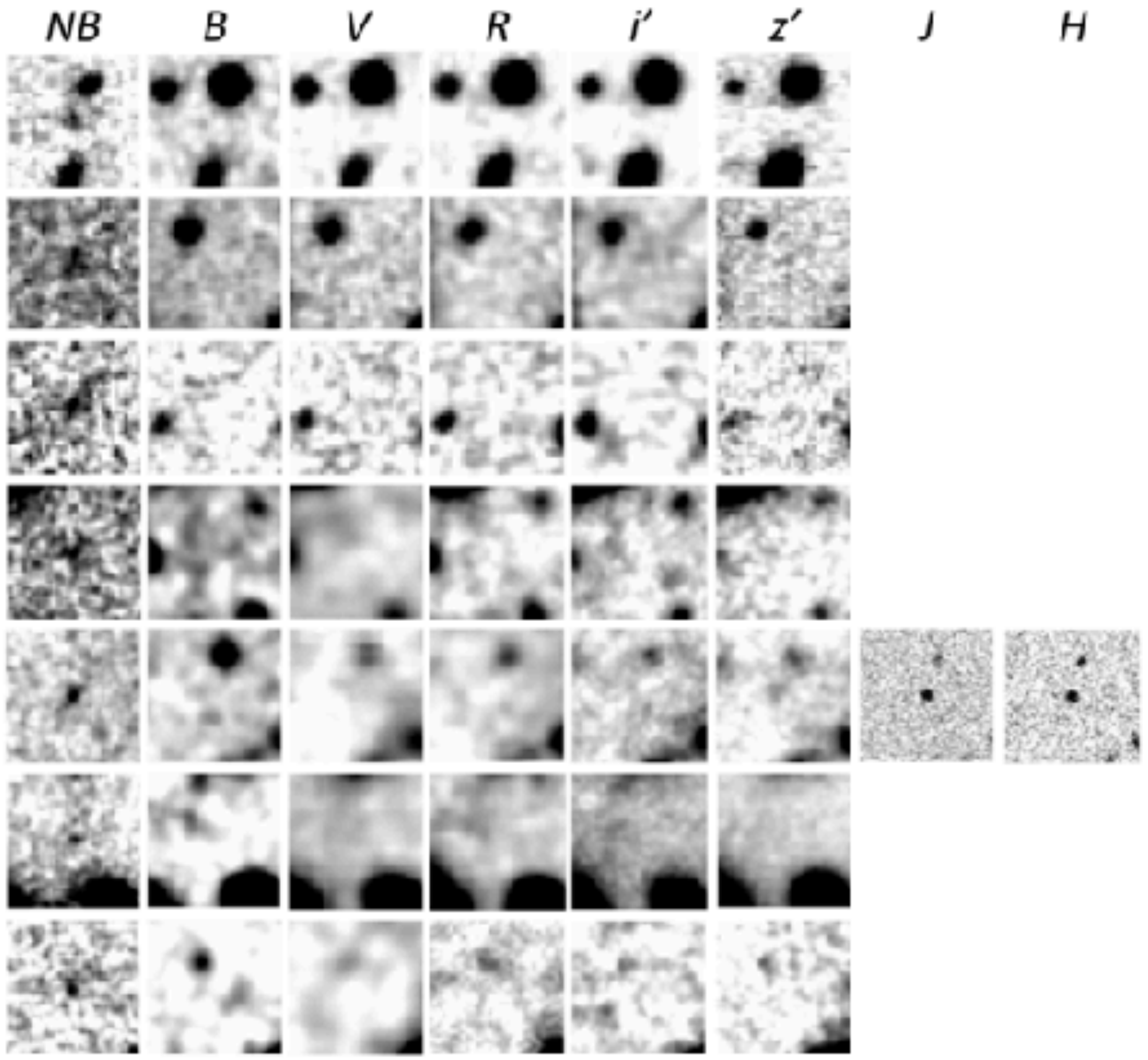


Banados et al. 2017

Some Selected Observations of the CD/EoR

Lyman alpha emitters seem to quickly decrease in number density at z>7, possibly suggesting that the neutral hydrogen density is increasing and ionised bubbles around these galaxies are small.



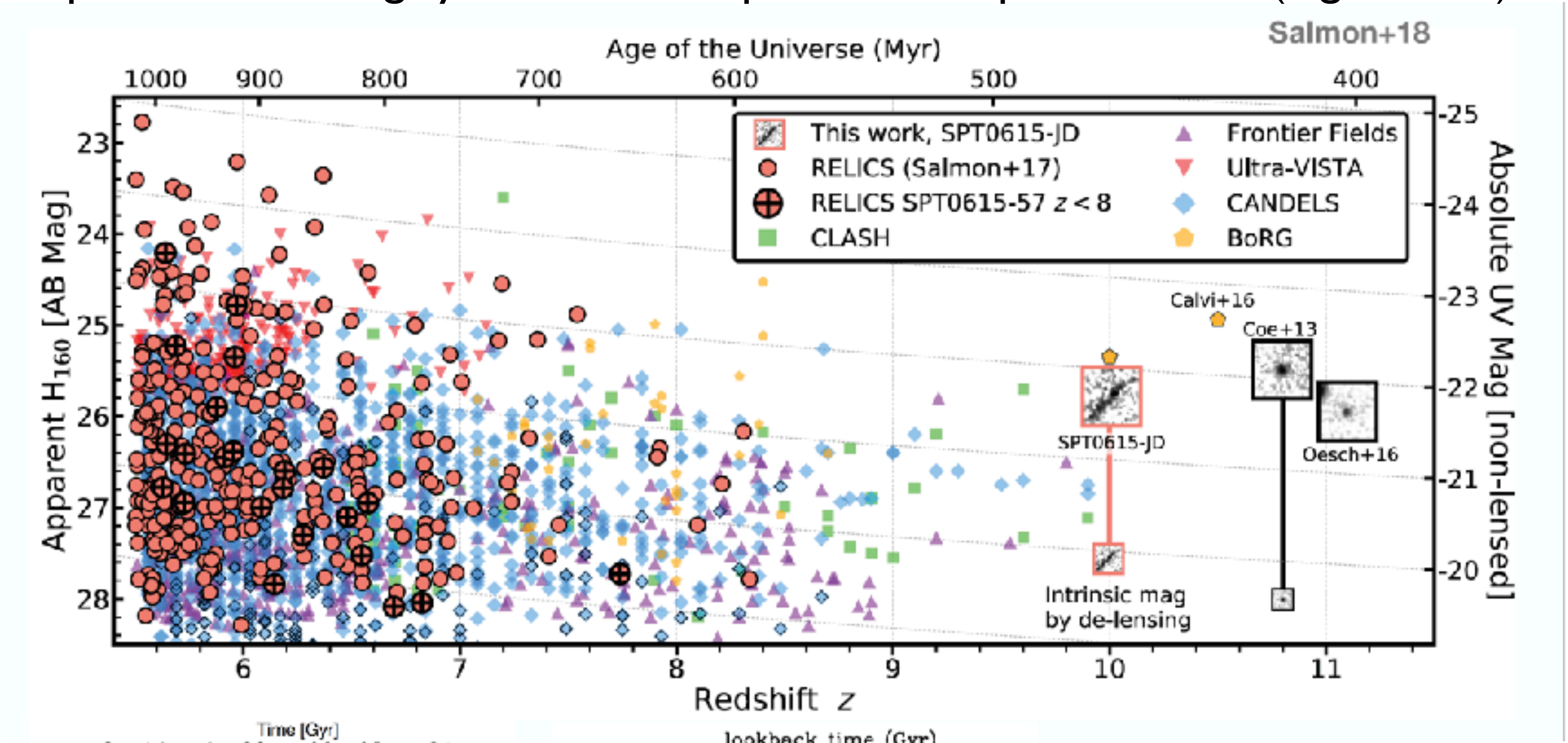


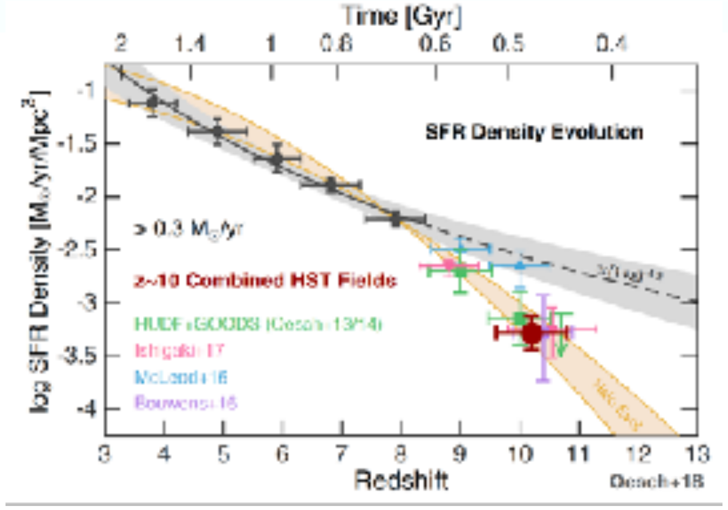
No continuum but strong narrow-band emission at z~7.3

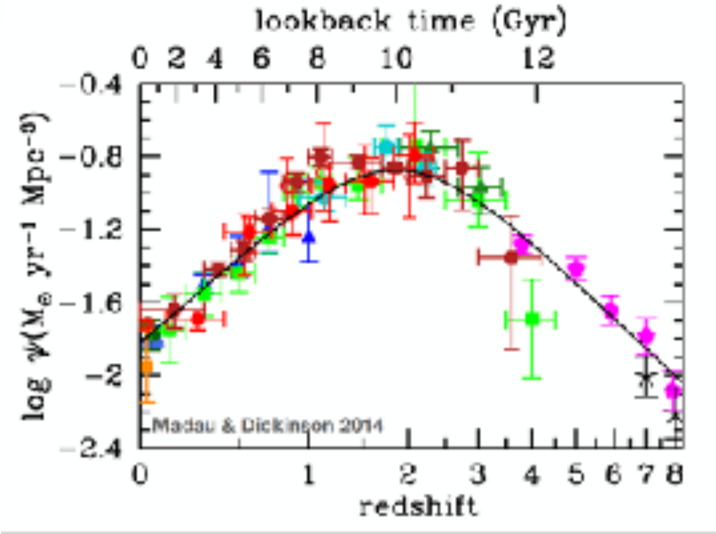
Konno+14

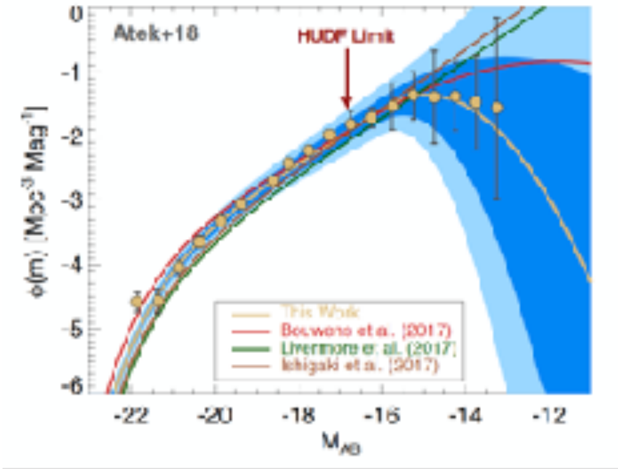
Some Selected Observations of the CD/EoR

A plethora of galaxies (some lensed) in the EoR are becoming available up to z~11+. Largely thanks to drop-out techniques in the IR (e.g. w/HST).









Summary of Current Constraints on the EoR/CD

- Scattering optical depths from CMB observations

  Ionised medium causes CMB polarisation: $z_{eor} \sim 8$ (latest Planck results!)
- High-z galaxies/Ly-alpha emitters

  IR drop-outs give SFR/LF to z~10: SFR rises fast below z~10 but there are not enough UV photons to reionize the Universe

  Ly-alpha emitters seem to drop out already at z>7.
- High-z QSOs

  Gunn-Peterson troughs suggest >30% neutral HI at z~7.5, i.e. the end of reionization occurs close to the highest z QSO/galaxies that we observe
- High-z GRBs

  GRBs traces massive star formation. Currently rare events, but z~8.2 GRB has been seen and could be a direct tracer of the SFR.
- Temperature of the IGM

  Extrapolation of the high-z IGM temperature suggest late reionization
- NIR/X-ray backgrounds

  Detection of NIR fluctuations made, but far above predictions.
  X-rays limit AGN contribution to reionization to ~10% max.

- Discovery of the global 21-cm signal from Cosmic Dawn (EDGES2) in 2018 ?

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Expectations of the 21-cm Signal of Neutral Hydrogen

Most evidence points at substantial reionization occurring at z<10, being halfway around z~8 and ending around z~6.

But the details are largely unknown: a complementary tracer is needed that is volume filling and actually traces what is being ionised and what forms stars/galaxies (i.e. hydrogen itself)

Joint Colloquium, Bologna, Feb. 14, 2019

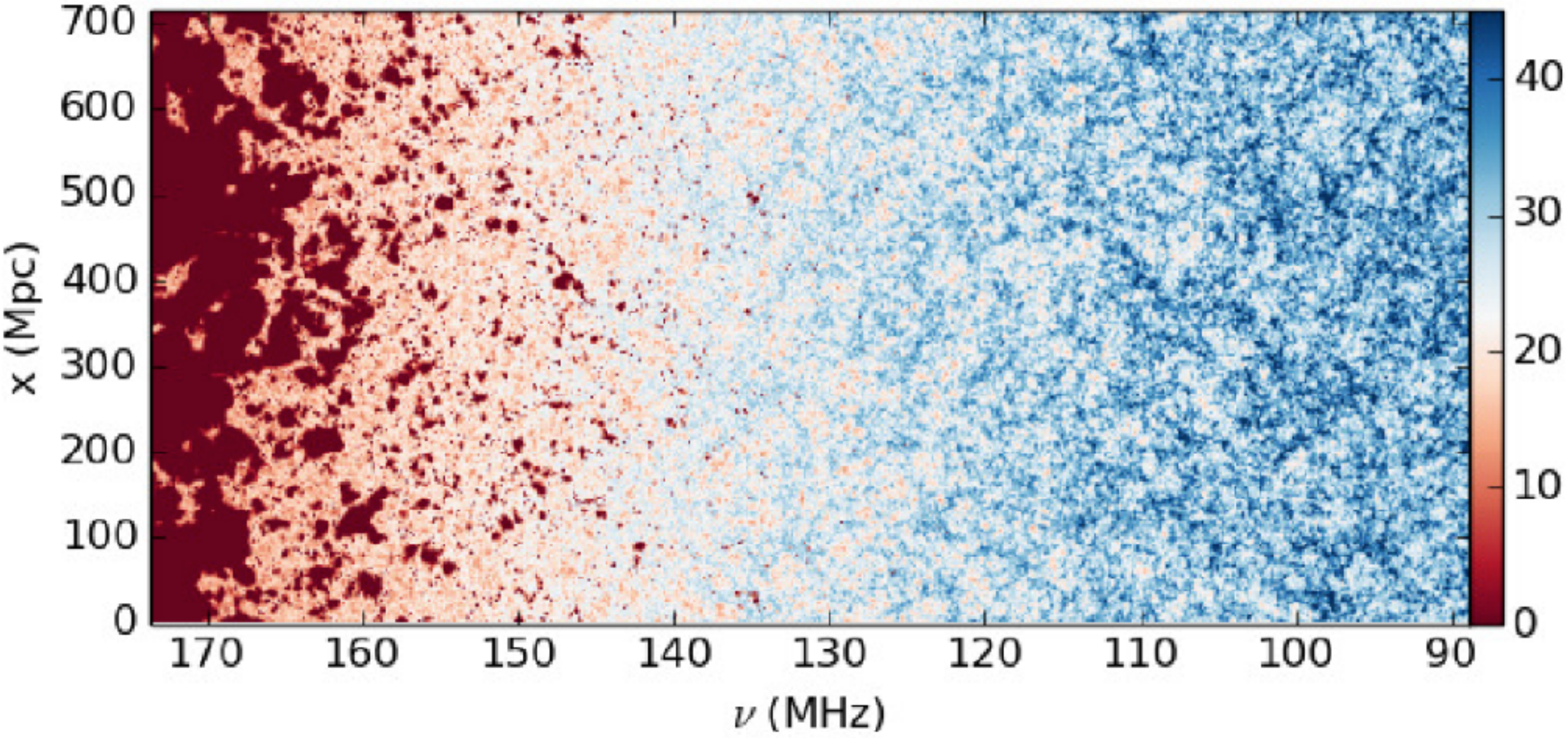
Hydrogen Brightness Temperature

The tomography of HI emission/absorption is a treasure trove of information for (astro)physics, cosmology & fundamental physics.

Post-Reionization

HI is found largely in galaxies ← HI has a filling factor of order unity

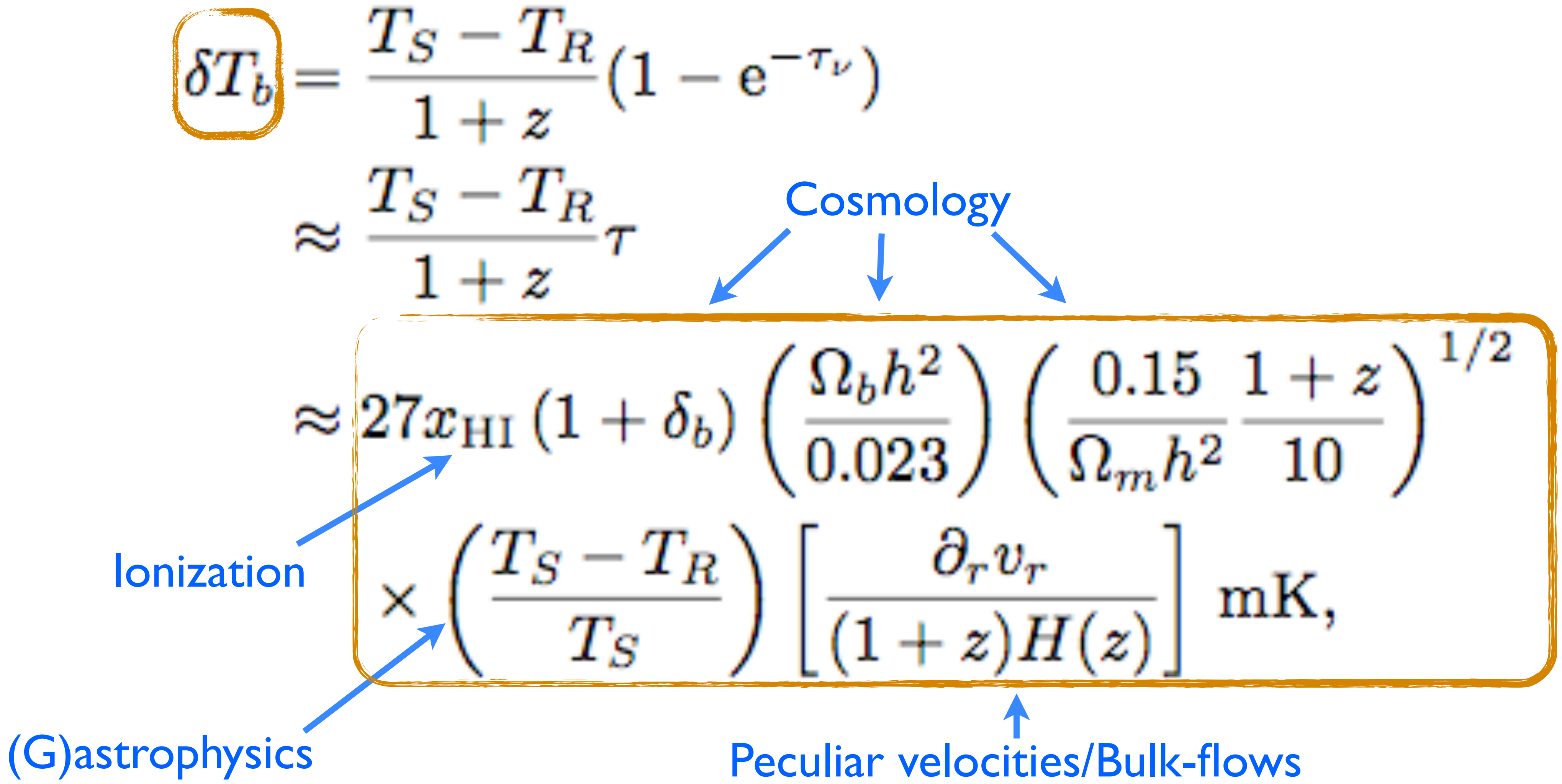
Dark Ages/Cosmic Dawn/Reionization



Credit: Dixon, Illiev et al.

Hydrogen Brightness Temperature

The brightness of the 21-cm signal (in Kelvin; Rayleigh-Jeans regime) that can be measured with radio telescopes is given by:



$$\boxed{\delta T_b} = \frac{T_S - T_R}{1+z}\left(1 - e^{-\tau_\nu}\right)$$

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

$$\approx \boxed{\begin{aligned} & 27 x_{\mathrm{HI}} (1+\delta_b) \left(\frac{\Omega_b h^2}{0.023}\right) \left(\frac{0.15}{\Omega_m h^2}\frac{1+z}{10}\right)^{1/2} \\ & \times \left(\frac{T_S - T_R}{T_S}\right) \left[\frac{\partial_r v_r}{(1+z)H(z)}\right] \mathrm{mK}, \end{aligned}}$$

Cosmology

Ionization

(G)astrophysics

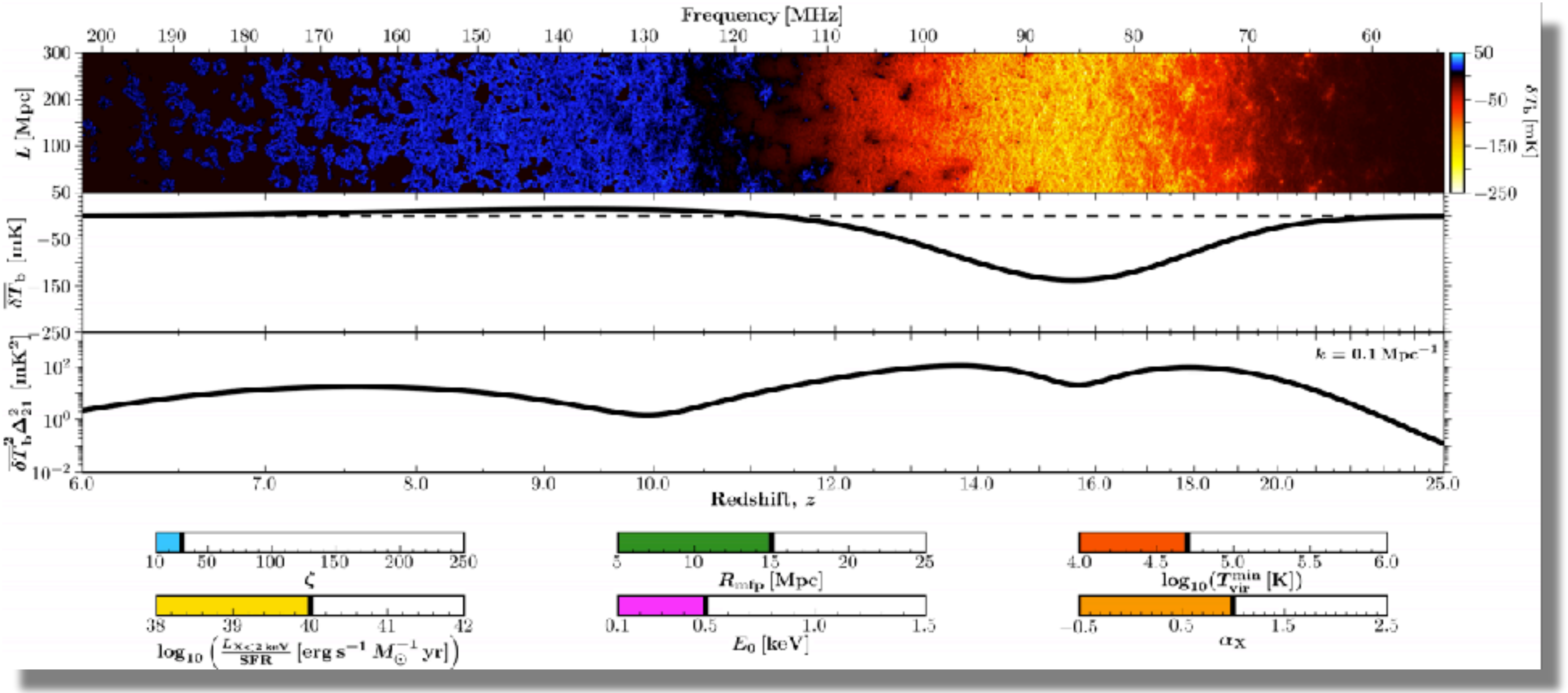
Peculiar velocities/Bulk-flows

The 21-cm signal is set by a complex interplay between cosmology and (g)astrophysics.

Hydrogen Brightness Temperature

Numerical Models

Many “ingredients” in the 21-signal models are effective descriptions of the underlying complex physical processes (sub-grid physics) that we hope to connect to these processes on smaller (galaxy/stellar) scales.



Meisinger & Geig

Hydrogen Brightness Temperature

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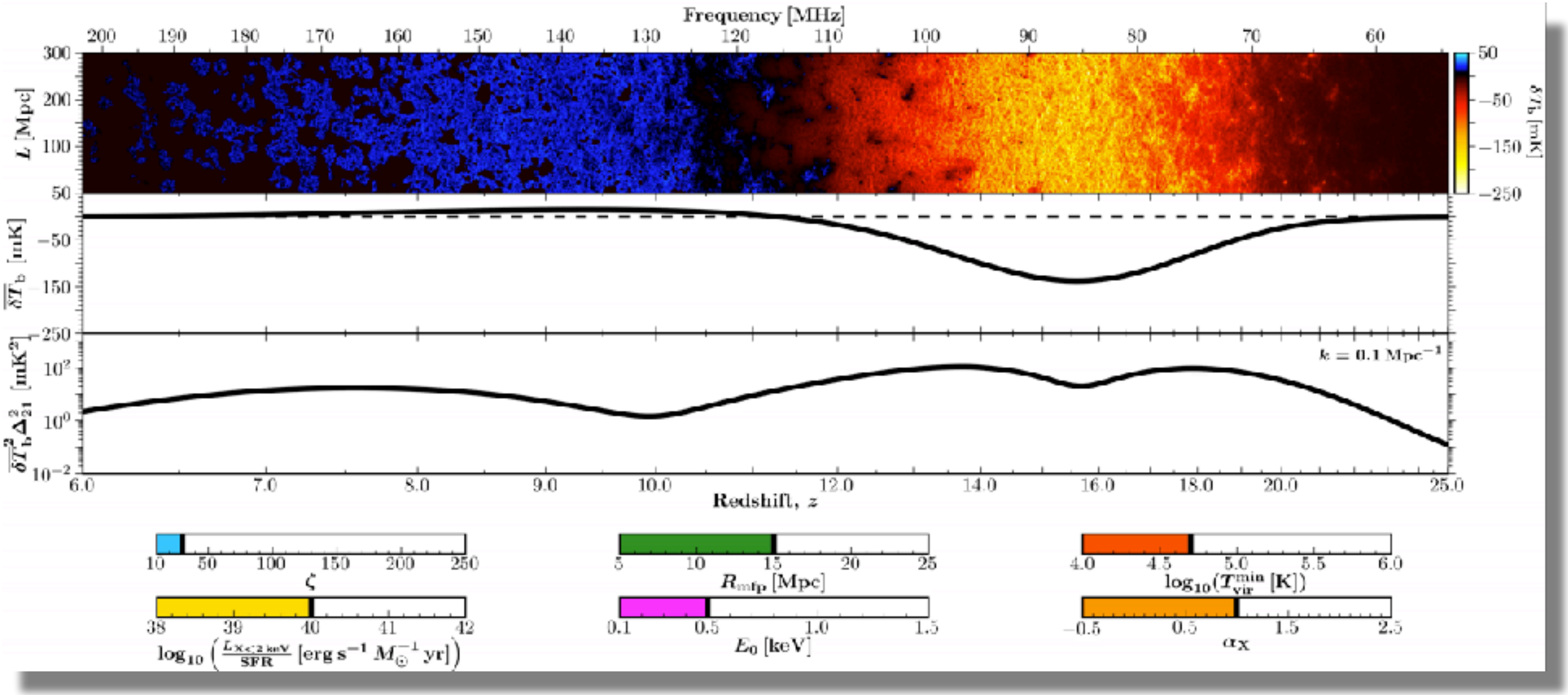
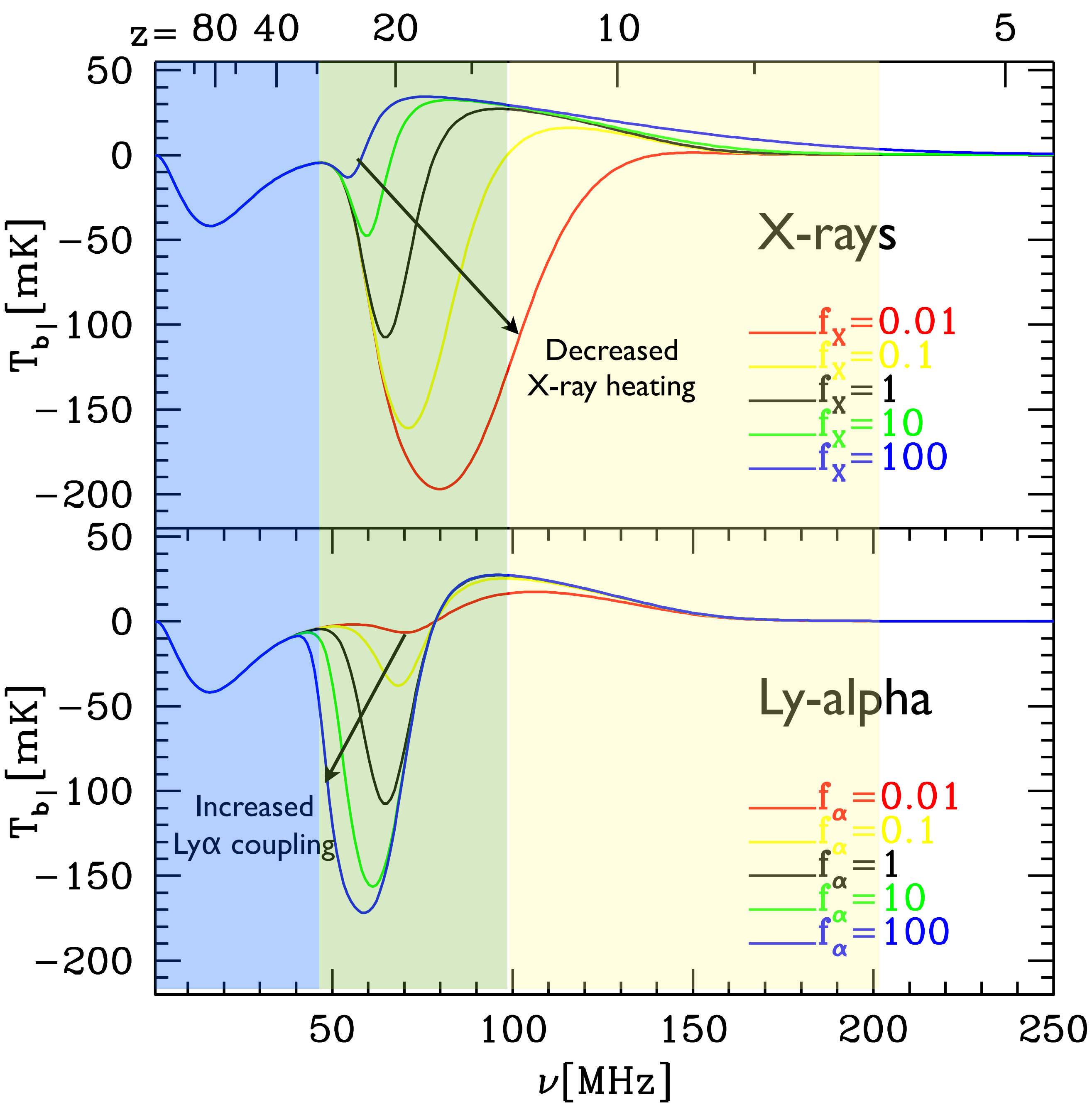
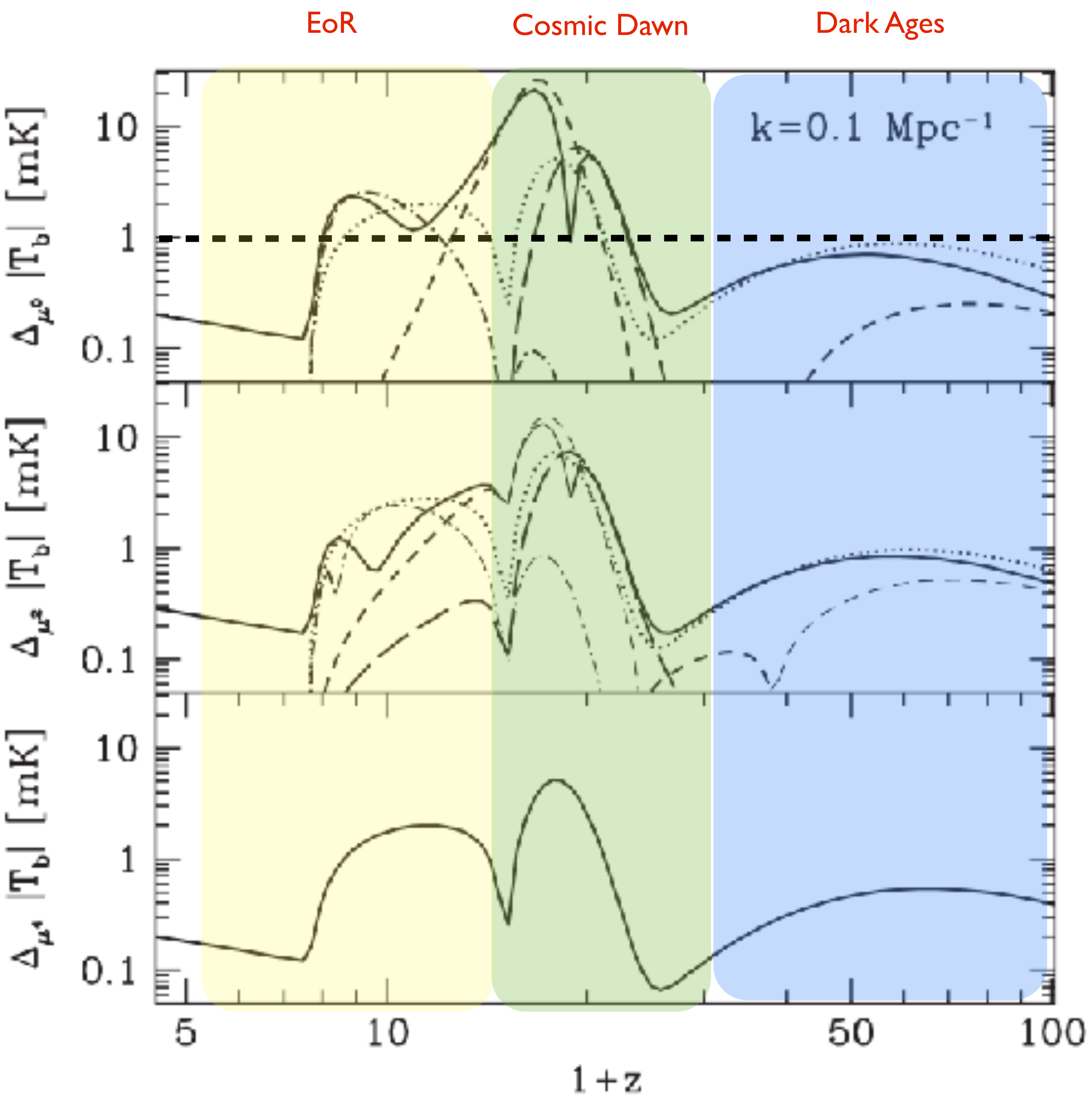


Meisinger & Geig

Hydrogen Brightness Temperature

Global Signal (left) and Intensity Fluctuations (right)





Pritchard & Loeb 2009; see also Santos et al. 2008, 2010, 2011

Observational approaches to 21-cm Cosmology

There are (currently) three different ways to analyse the 21-cm signal, each being pursued (or will be):

Today's talk

- Spatial/spectral 21-cm signal intensity fluctuations:
    - Expensive, using multiple (cross-correlation) receivers (needs large A_{eff}/FoV)
    - Power-spectra, bi-spectra, moments, etc.
    - LOFAR/AARTFAAC, MWA, PAPER, GMRT, LEDA, NenuFar, HERA, SKA, …

- Globally-averaged total intensity 21-cm signal:
    - Cheap and fast, using single (auto-correlation) di-/tripole- receivers.
    - Loss of all spatial information but retains spectral/redshift information
    - EDGES, SARAS, LEDA, SCI-HI/PRI^{Z}M, BIGHORNS, NCLE, DARE, …

- Tomography/Imaging:
    - Retains all information (if above the noise)
    - SKA (on few to tens of arcmin scales), HERA (on degree scales)

Interferometric 21-cm Signal Experiments

Many experiments to measure the 21-cm signal are ongoing, but they extremely hard. The signal is very faint and is affected by many effects (RFI, ionosphere, bright polarised foregrounds, instrumental distortions, calibration/ signal processing artefacts, etc.).

Process is made with two steps forward for every step backward

Current (large) 21-cm Power-Spectrum Detection Experiments

Specs
- 40 hrs data [12/2007] on PSRB0823+26
- FWHM = 3.1d primary beam
- Resolution 20 arcsec
- Freq = 139.3-156.0 MHz [64x0.25MHz]
- Time resolution = 64 sec
- $z = 8.1\text{-}9.2$

Paciga et al. 2013

Specs:
- 3 hrs of data; - August 23 2013
- R.A.(J2000) = 0h 0m 0s,
  Decl.(J2000) = $-30^\circ\ 0'\ 0''$
- high-band of 30.72 MHz, centered at
  182 MHz i.e. $6.2 < z < 7.5$

Dillon et al. 2015

Specs:
- 1148 hrs of data
  (8/11/2012 to 23/3/2013)
- 100 to 200 MHz, 1024 chan
- visibility integr.: 10.7 seconds

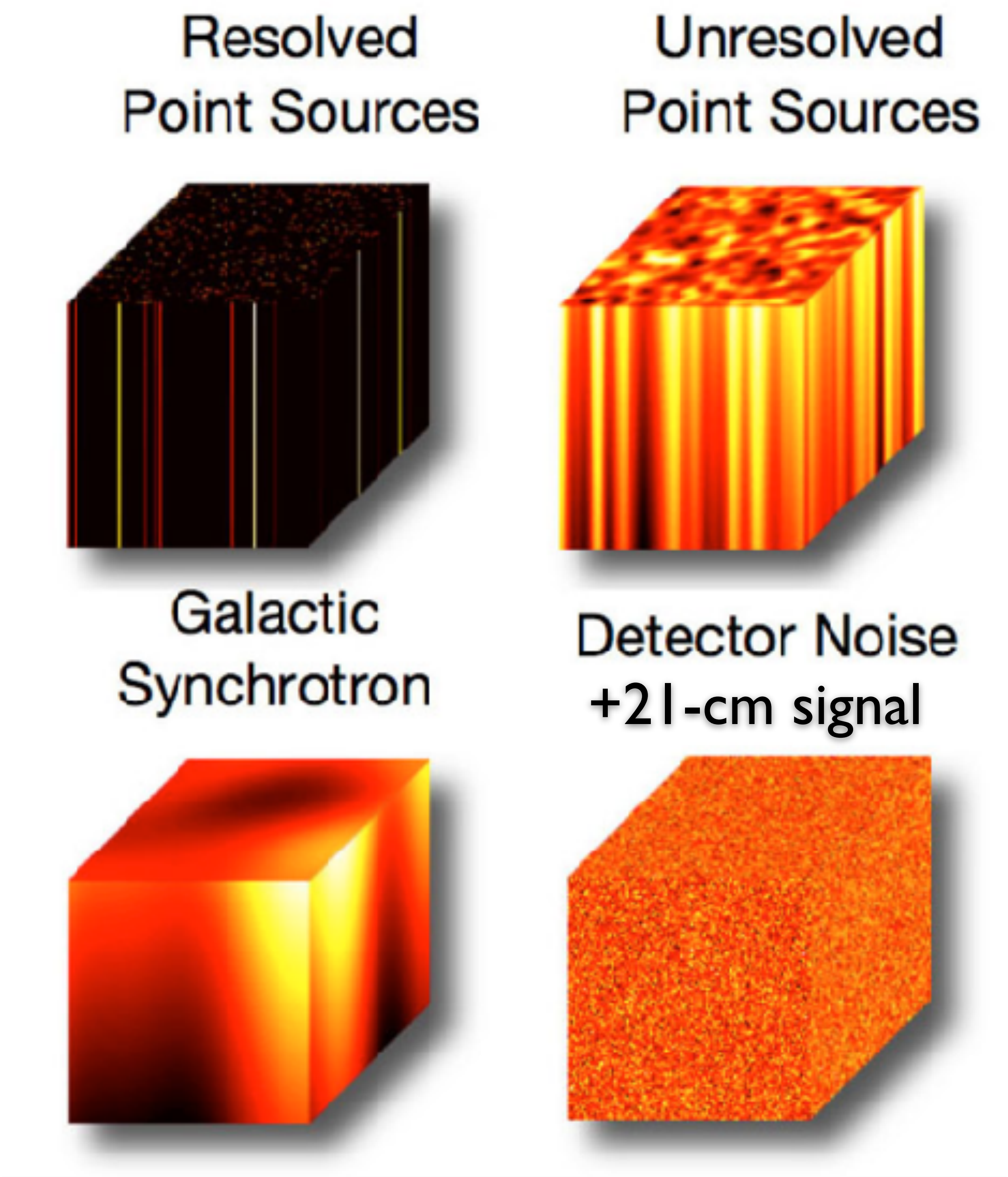
Ali et al. 2015

Today

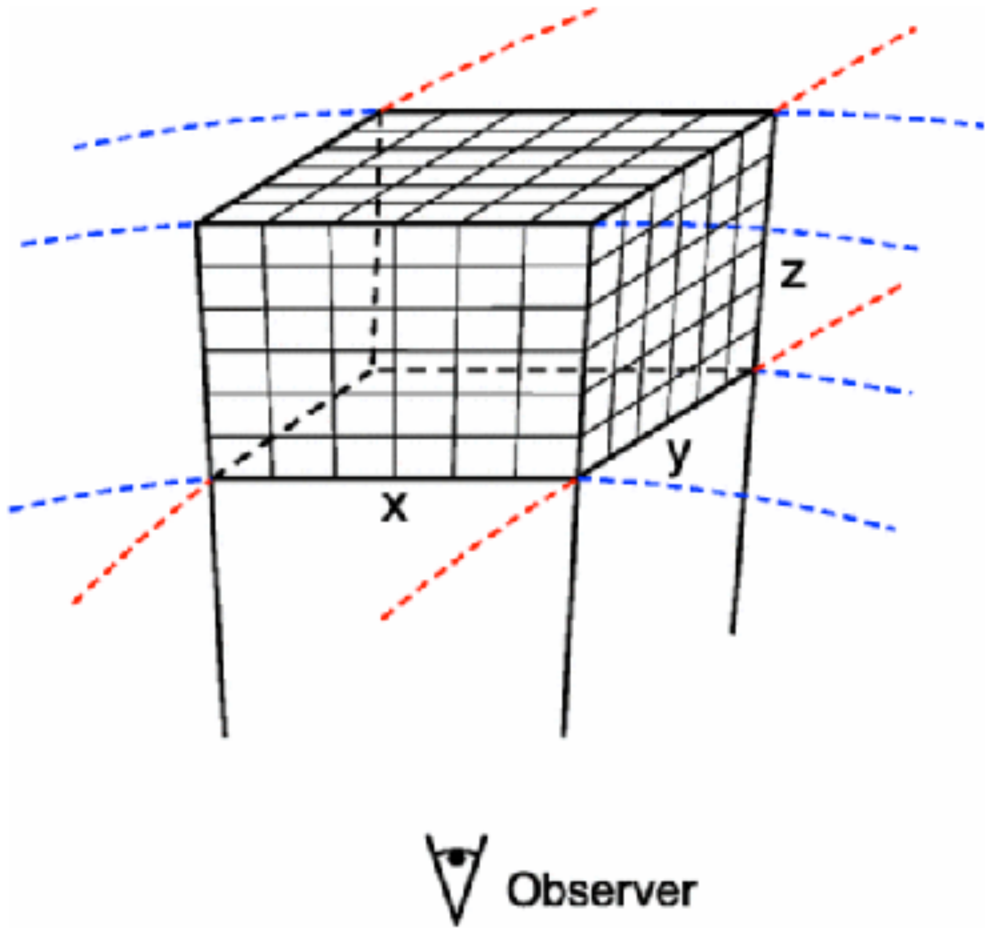
Specs:
- 13 hrs of data; - Feb11/12 2013
- R.A.(J2000) = 0h 0m 0s,
  Decl.(J2000) = $90^\circ\ 0'\ 0''$
- high-band of 115-189 MHz

Patil et al. 2017

Measuring the brightness temperature fluctuations of HI

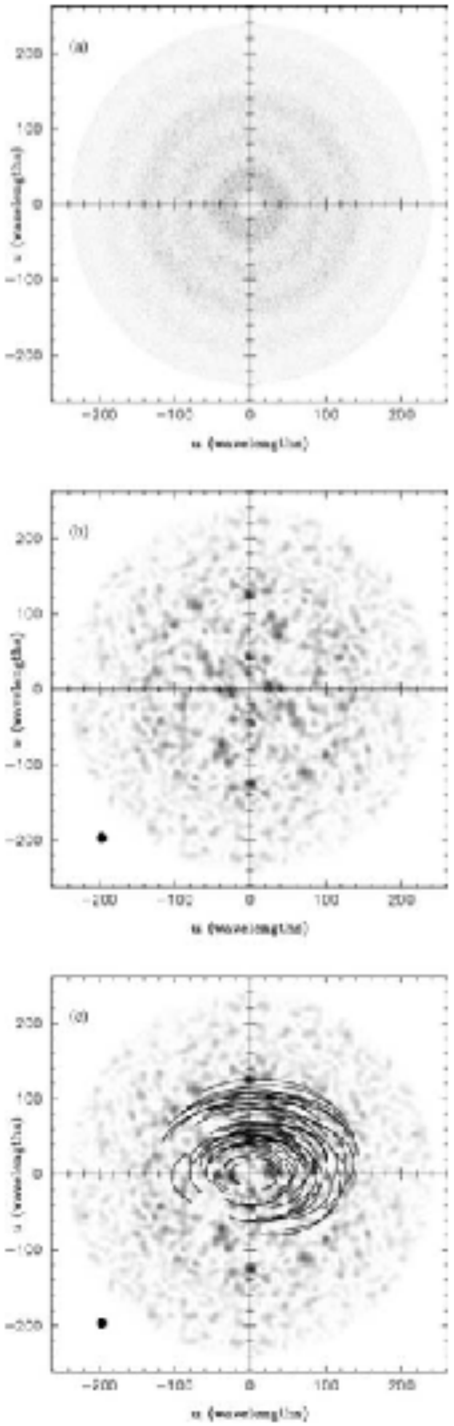


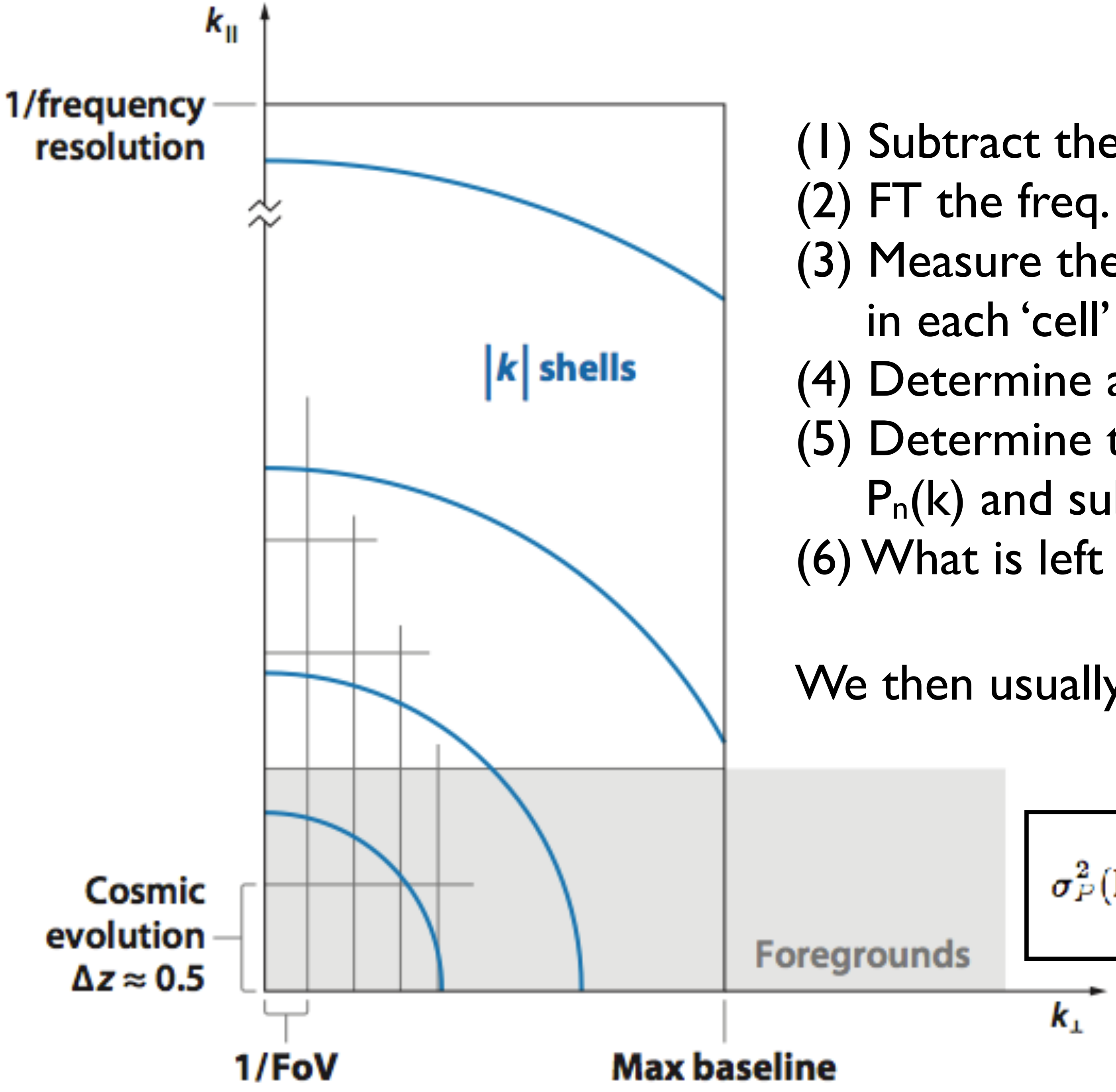
Figures: Dillon et al



After removal of the spectrally smooth FGs, one can Fourier transform the box in 3D (2D spatial FT is already done in the correlator) to obtain power spectra.

Measuring the brightness temperature fluctuations of HI





Figures: Meisinger et al; Morales et al.

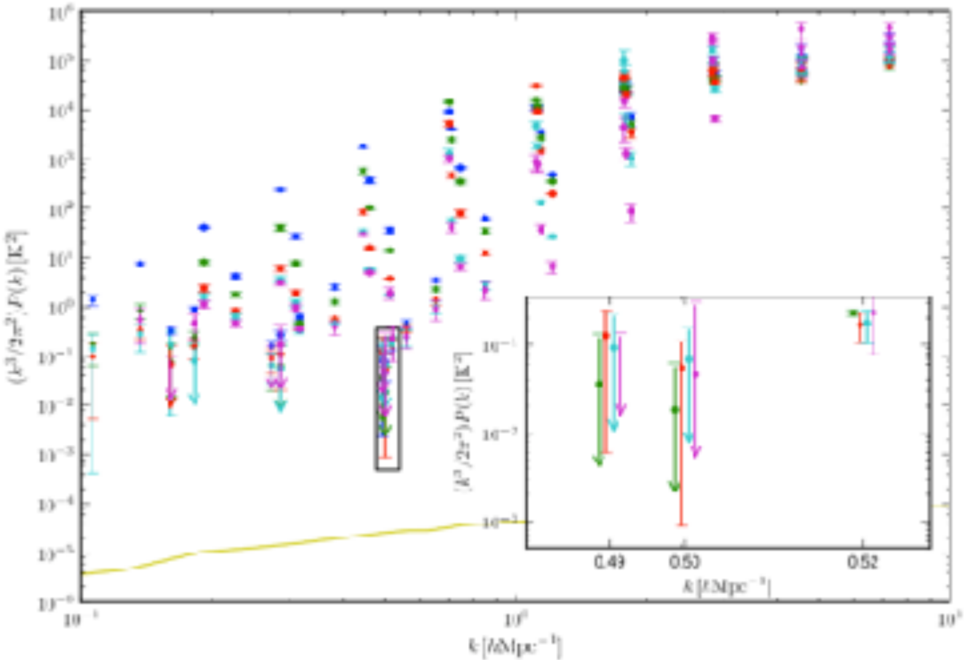
(1) Subtract the FGs [MW+extra-Gal.]
(2) FT the freq. axis of the data-cube
(3) Measure the visibility amplitudes A
in each 'cell' as function of k.
(4) Determine average of A^2 => P(k)
(5) Determine the noise power-spectrum
$P_n(k)$ and subtract.
(6) What is left is $P_{21}(k)$ + error (below)

We then usually display $\Delta^2(k)=(k^3/2\pi^2)P(k)$

$$\boxed{\sigma_P^2(\mathbf{k}) = \left(P_{21}(\mathbf{k}) + \frac{T_{\rm sys}^2 D^2 \Delta D \lambda^2}{B \tau A_e}\right)^2}$$

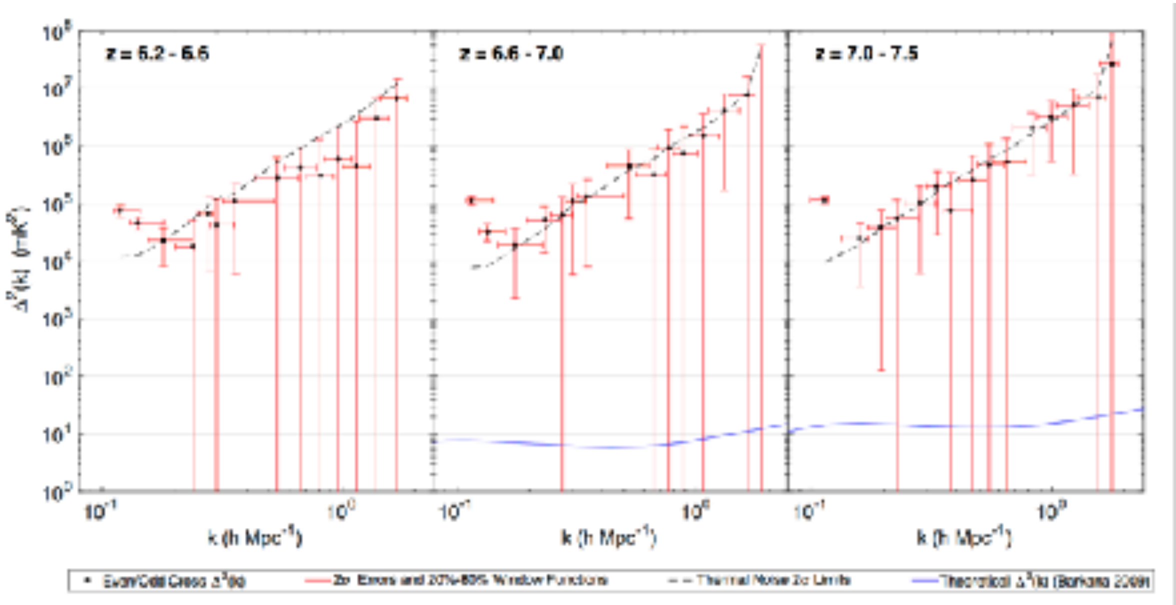
Sample Variance per cell + Noise Variance per cell

Current 21-cm Power-Spectrum Detection Experiments



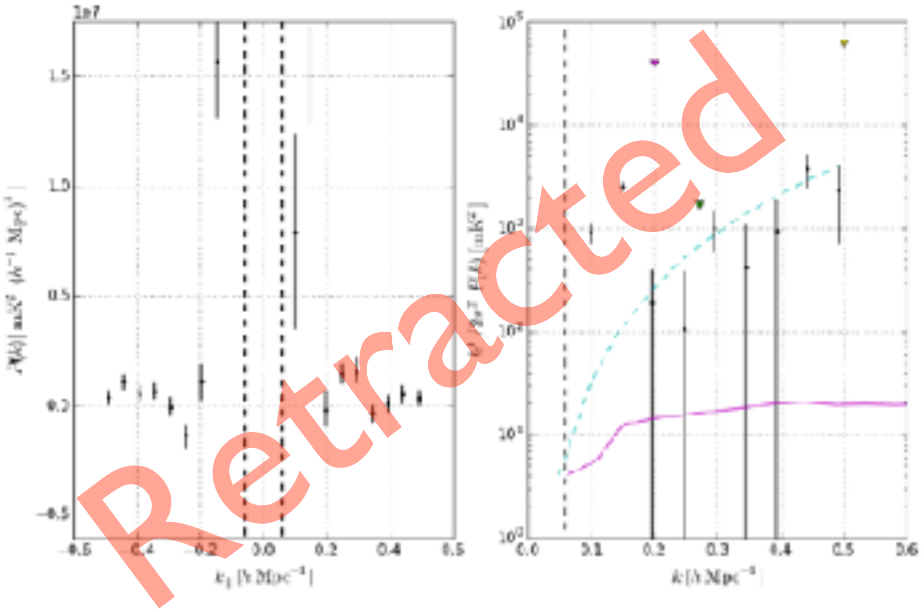
GMRT: Measurement of a 2σ upper limit of Δ(k) < 248 mK for $k = 0.50\ h\ \mathrm{Mpc}^{-1}$ at $z = 8.6$.

Paciga et al. 2013



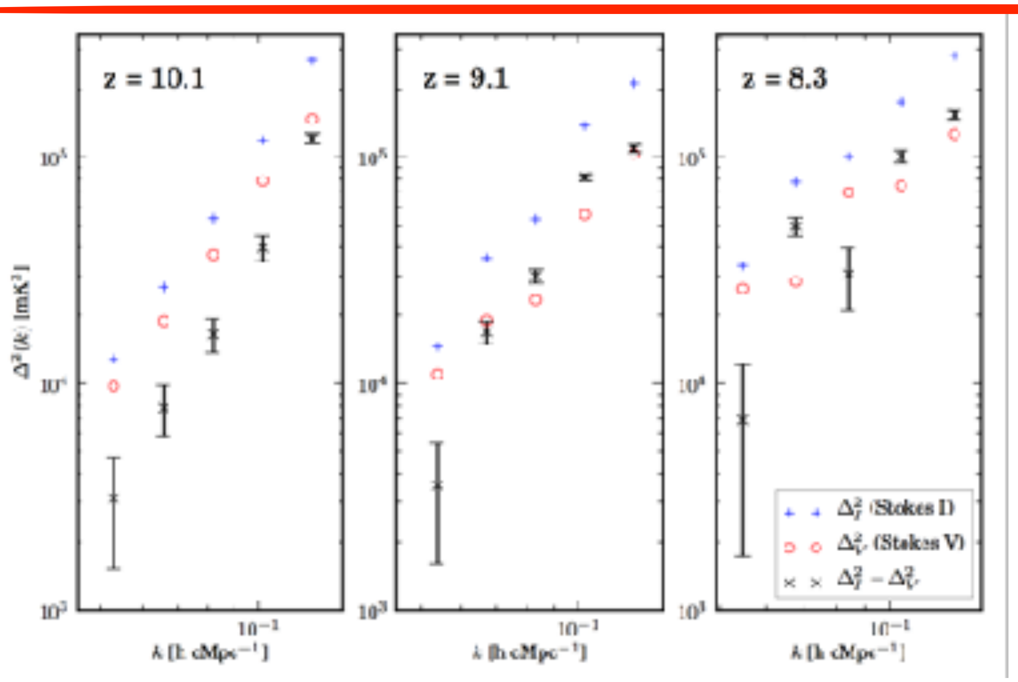
MWA-128T: Upper limits on the power spectrum from z = 6.2 to z = 7.5. The lowest limit is Δ(k) < 192 mK at 95% confidence at a co-moving scale $k = 0.18\ \mathrm{Mpc}^{-1}$ at $z = 6.8$.

Dillon et al. 2015



PAPER 64-antenna: A best 2σ upper limit of Δ(k) < 22 mK for $k = 0.15\text{-}0.5\ h\ \mathrm{Mpc}^{-1}$ at $z = 8.4$.

Ali et al. 2015



LOFAR: Measurement of a 2σ upper limit of Δ(k) < 80 mK for $k = 0.05\ h\ \mathrm{Mpc}^{-1}$ at $z = 10.1$.

Patil et al. 2017

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The LOFAR Epoch of Reionization (EoR) Key Science Project (status update)

Where do we stand at the moment and what keeps us busy?

Joint Colloquium, Bologna, Feb. 14, 2019

The Low Frequency Array

LOFAR is now a European telescope with its core in the Northern Netherlands, developed by ASTRON+Dutch Universities

(ILT Members: Netherlands, Germany, UK, France, Sweden, Poland, Ireland, Estonia, ***Italy****; interests in Spain, Austria+Ukraine)*

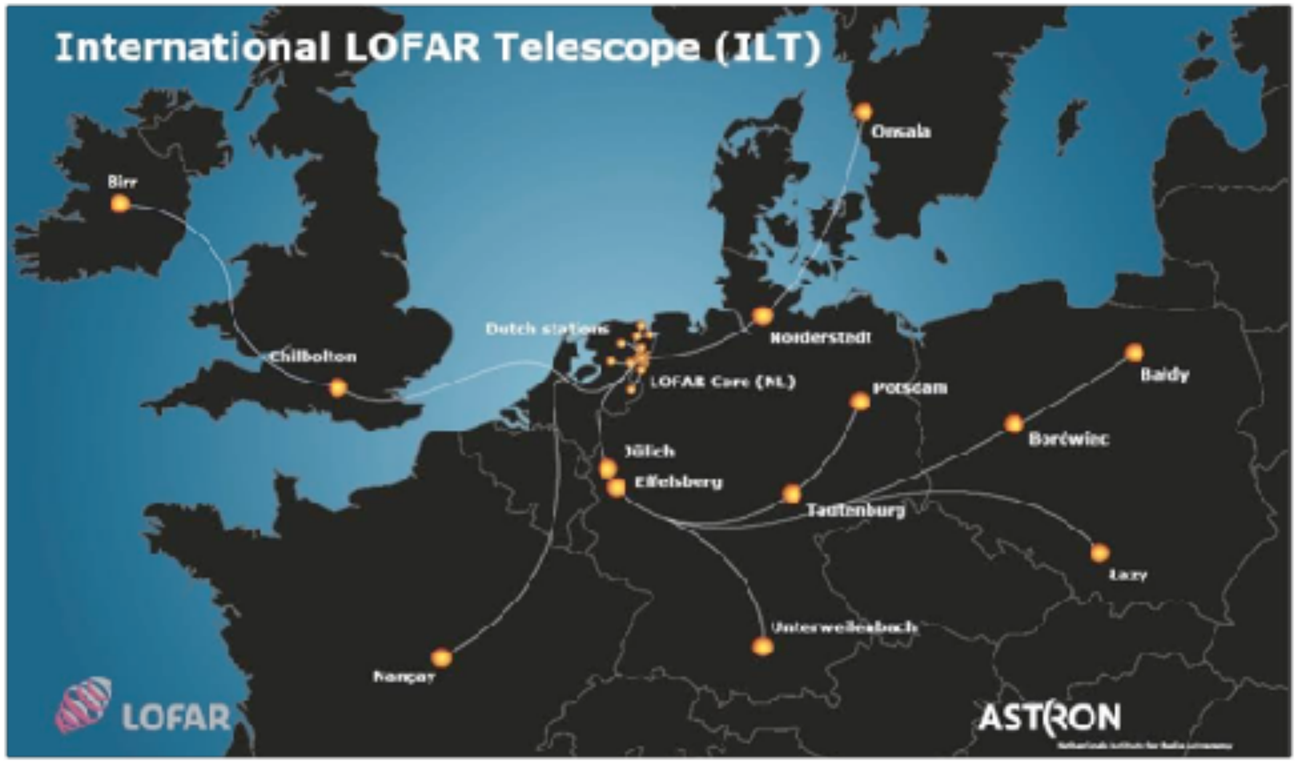
Core	3 km	(2x)24	stations
NL	80 km	14	stations
Europe	>1000 km	12	stations

Stations have 24 – 48 – 96 antennas/tiles

Principle of Aperture Synthesis
Array resolution: sub-arcsec to degrees

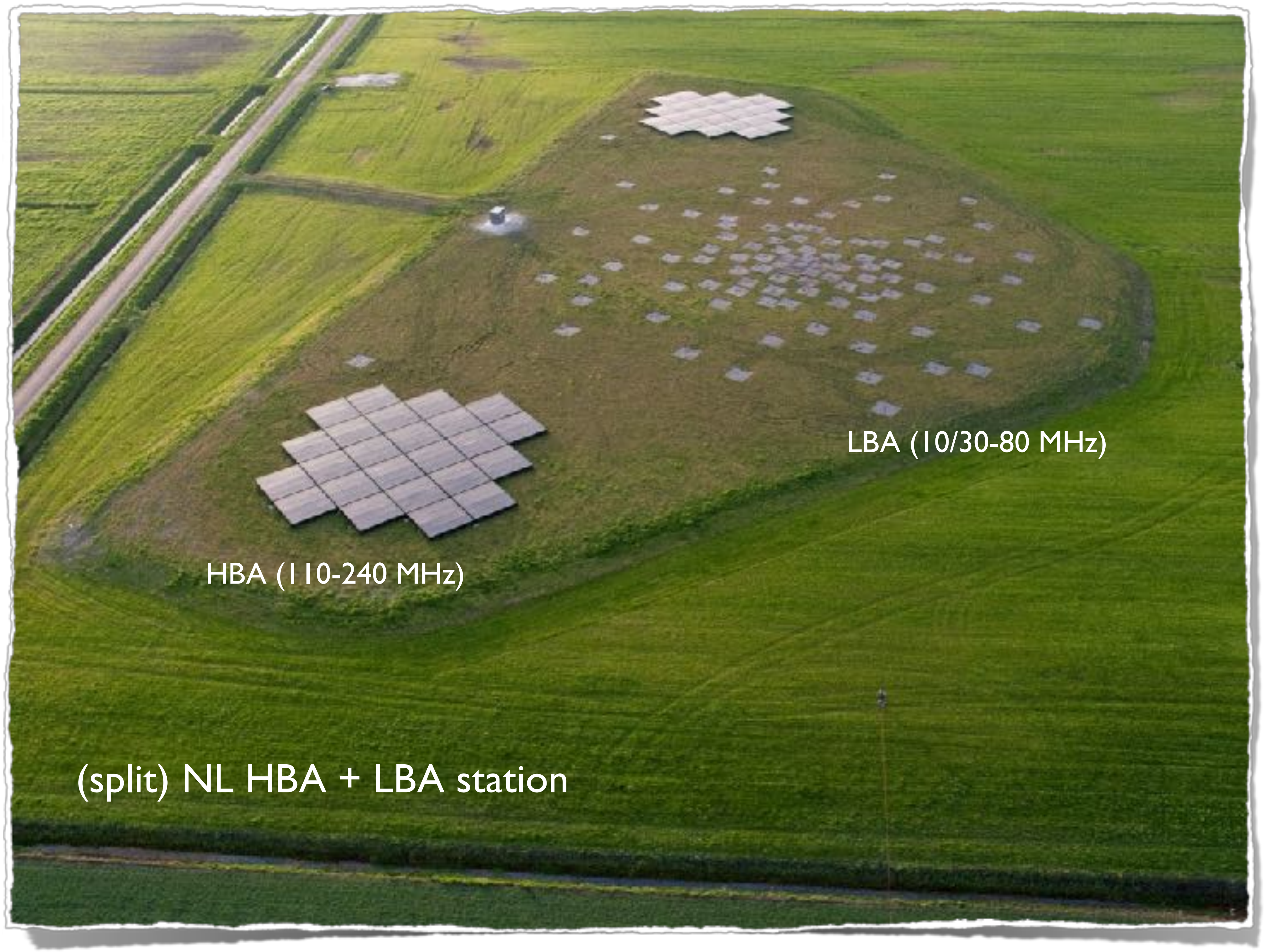
Pulsars: tied-array(s), (in)coherent sums

Sensitivity (8h, 4 MHz, Core/all NL stations)
@ 60 MHz ~ 6.2/3.9 mJy (LBA)
@ 150 MHz ~ 310/240 μJy (HBA)



van Haarlem et al. 2013

The Low Frequency Array



LBA (10/30-80 MHz)

HBA (110-240 MHz)

(split) NL HBA + LBA station

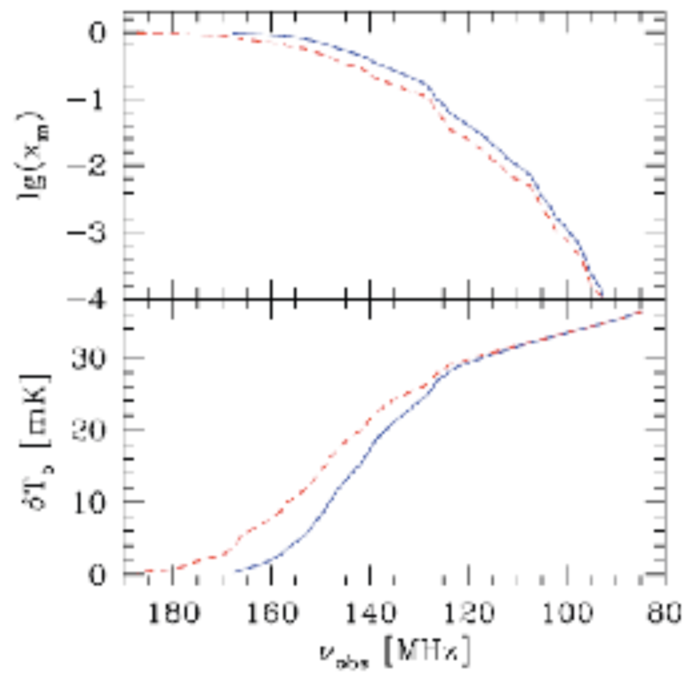
The Low Frequency Array

“Superterp” aka “Six-pack”
6 densely packed stations

LOFAR from Space

LOFAR from Space

LOFAR EoR KSP: Goals



Signal Variance

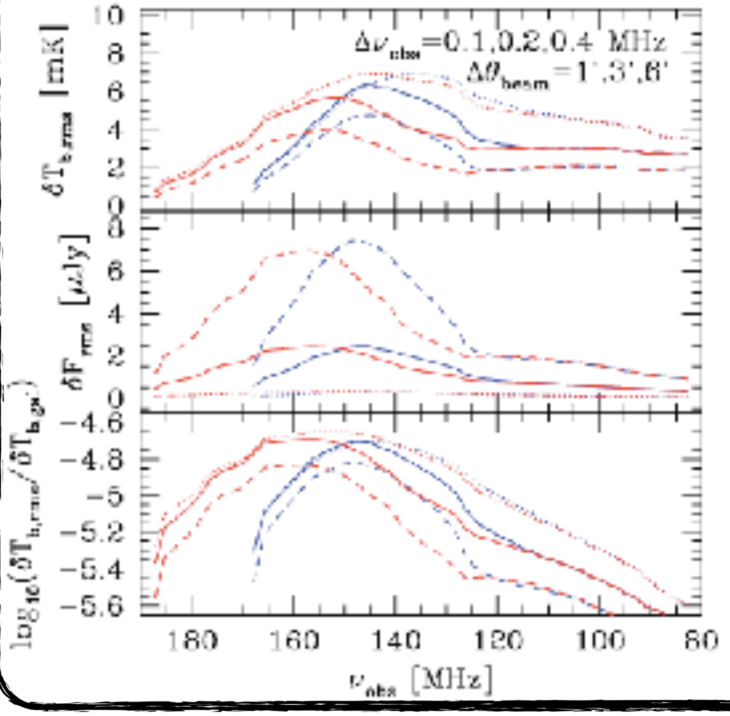
Key Questions
versus
Observations

When/how did reionization occur?

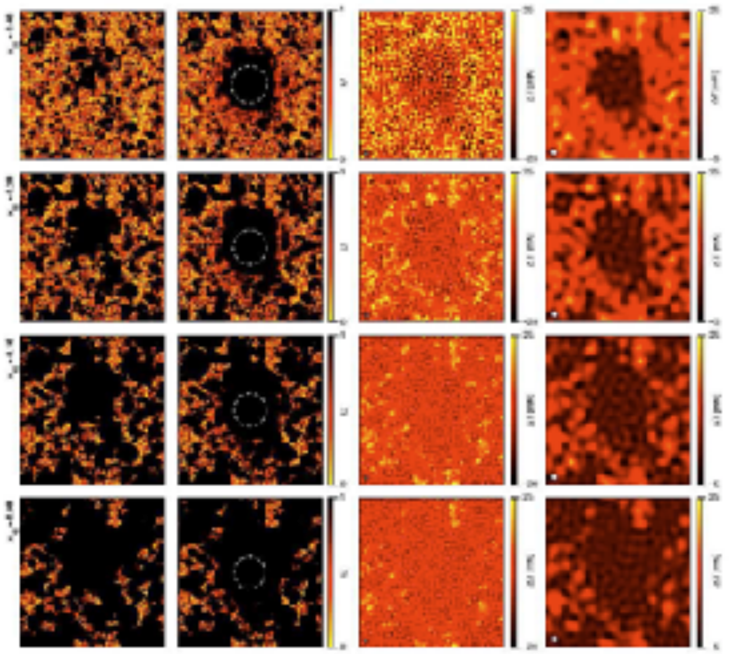
Which sources (Pop II/III stars or quasars/IMBHs) were responsible?

How did these first sources form?

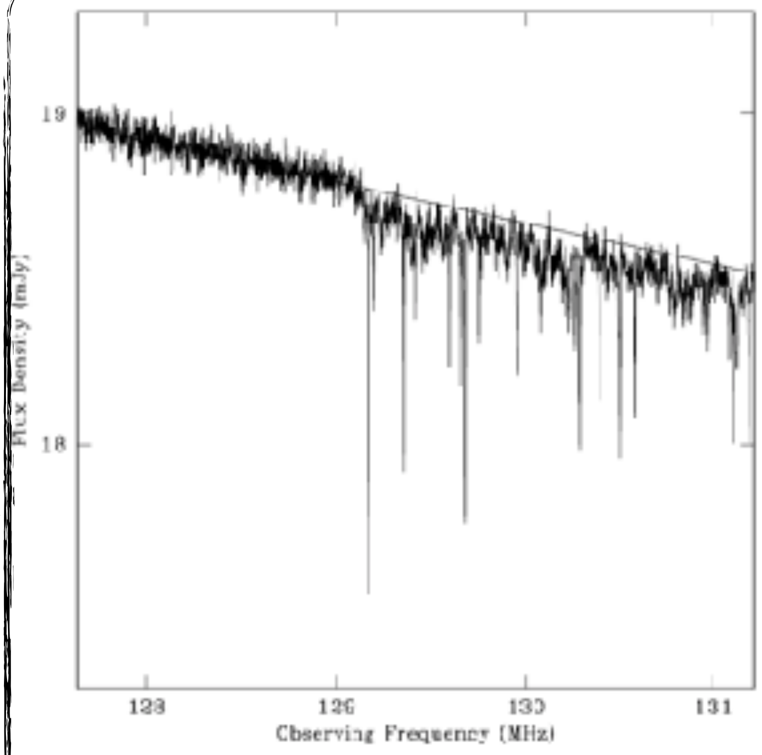
What was their impact & feedback on the IGM/ISM?



Power-Spectra



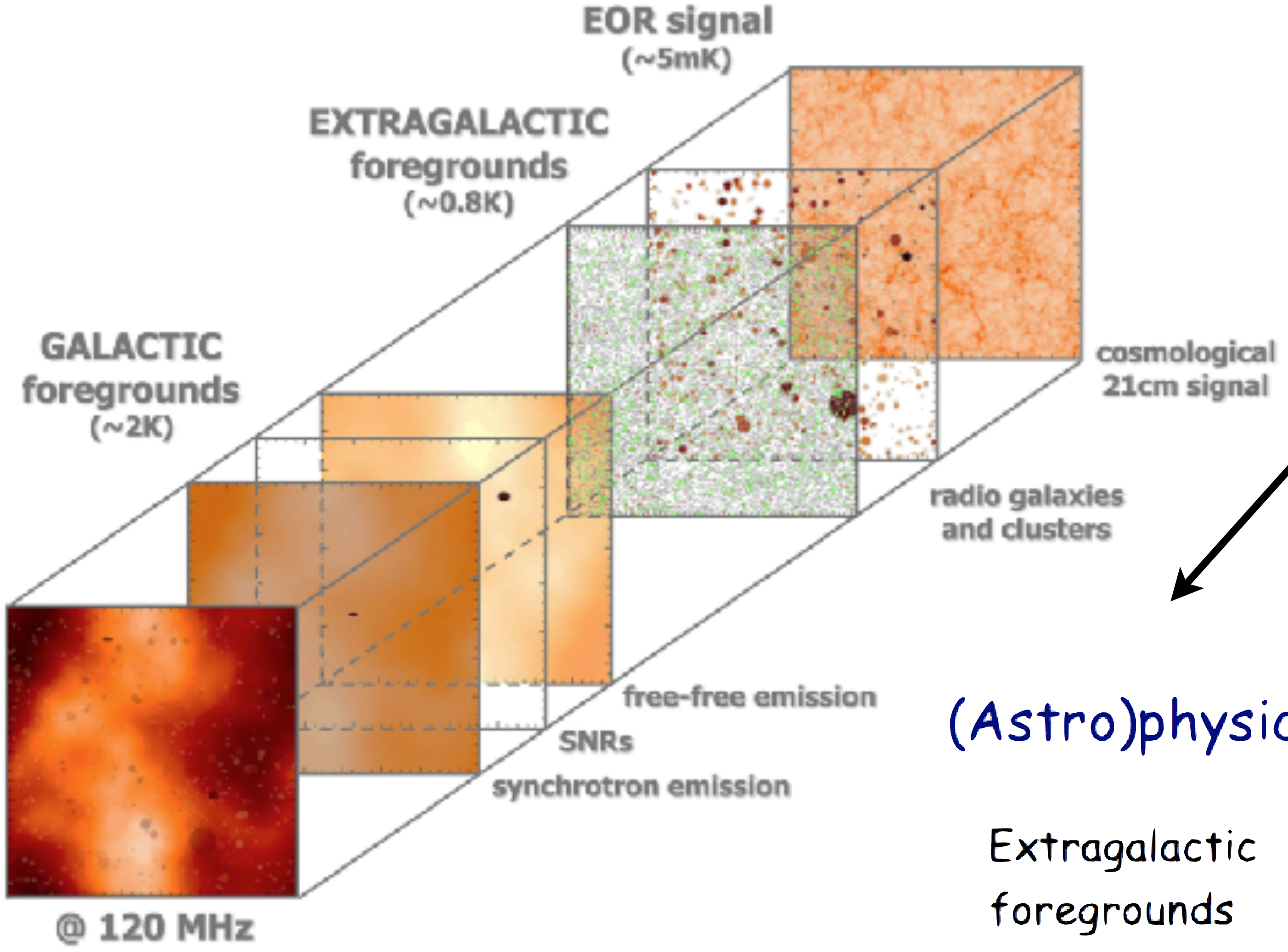
Strömgren Bubbles

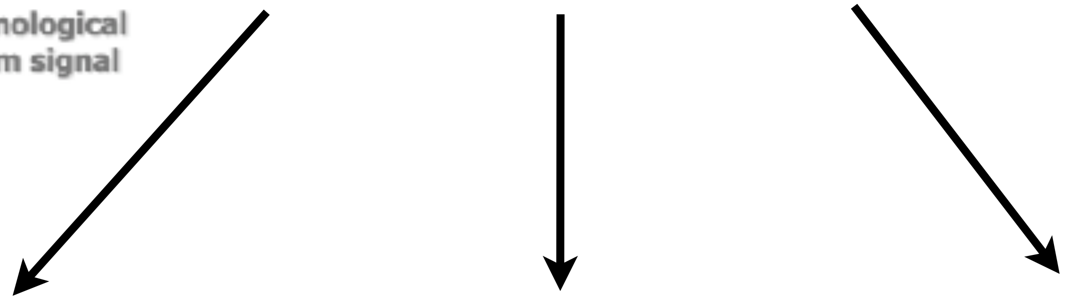


HI Absorption

LOFAR 21-cm signal Detection Challenges

Detecting the CMB is hard, but detecting the 21-cm signal is even harder!!





Many Challenges

(Astro)physical

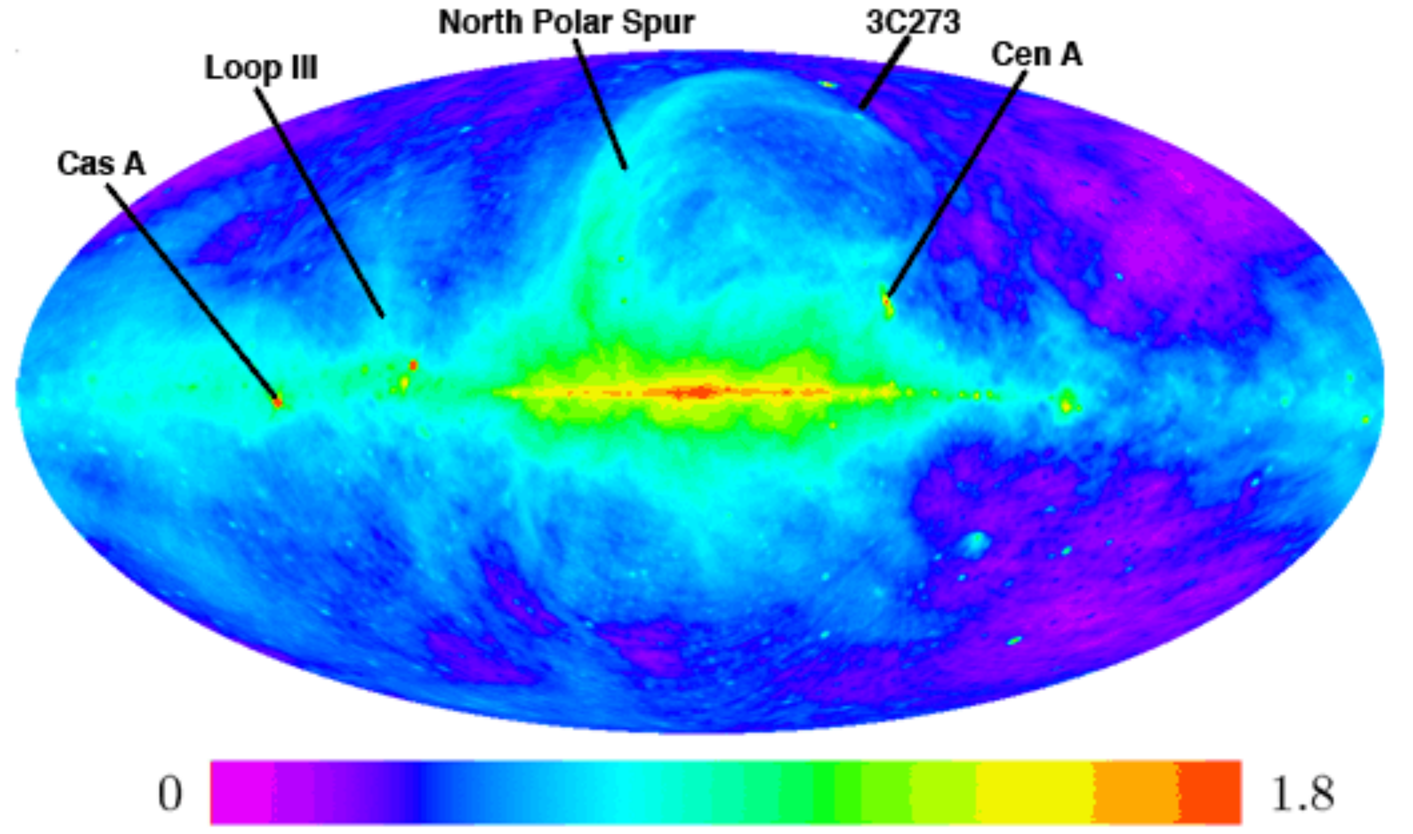
Extragalactic foregrounds
Galactic foregrounds
Ionosphere
Interference
Polarized emission
Variability

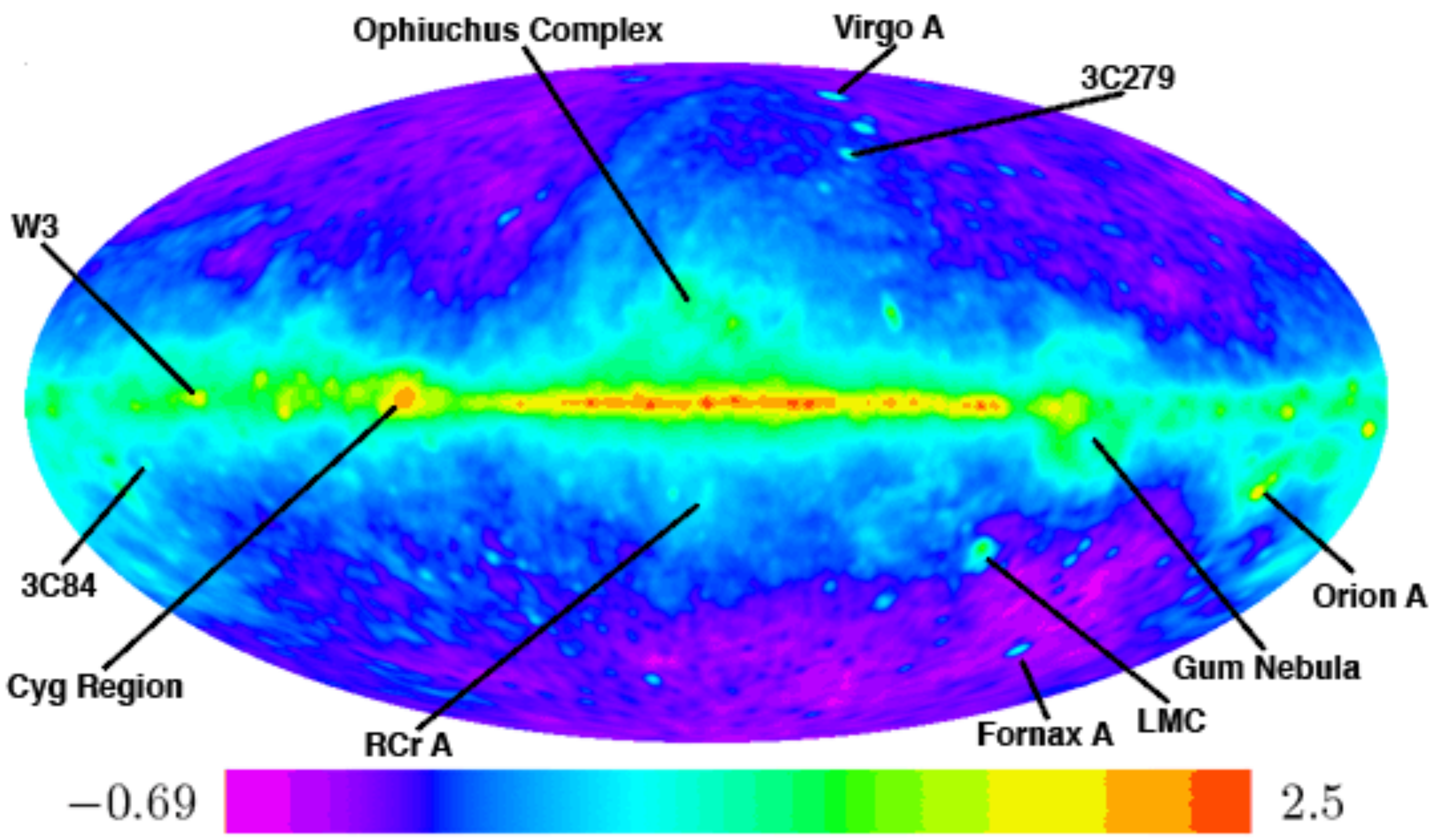
Instrumental

Beam stability
Sensitivity
Dynamic Range
UV Coverage
Calibratability
...

Computational

Large data rate
~1 Pb raw data
(Non) linear optim. of coupled equations
10s Tflop*year
...





Foregrounds

Main challenge

The radio sky is extremely bright (few x $10^{2\text{-}3}$ K):

- Diffuse (polarised) emission of the Milky Way
- Compact extra-galactic sources

The 21-cm signal is few x 10^{-3} K

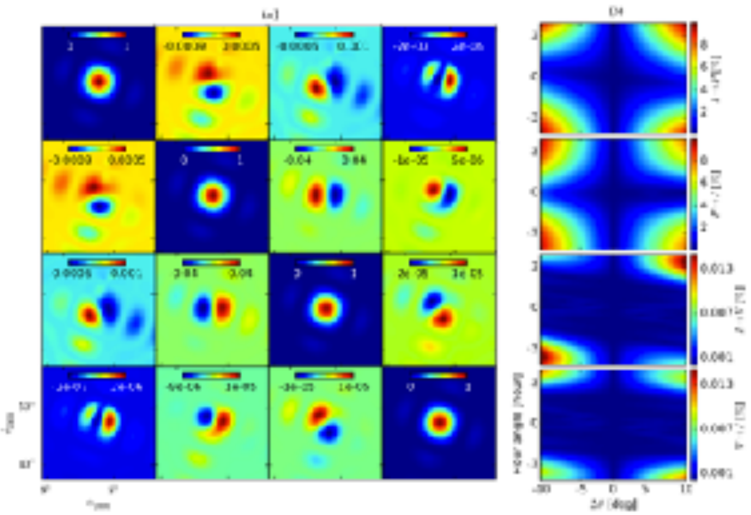
We need to remove the bright "foregrounds" from the 21-cm signal.

Luckily: Foreground as spectral smooth 21-cm signal fluctuates spectrally.

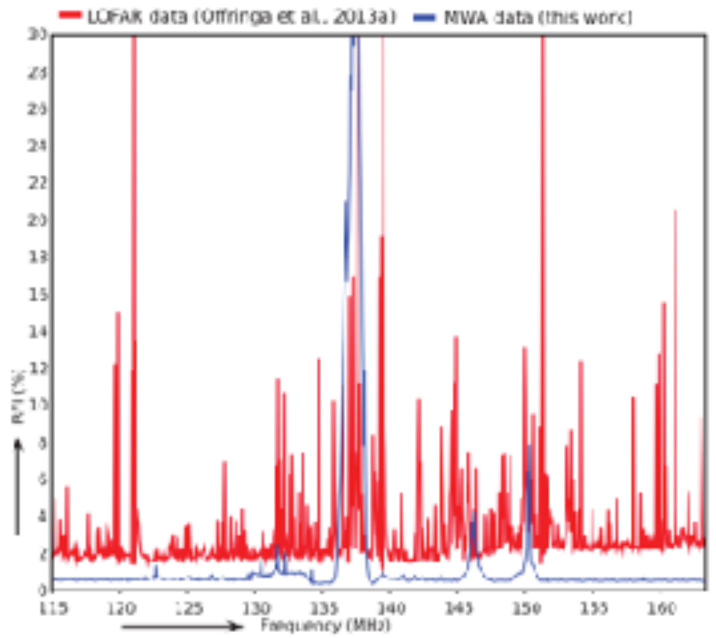
Many Other Challenges

- Ionospheric refraction/diffraction
- Radio Frequency Interference
- Beam/Band-pass calibration
- Polarisation leakage from Q/U <=> I

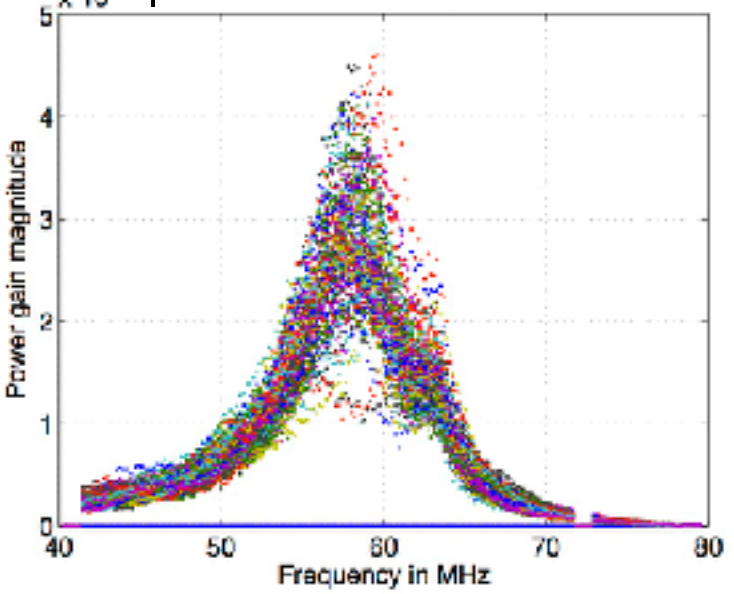
The instrument is polarised

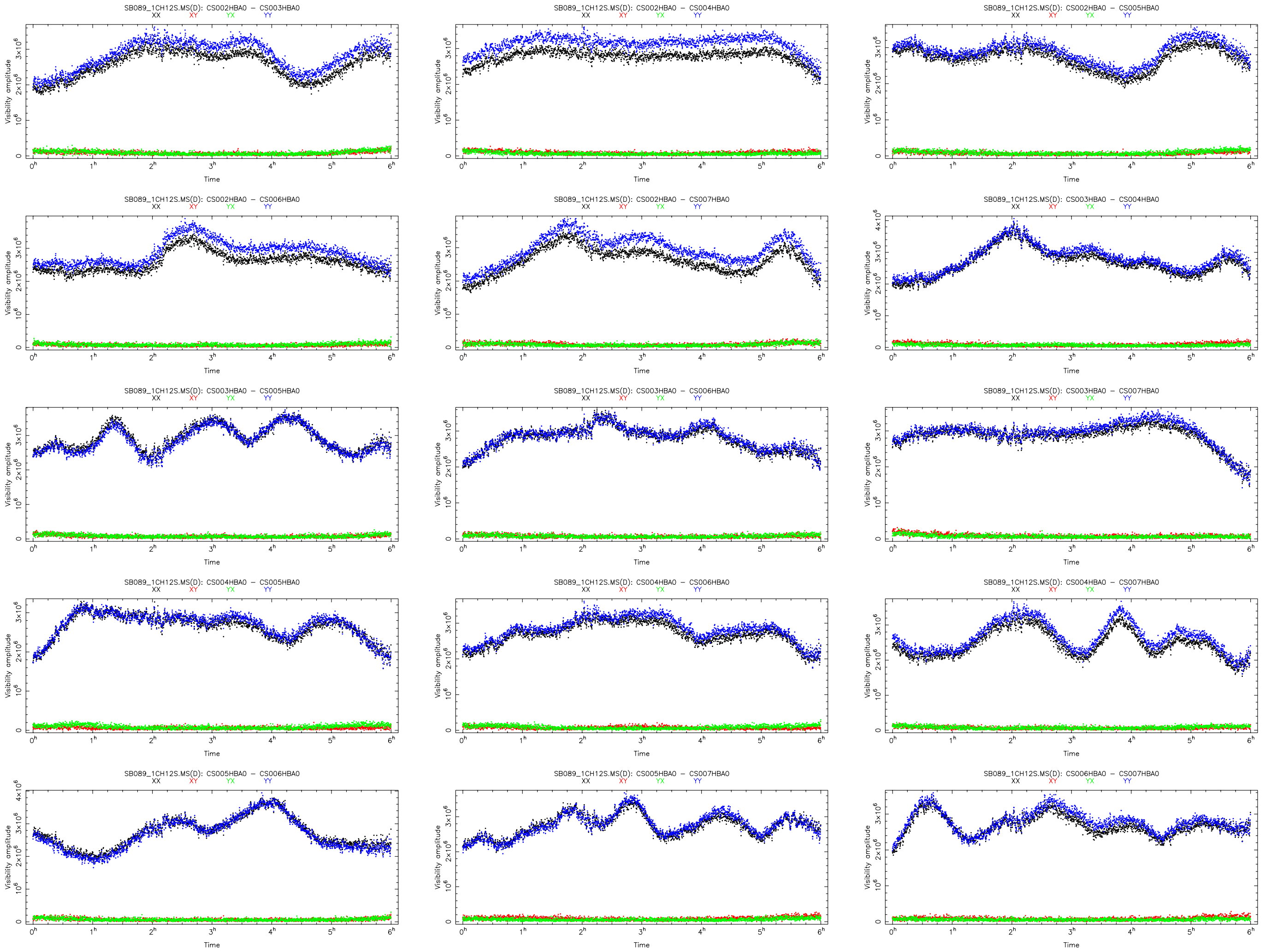


Even the best sites have RFI



Band/pass and beam are not the same





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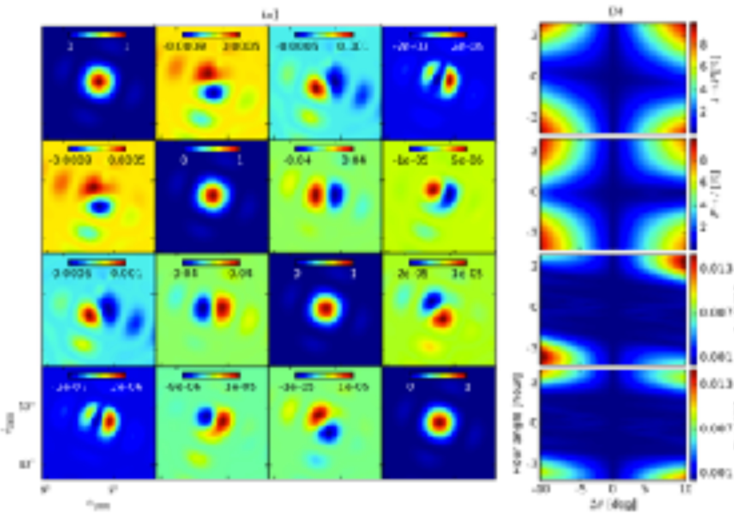

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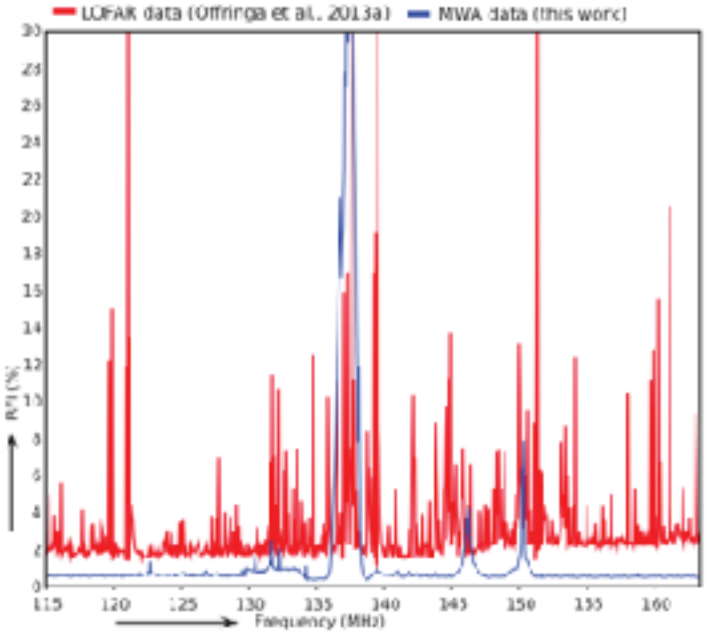

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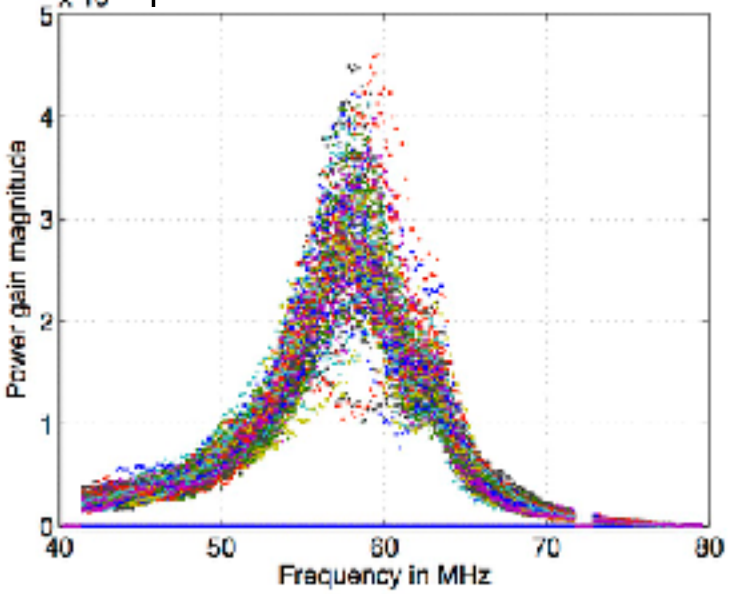
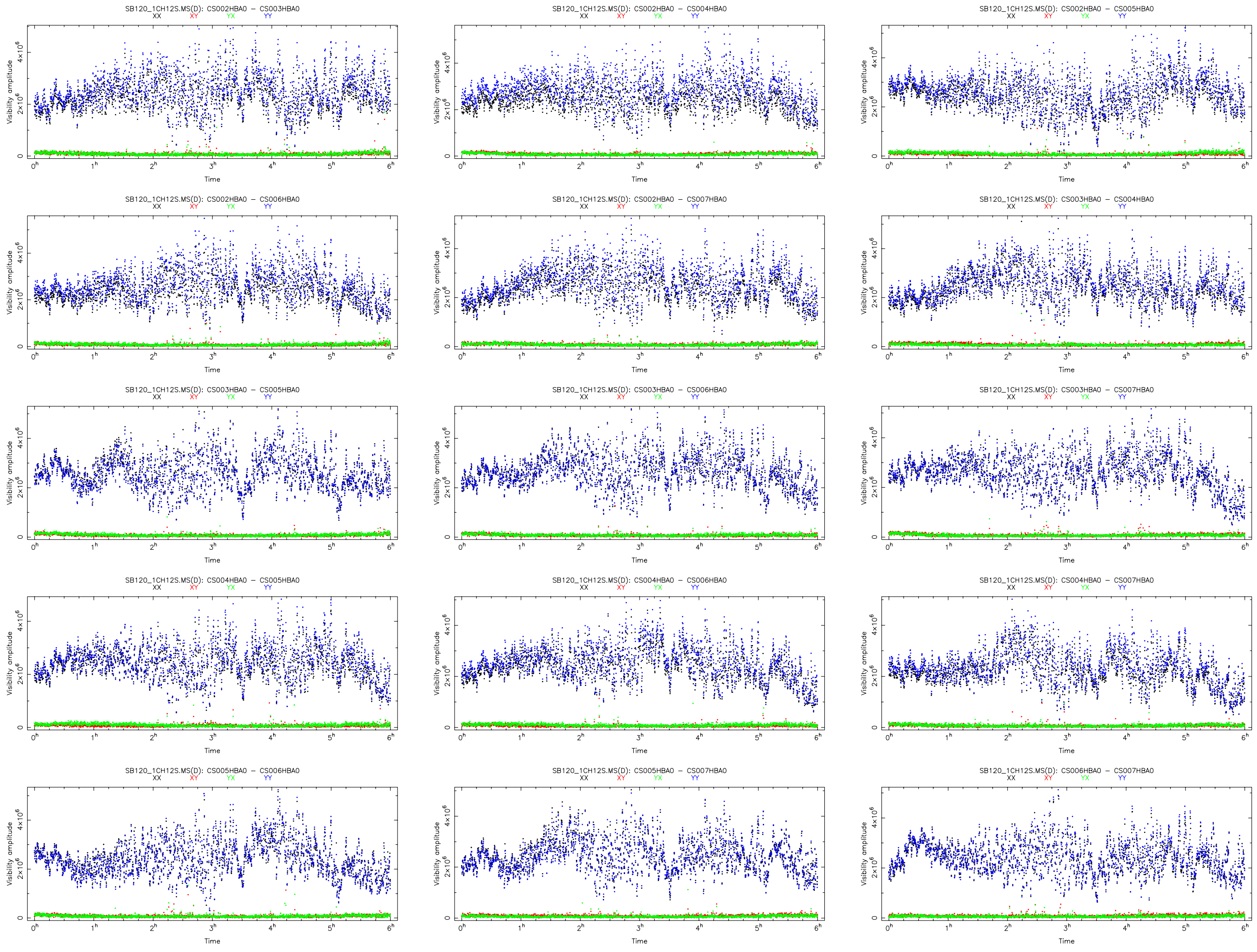




LOFAR-HBA NCP — Data Products

- Night-time observing, elevation > 50°
- Frequency range 115-190 MHz (Cycle 6: 2-3 beams x 32MHz; Cycle 8-9: 7 beams x 12 MHz on NCP→"Fast track")
- Time/spectral resolution: 2s, 3.2kHz
- Raw data volume: 20 - 70 TB / night

Currently 1st stage processing ongoing
(RFI flagging, averaging, initial calibration, imaging)

✓ ~2200 hrs on NCP
✓ ~1100 hrs on 3C196
✓ ~250hrs out of 1000 hrs awarded on NCP with AARTFAAC/LBA

>5 PB on disk

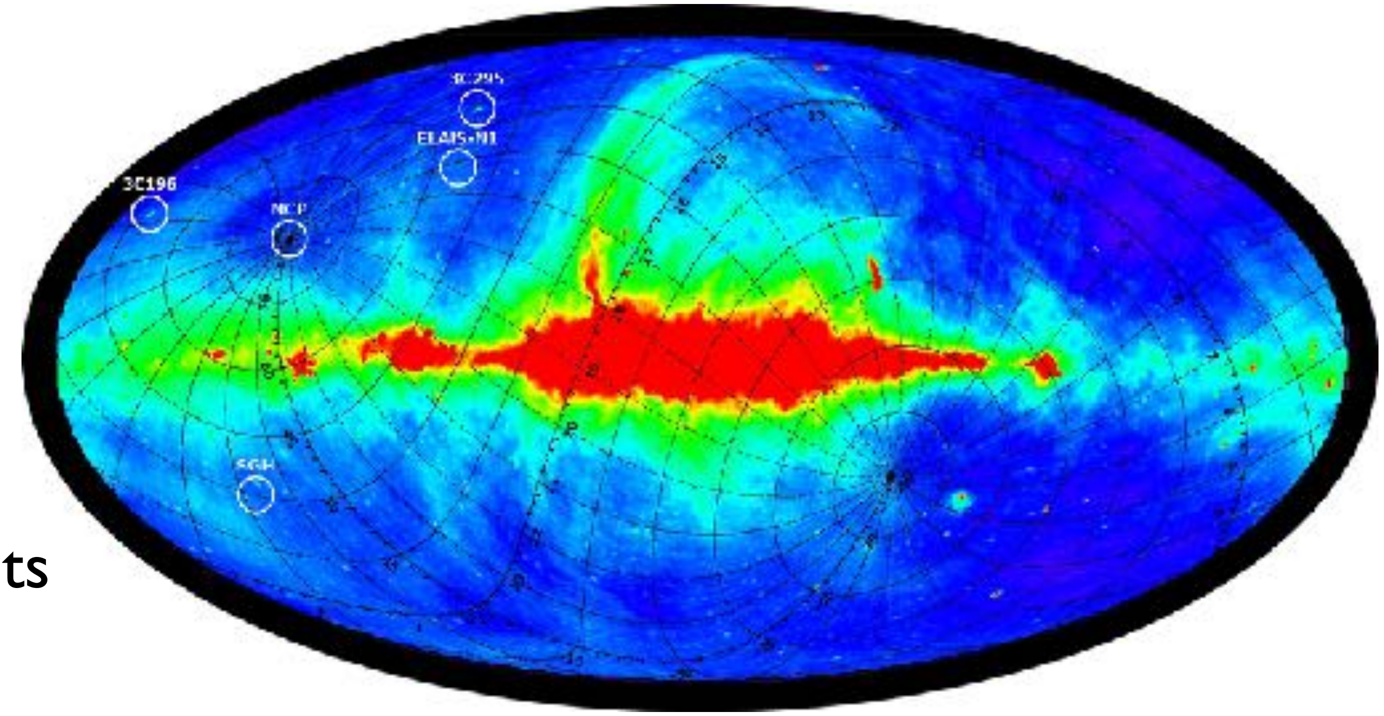
- NCP: constant beam, all-year observable
- 3C196: bright, compact, wintertime

- 2-3 other windows for various other projects

LOFAR spectral capabilities:

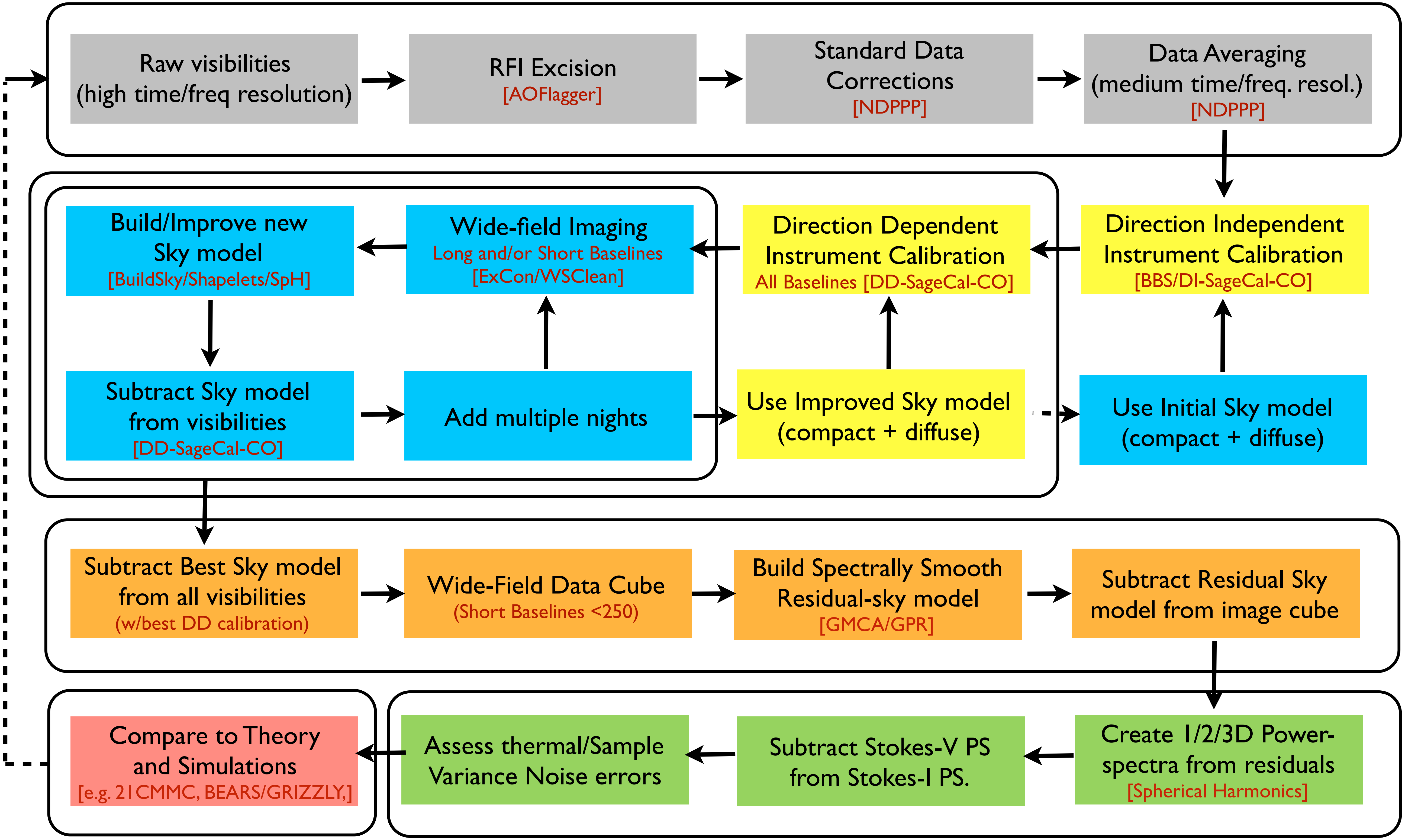
- 8-bit mode 488 sub-bands
- 1sub-band = 0.195 MHz
- 96 MHz total bandwidth

One sub-band can have up to 256 ch. We opted to store 64 ch. max. We analyse 3-ch. data (~60kHz).



LOFAR EoR Data-Processing Flow Diagram

Nearly all processing software has been developed in house by our team.



Raw visibilities (high time/freq resolution)

RFI Excision [AOFlagger]

Standard Data Corrections [NDPPP]

Data Averaging (medium time/freq. resol.) [NDPPP]

Direction Independent Instrument Calibration [BBS/DI-SageCal-CO]

Use Initial Sky model (compact + diffuse)

Direction Dependent Instrument Calibration All Baselines [DD-SageCal-CO]

Use Improved Sky model (compact + diffuse)

Wide-field Imaging Long and/or Short Baselines [ExCon/WSClean]

Build/Improve new Sky model [BuildSky/Shapelets/SpH]

Subtract Sky model from visibilities [DD-SageCal-CO]

Add multiple nights

Subtract Best Sky model from all visibilities (w/best DD calibration)

Wide-Field Data Cube (Short Baselines <250)

Build Spectrally Smooth Residual-sky model [GMCA/GPR]

Subtract Residual Sky model from image cube

Create 1/2/3D Power-spectra from residuals [Spherical Harmonics]

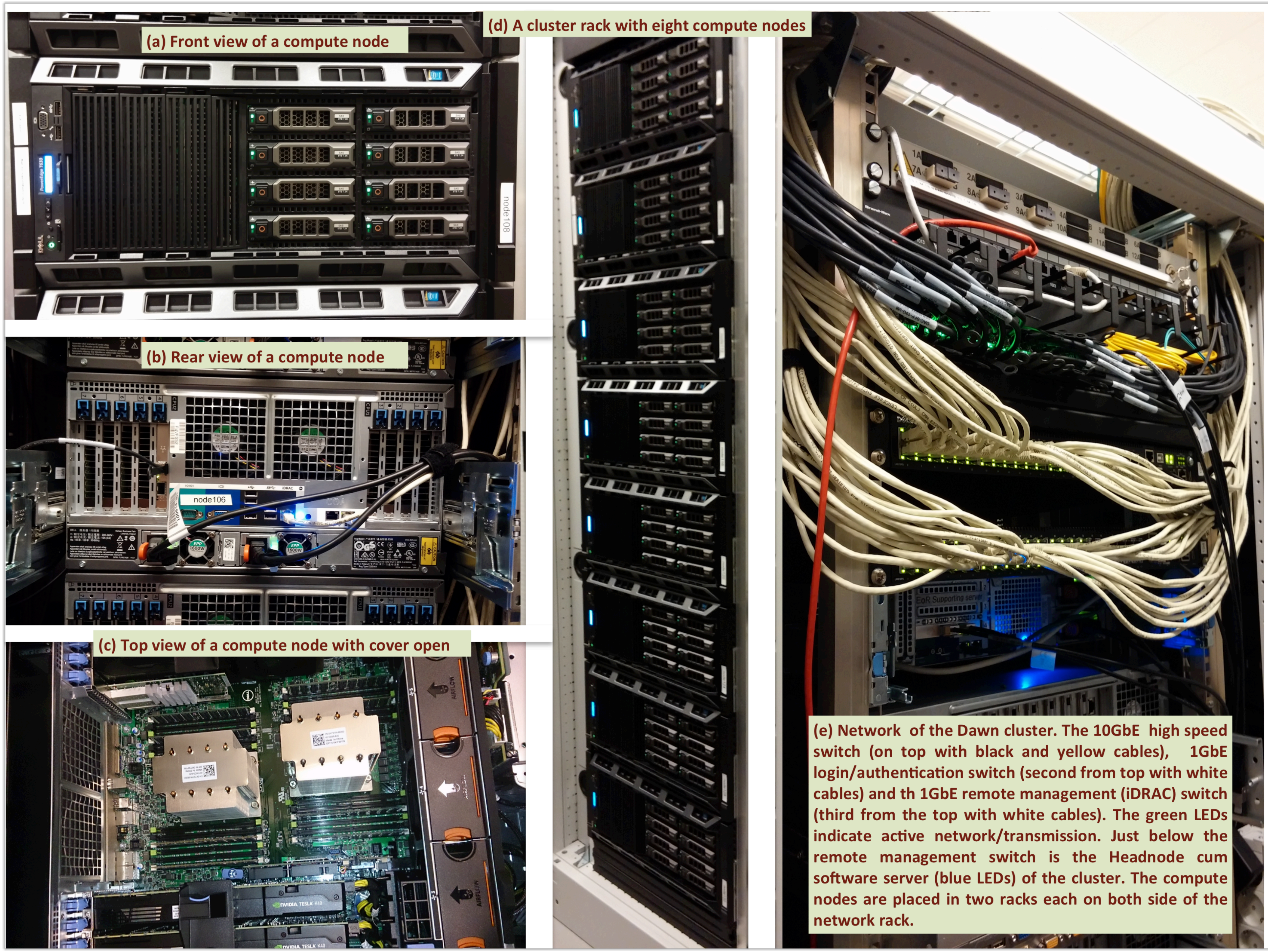
Subtract Stokes-V PS from Stokes-I PS.

Assess thermal/Sample Variance Noise errors

Compare to Theory and Simulations [e.g. 21CMMC, BEARS/GRIZZLY,]

LOFAR EoR-KSP GPU HPC Cluster: “*Dawn*”

Hard-core number crunching on a dedicated GPU-based cluster in Groningen.



(a) Front view of a compute node

(b) Rear view of a compute node

(c) Top view of a compute node with cover open

(d) A cluster rack with eight compute nodes

(e) Network of the Dawn cluster. The 10GbE high speed switch (on top with black and yellow cables), 1GbE login/authentication switch (second from top with white cables) and th 1GbE remote management (iDRAC) switch (third from the top with white cables). The green LEDs indicate active network/transmission. Just below the remote management switch is the Headnode cum software server (blue LEDs) of the cluster. The compute nodes are placed in two racks each on both side of the network rack.

32 nodes in
four 19” racks
(K40)
32x4 GPU
32x48 (HT) cores

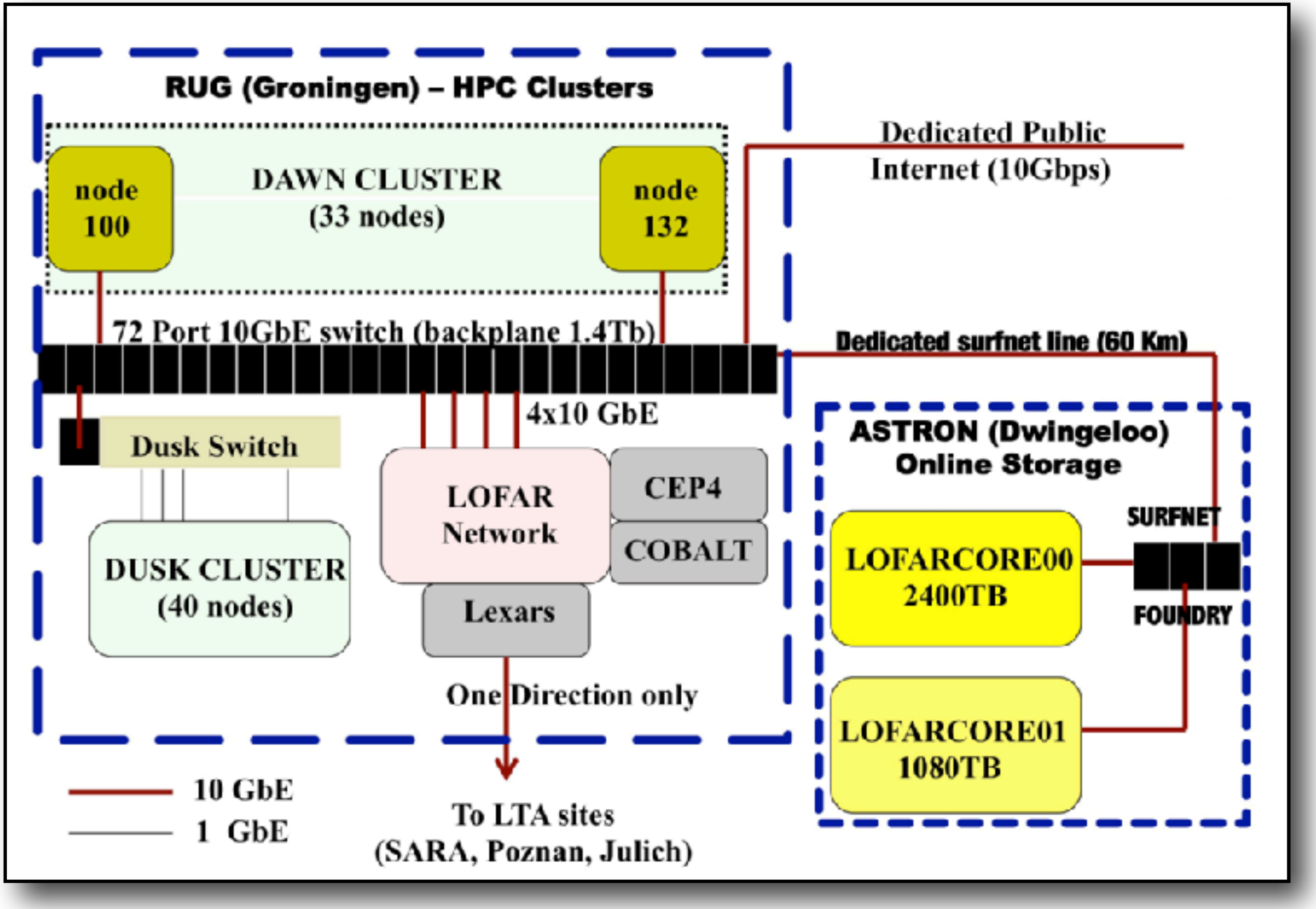
0.6/0.2 Petaflops
in GPU power

For details:

Pandey etal,
ASTRON
Newsletter
Dec 2015

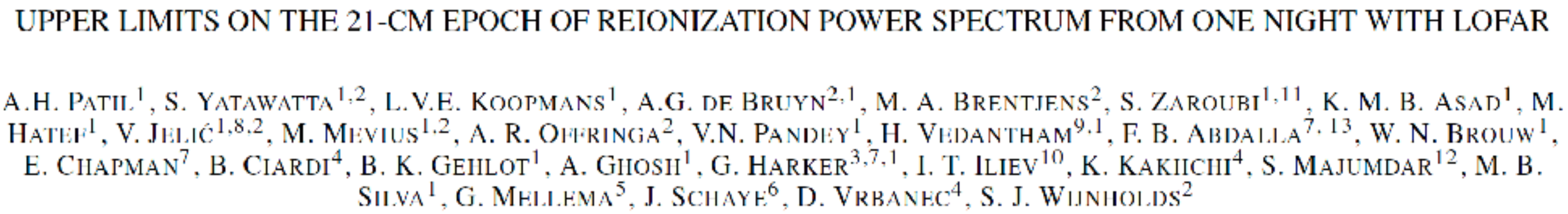
LOFAR EoR-KSP GPU HPC Cluster: *"Dawn"*

Cluster is connected to storage clusters and external world via 1-10Gb/s connections.



rijksuniversiteit groningen / faculteit wiskunde en natuurwetenschappen / kapteyn instituut

LOFAR EoR Upper Limits on the 21-cm Power-Spectrum during Reionization



UPPER LIMITS ON THE 21-CM EPOCH OF REIONIZATION POWER SPECTRUM FROM ONE NIGHT WITH LOFAR

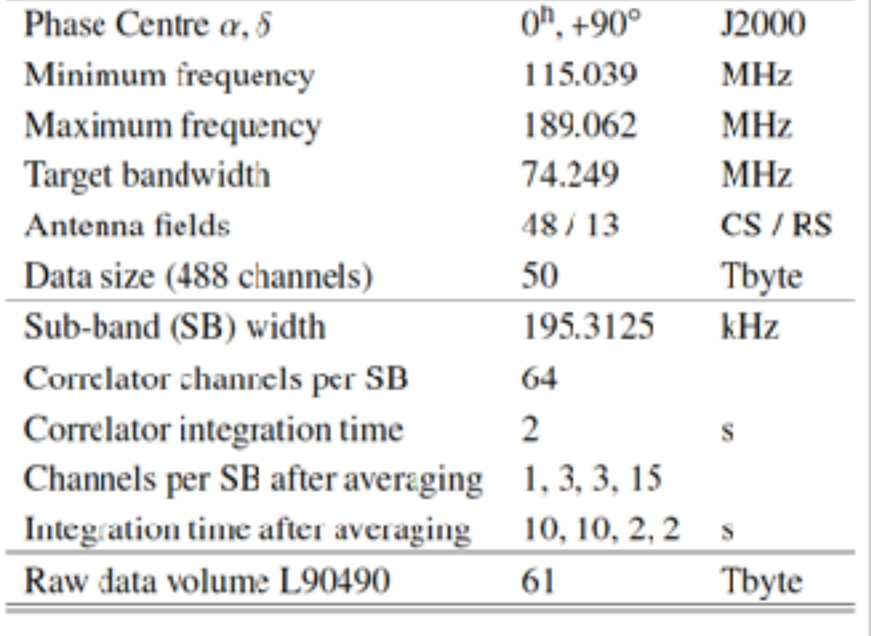
A.H. Patil[1], S. Yatawatta[1,2], L.V.E. Koopmans[1], A.G. de Bruyn[2,1], M. A. Brentjens[2], S. Zaroubi[1,11], K. M. B. Asad[1], M. Hatef[1], V. Jelić[1,8,2], M. Mevius[1,2], A. R. Offringa[2], V.N. Pandey[1], H. Vedantham[9,1], F. B. Abdalla[7,13], W. N. Brouw[1], E. Chapman[7], B. Ciardi[4], B. K. Gehlot[1], A. Ghosh[1], G. Harker[3,7,1], I. T. Iliev[10], K. Kakiichi[4], S. Majumdar[12], M. B. Silva[1], G. Mellema[5], J. Schaye[6], D. Vrbanec[4], S. J. Wijnholds[2]

Joint Colloquium, Bologna, Feb. 14, 2019

NCP Observations

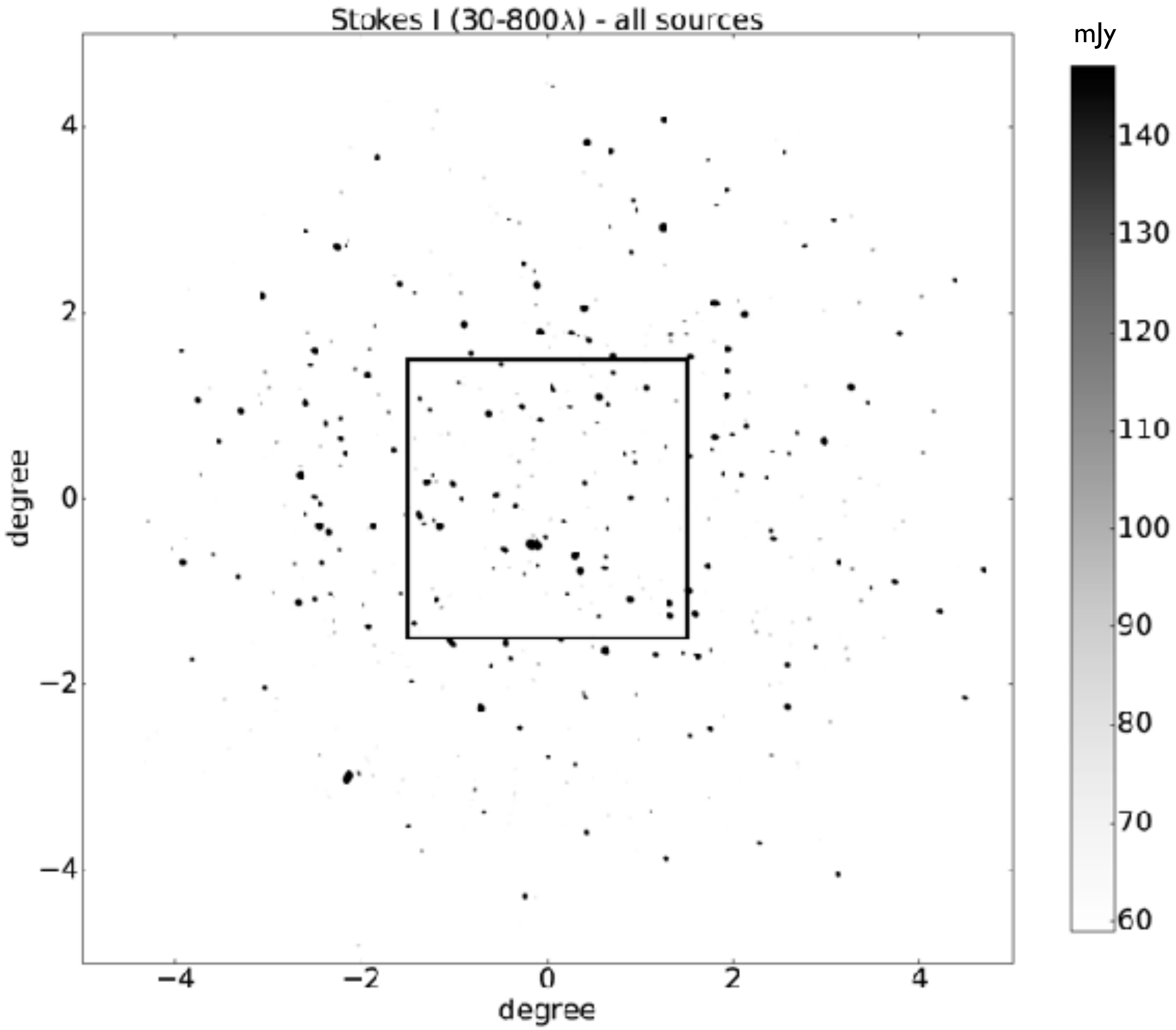
Results presented today are based on a single 13-hr run
taken 2nd Nov. 2013 @ 17:20:01 (UTC)

Observational and correlator set-up



Phase Centre α, δ	$0^h, +90^\circ$	J2000
Minimum frequency	115.039	MHz
Maximum frequency	189.062	MHz
Target bandwidth	74.249	MHz
Antenna fields	48 / 13	CS / RS
Data size (488 channels)	50	Tbyte
Sub-band (SB) width	195.3125	kHz
Correlator channels per SB	64	
Correlator integration time	2	s
Channels per SB after averaging	1, 3, 3, 15	
Integration time after averaging	10, 10, 2, 2	s
Raw data volume L90490	61	Tbyte

Patil et al. (2017, ApJ)



A continuum (134.5-137.5 MHz) LOFAR-HBA image of 10x10 deg2 centred on the North Celestial Pole (NCP) field. Baselines between 30-800 were included. No sources have been subtracted and the image is partially cleaned. The 3x3d box delineates the area where we measure the power spectra. The bright source to the lower-left of the box is 3C61.1. The units are mJy/PSF. Right Ascension (RA) 00h is towards the bottom and increases clockwise.

Deep Continuum Image of the NCP

Confusion limited images:

- BW=60 MHz
- 20° x 20° ; 3' FWHM PSF

Note that this image is the sky residual: the 28,000 bright(est) sources are removed after calibration in 122 direction, per station, per frequency channel, per ~20 min time interval.

All of this emission, should be spectrally smooth, otherwise one would not be able to detect the EoR 21-cm signal.

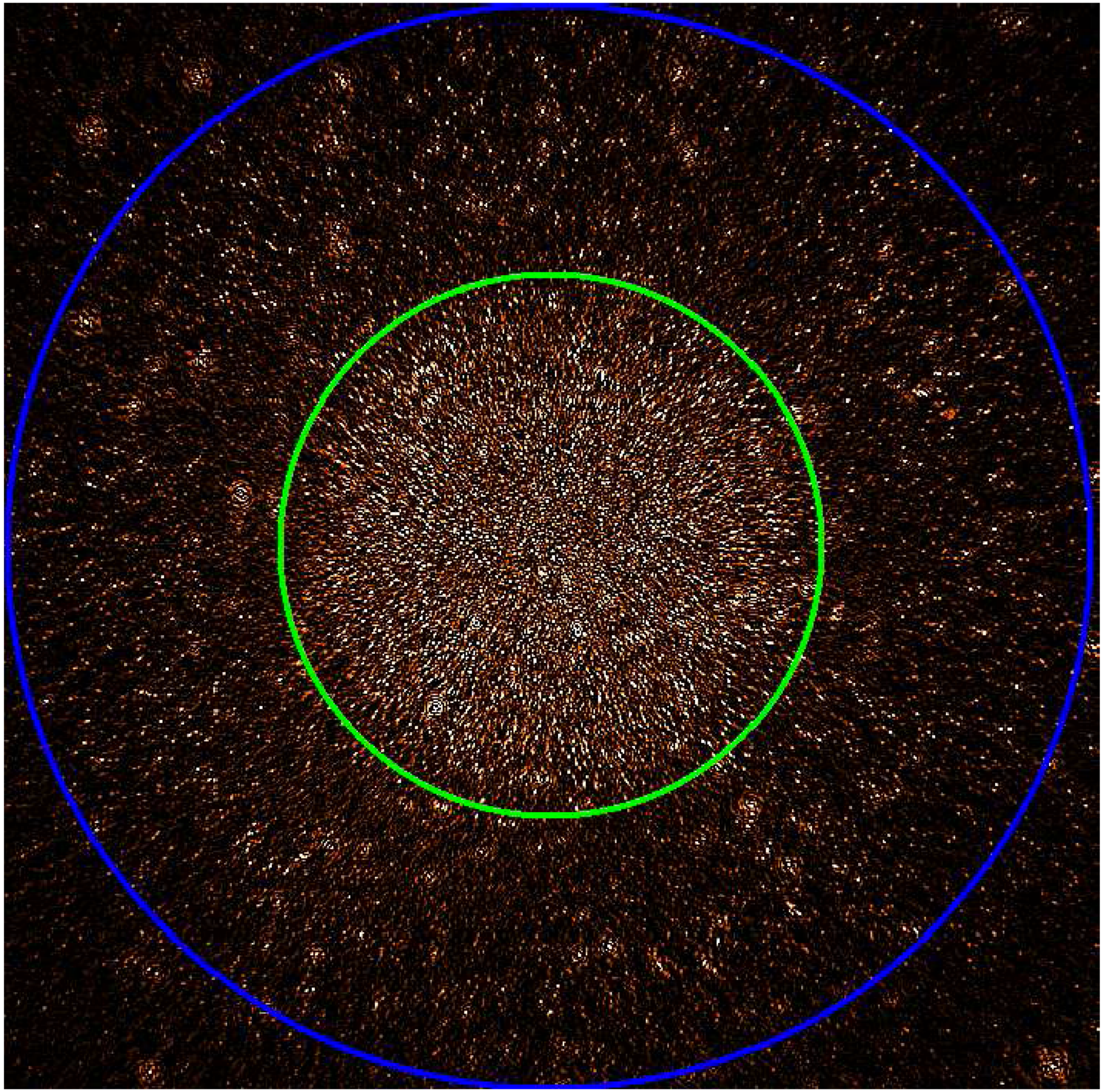
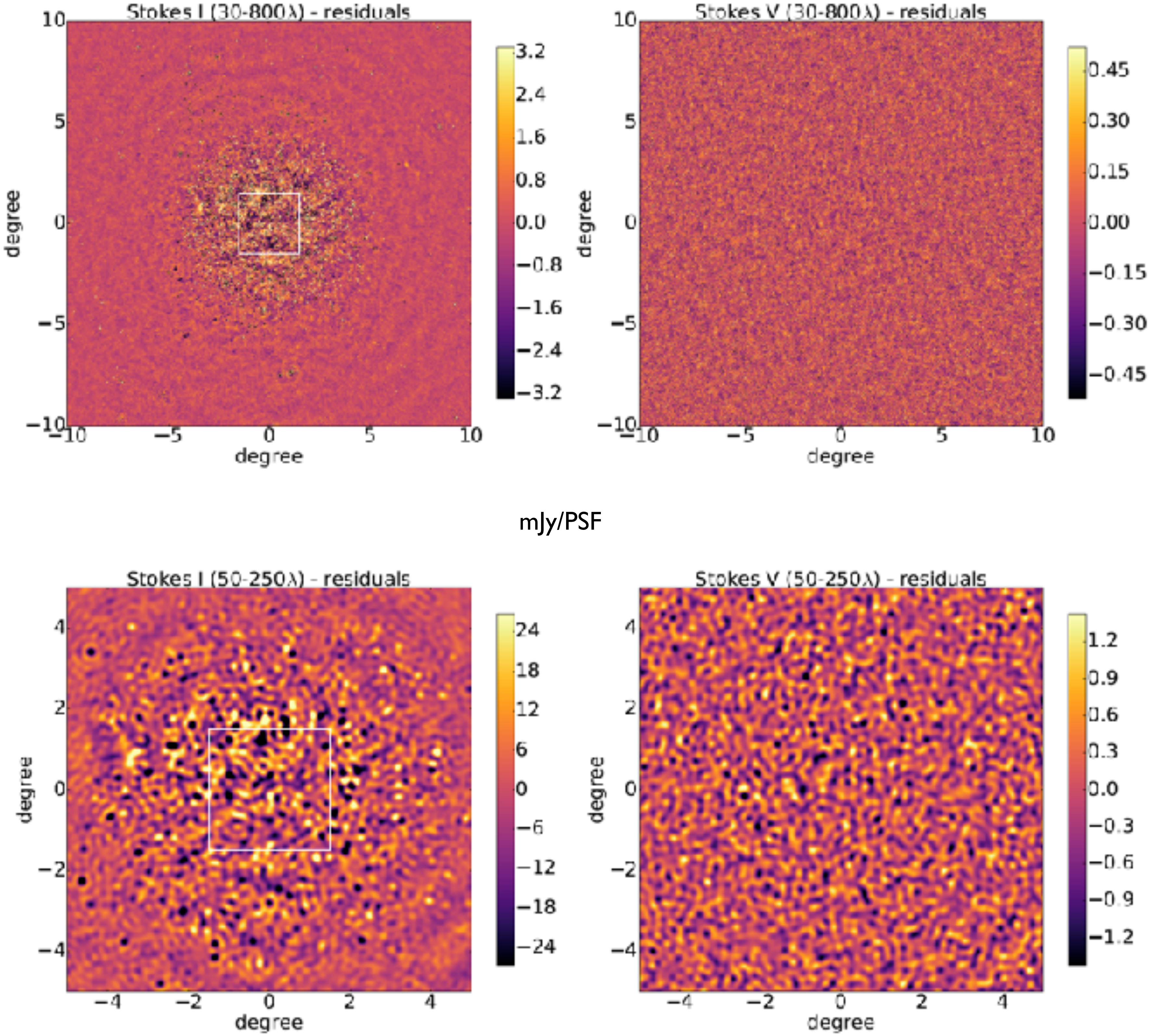


Image Credit: Pandey

NCP Residuals after Sky-Model Subtraction



Top images shows 20x20d FoV in Stokes I (left) and V (right) with 3’ resolution.

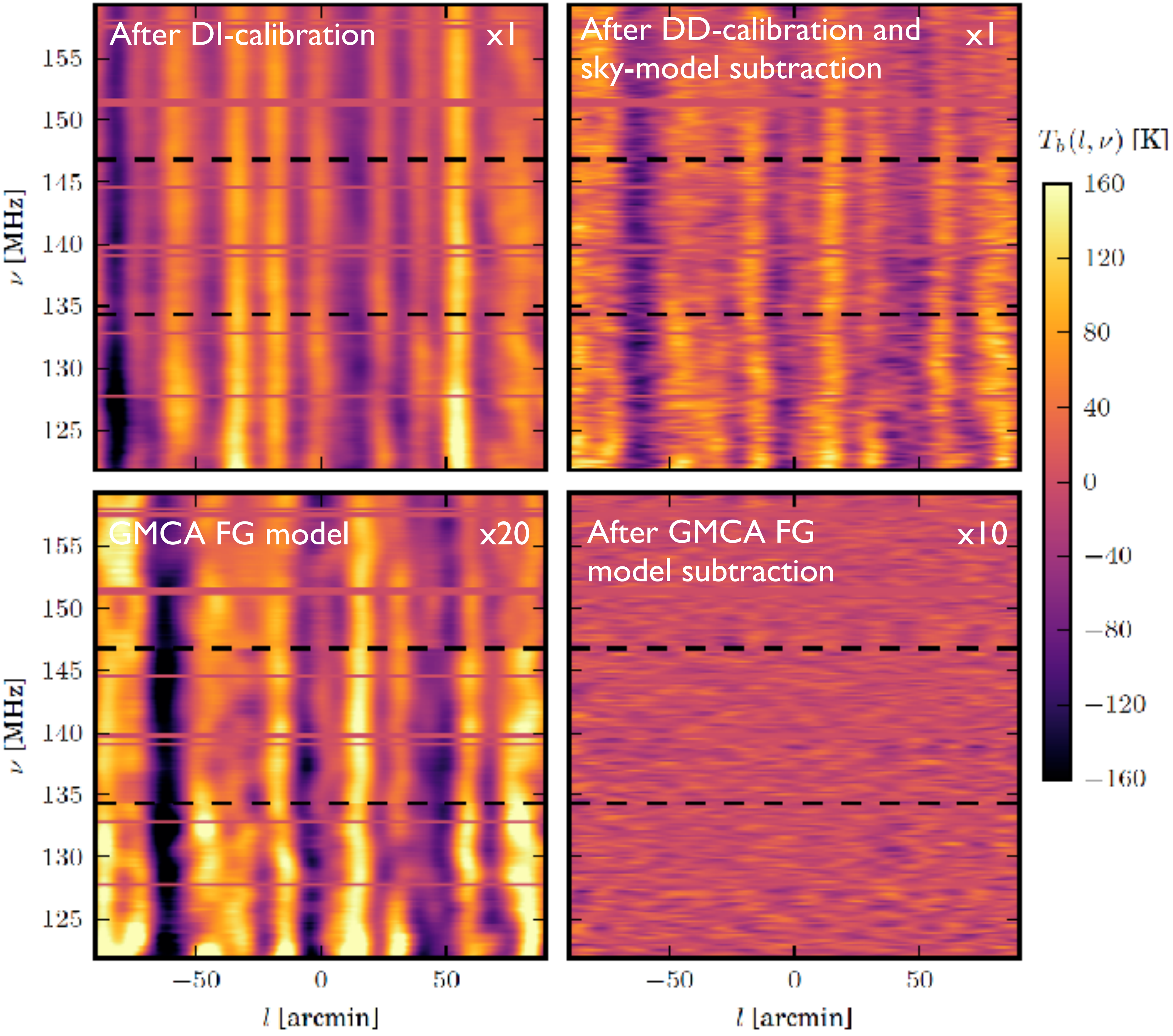
Stokes I shows the primary beam and is confusion limited; Stokes V is consistent with thermal noise to within ~5%.

White box in top of primary beam: region being analysed for power-spectrum

Bottom images shows 10x10d FoV in Stokes I (left) and V (right) with 10’ resolution.

Patil et al. (2017, ApJ)

NCP Residuals after Sky-Model Subtraction



Slice (3°) trough the cube in one spatial direction and frequency (note scaling in brightness for some panels).

Note the resemblance between GMCA model (Chapman et al. 2013) and data after DD calibration.

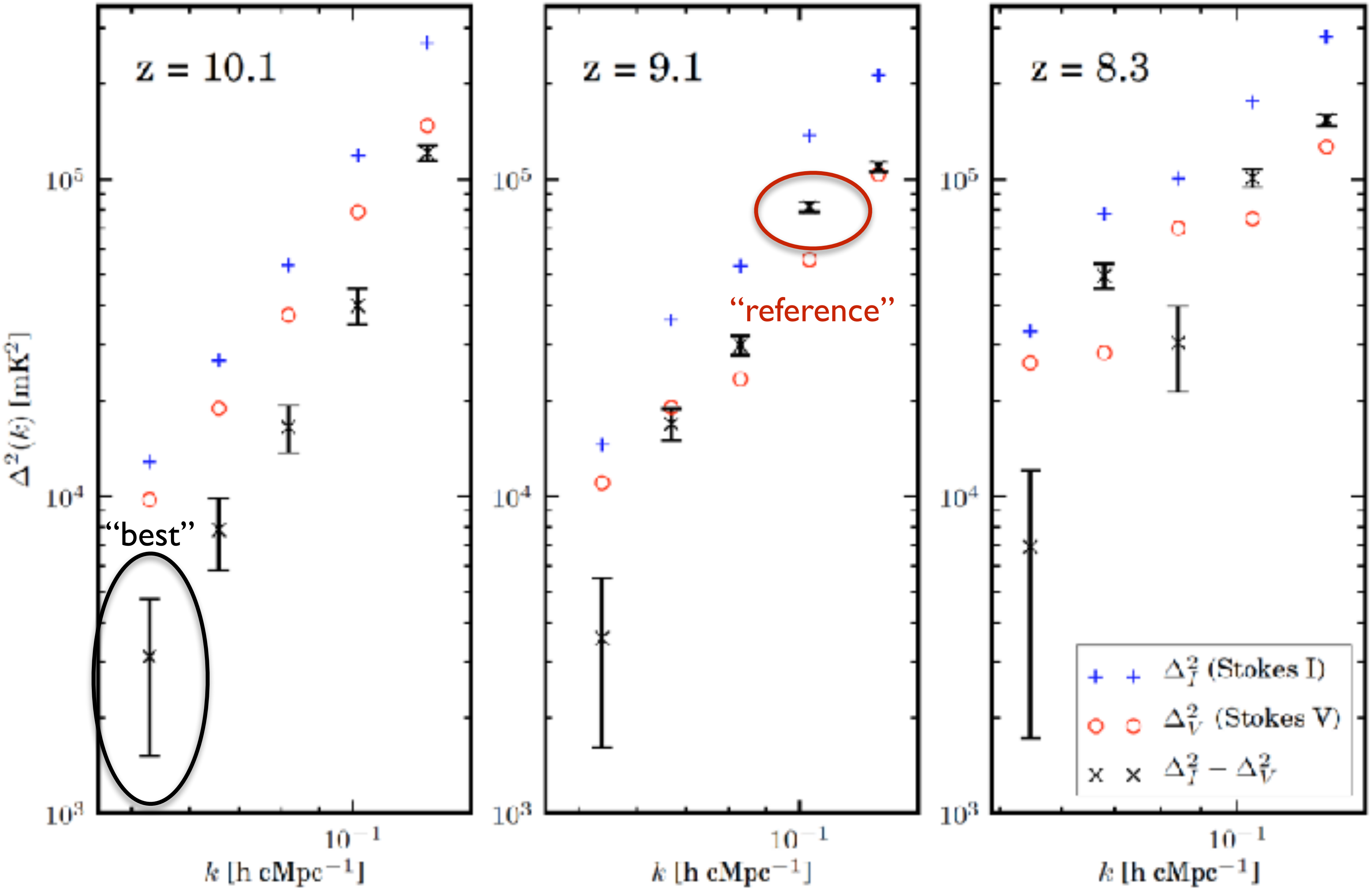
Dashed lines are the three redshift ranges: z=7.9-8.7, 8.7-9.6, 9.6-10.6

Patil et al. (2017, ApJ)

LOFAR-HBA NCP — Power Spectra Results

Currently these are the deepest 21-cm power spectrum limits of all experiments but still far away (factor ~10^4) from a detection of the signal!

Averaging spherically provides the lowest errors (maximum # of samples per shell).



“best”

“reference”

Patil et al. (2017, ApJ)

LOFAR-HBA NCP — Our 2017 Roadmap

Improvements
since 2017

Improve calibration

- ➤ Remove/reduce "excess variance" (3-4x thermal variance).
- ➤ Improve the sky/calibration model further reducing gain errors transferred to shorter baselines; Improve DD calibration; Improve beam-model
- ➤ Include diffuse emission from Stokes, Q, U and possible I to enable including short baselines in calibration (currently not possible)
- ➤ Improve diffuse FG subtraction via various methods (e.g. above).
- Use cross-variance methods to avoid the noise bias in PS analysis.
- ➤ Improve cross-correlation of gain solutions with various metrics to gain insight.

Improve sensitivity

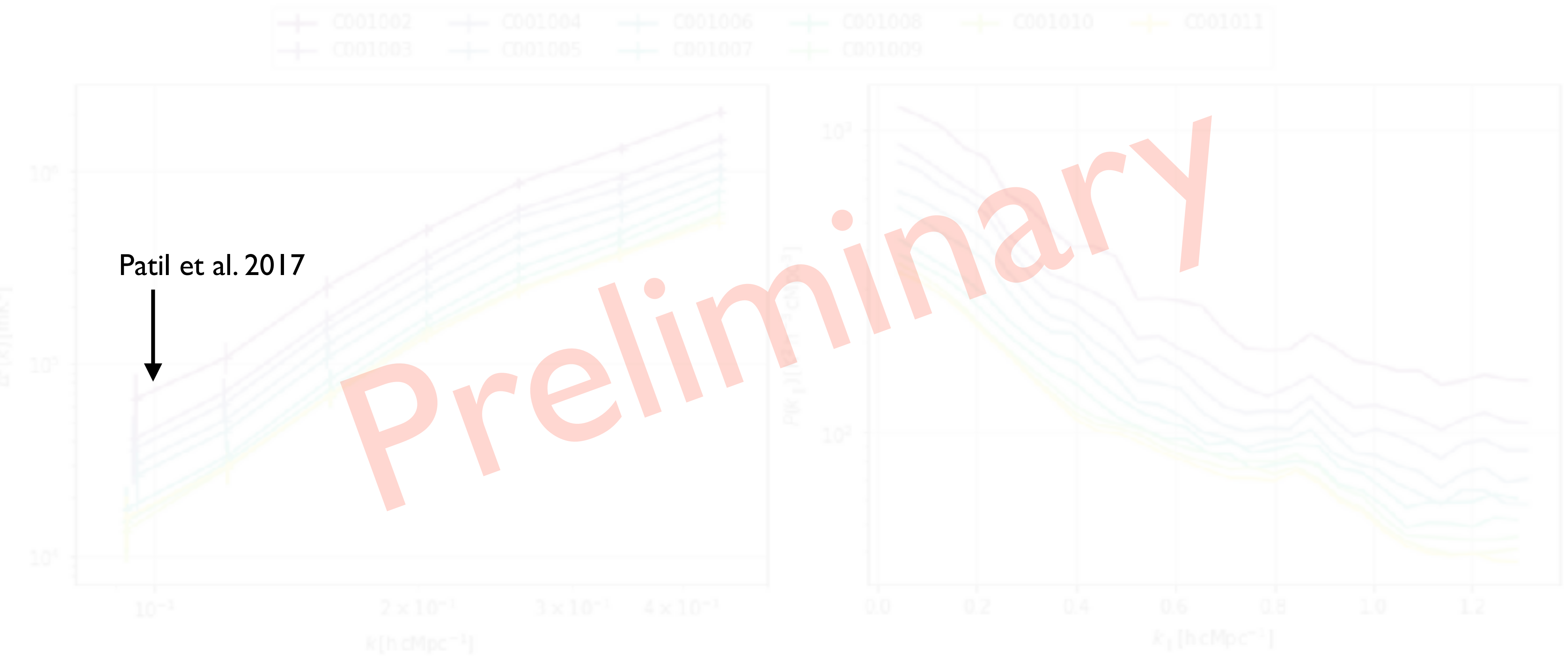
- ➤ If OK, include previously flagged short (30-60 lambda) baselines that have very high PS sensitivity (~10x deeper at k~0.03, vs k~0.05 at the moment).
- ➤ Analyse and combine more of the data (1➠10➠100 nights, rather than ~1 night).

Second window/more data

- ➤ Add second field to the processing/results: 3C196
- ➤ Keep collecting data (~3000hr total)

Current Status: LOFAR-HBA NCP — 11 nights

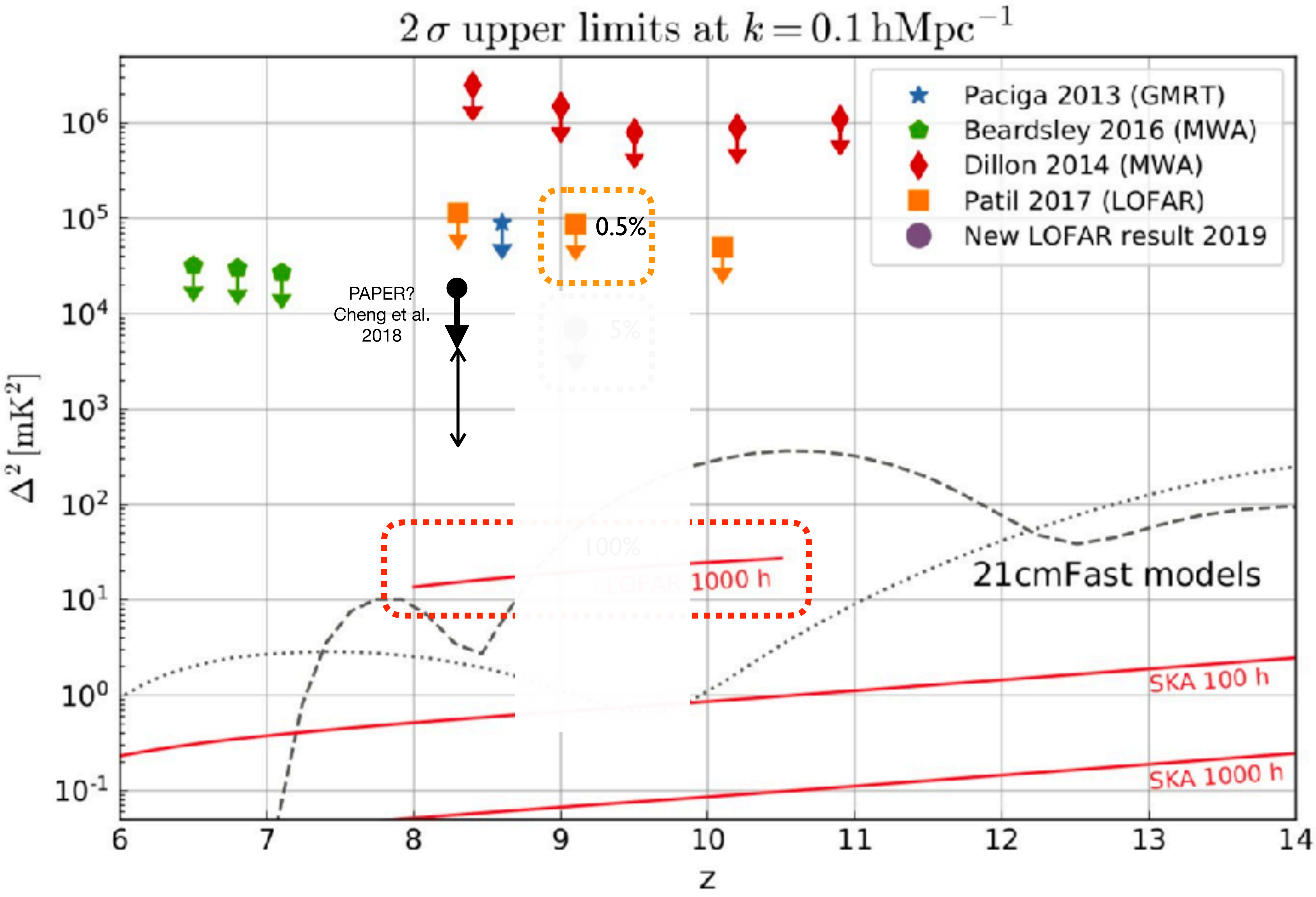
Much deeper (~10x) than in Patil et al. (2017) due to improvements in calibration and foreground removal



Caution! No optimal weighting, but the PS has been tested for signal bias/suppression in DI/DD-cal steps (expensive tests!).

Merten et al. 2019, in prep.

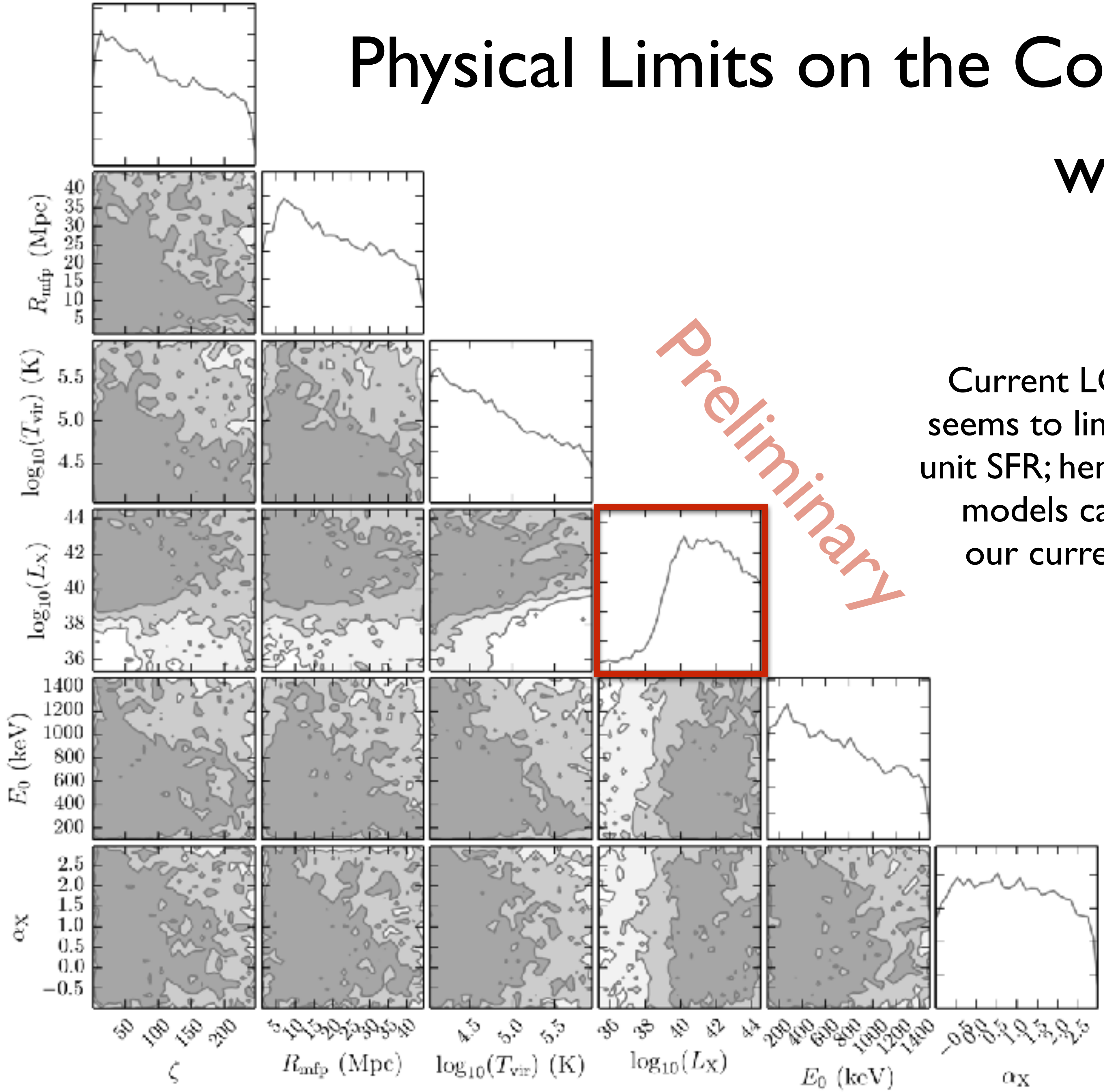
LOFAR-HBA NCP — Forecast



Mertens et al. 2019, in prep.

Physical Limits on the Cosmic Dawn w/21CMMC

Greig et al. 2015, 2017



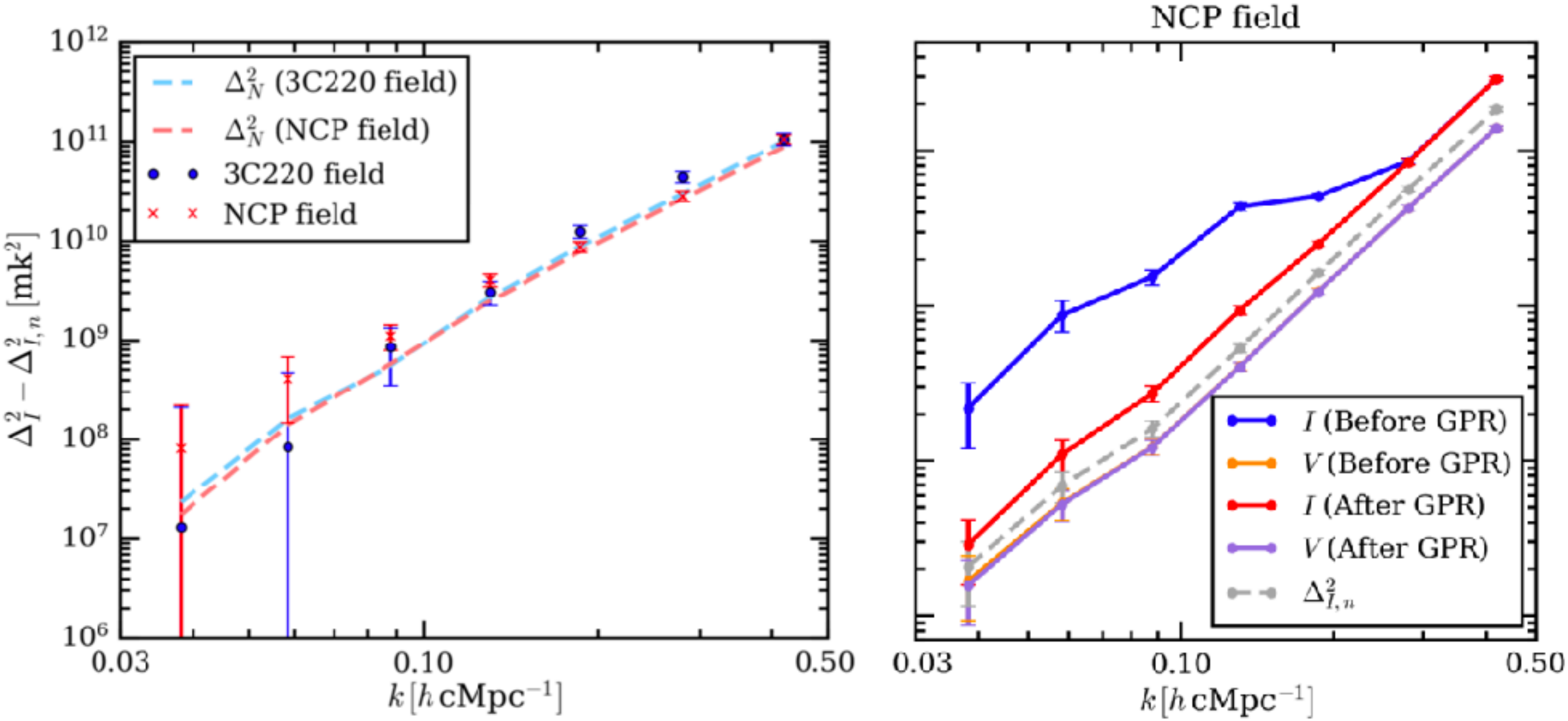
Current LOFAR EoR PS already seems to limits X-ray heating per unit SFR; hence cold IGM and CD models can be tested based on our current z=8, 9,10 PS limits.

(w/help of Brad Greig)
(1) no tau constraint,
(2) co-eval, no light cone

New Result: LOFAR-LBA NCP (dual beam)

The deepest power spectra limits at z=20-25 currently, but not yet very interesting, except to exclude “exotic models” (?).

$\Delta_{21} < (14.6\ \mathrm{K})$ (2-σ) in both NCP and 3C220 fields @ k ~ 0.04 cMpc^{-1}, z=20-25



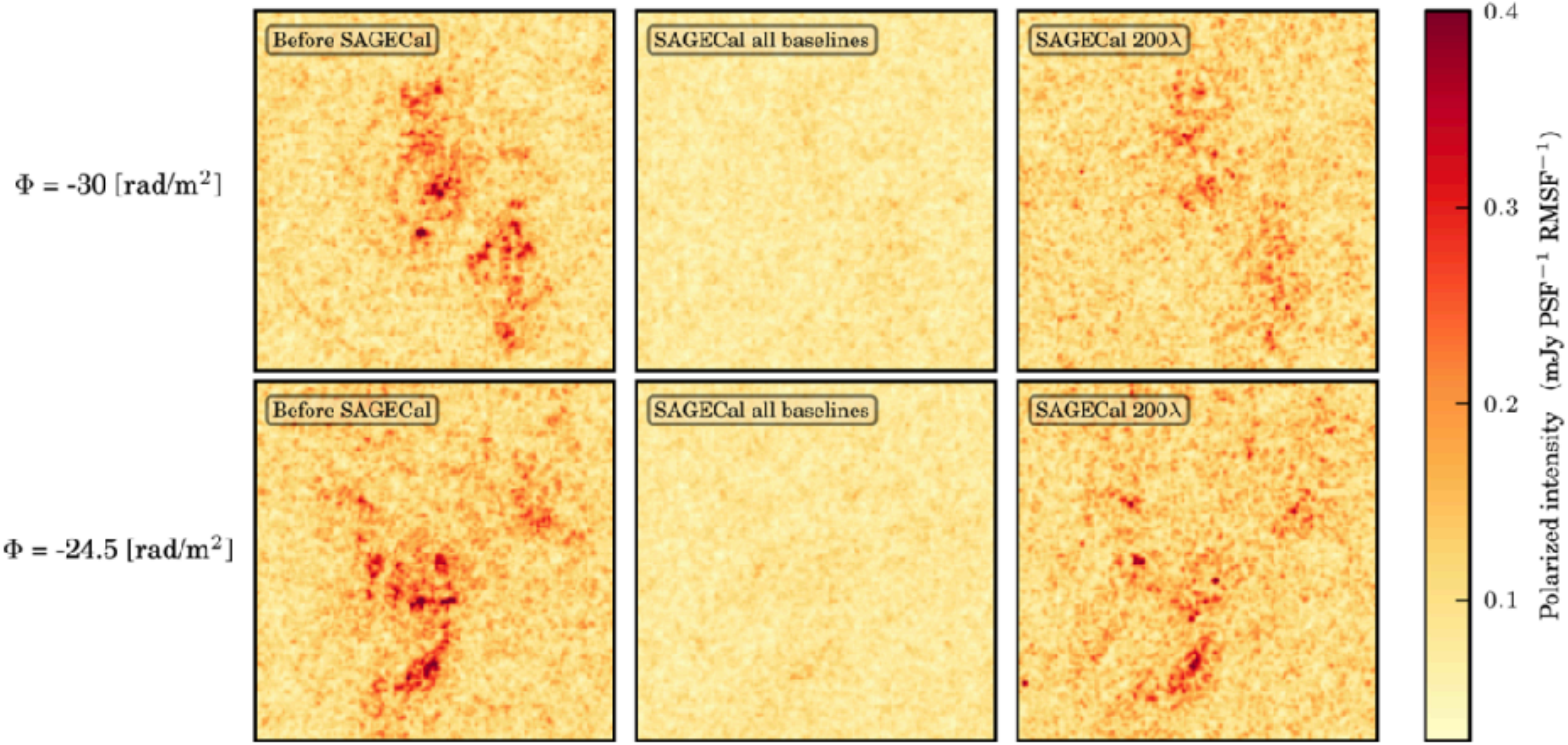
Gehlot et al. 2019, under review

Critical Aspect of Calibration: Bias/Variance Trade-Off

Signal Processing can remove signals and add signals. It is critical to get this right for any power-spectrum analysis.

LOFAR-HBA NCP — Bias/Variance Tradeoff

DD-calibration can remove diffuse emission if not properly regularised (see also Sardarabadi & Koopmans 2018).

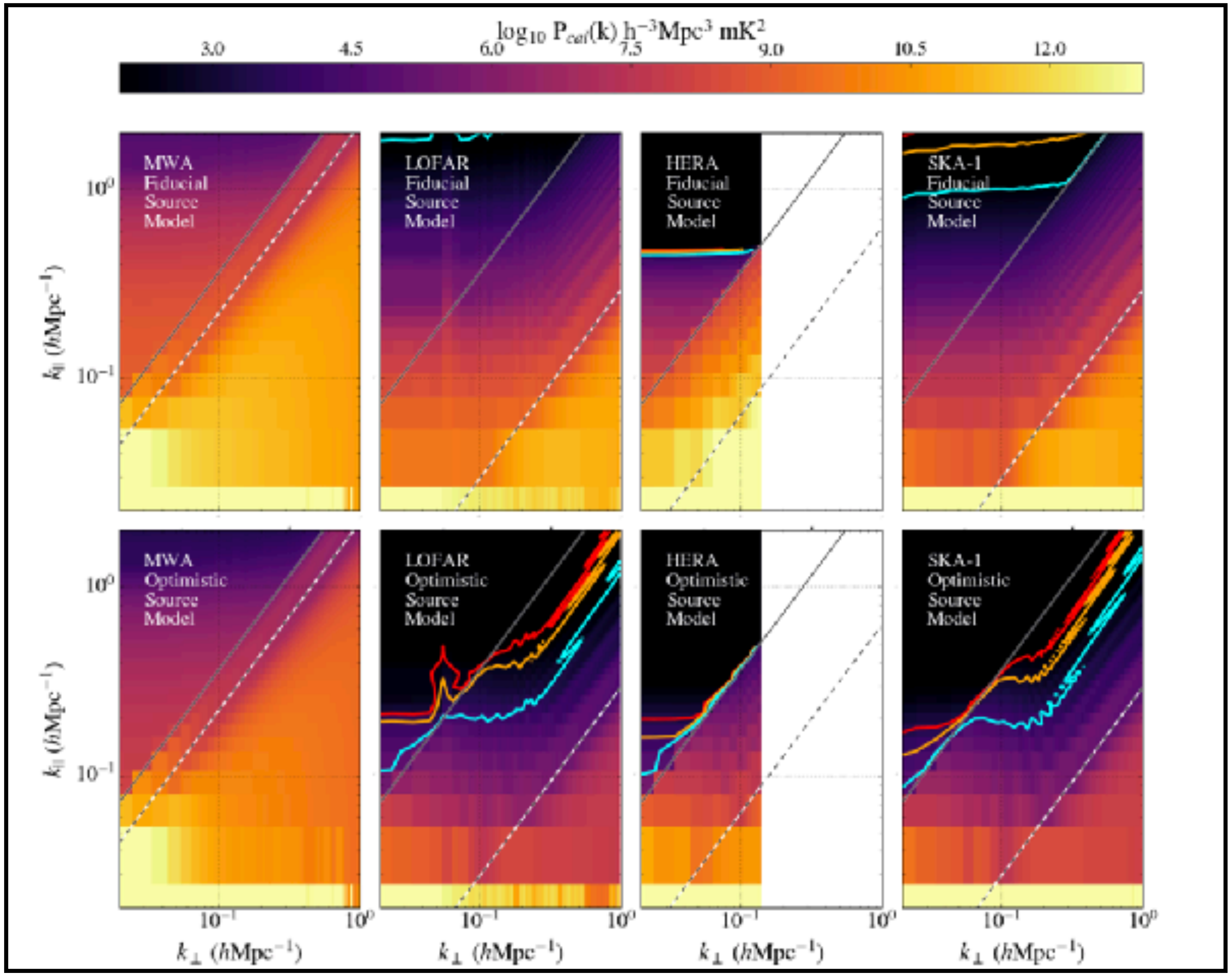


Patil et al. 2016

LOFAR-HBA NCP — Bias/Variance Tradeoff

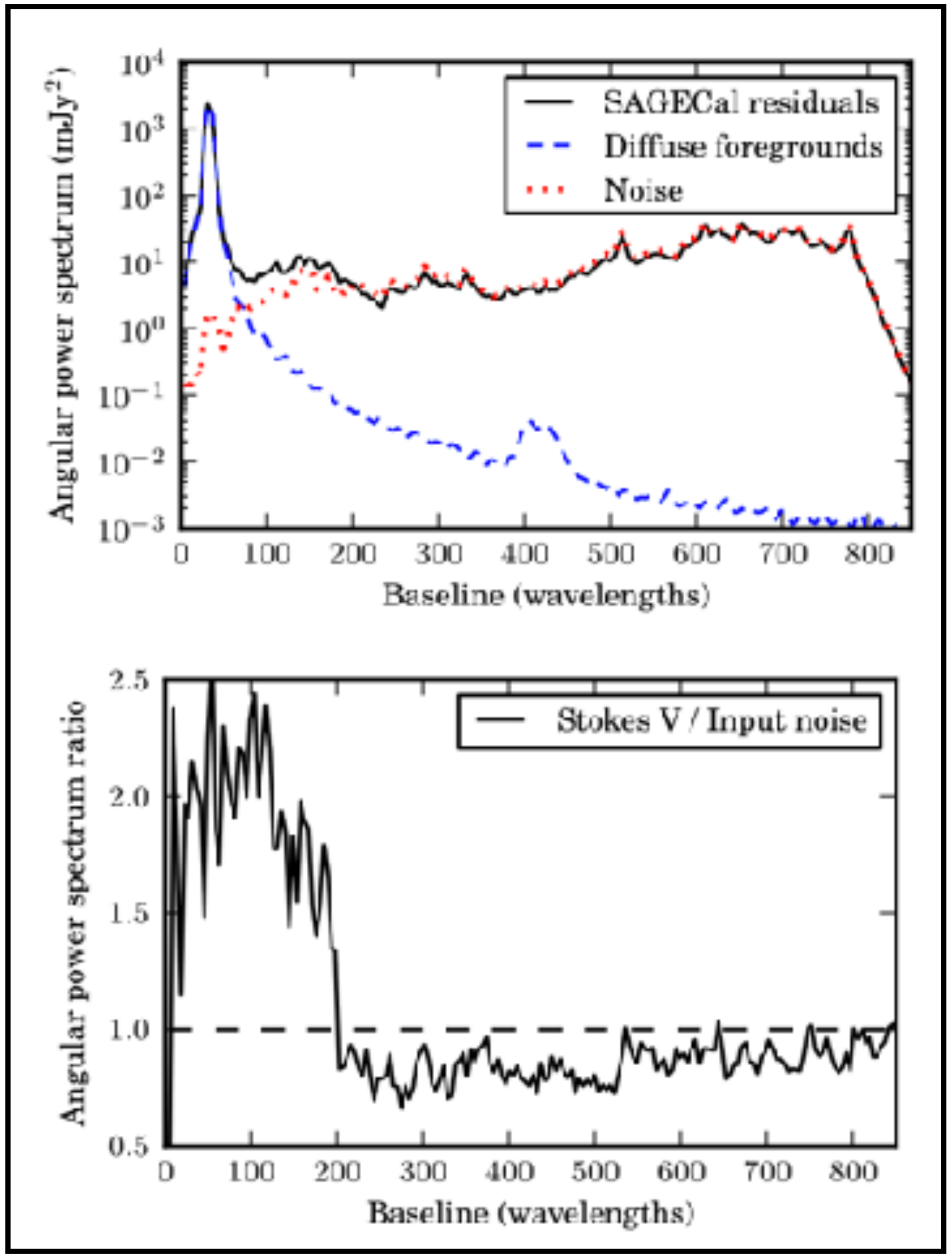
An incomplete sky model + baseline cut also causes extra variance in gain solutions and the residual power spectrum! Hence mitigating bias/signal suppression this way leads to an enhancement in power on short baselines.

Incomplete sky-model causes gain errors and enhanced power on short baselines



Ewall-Wice et al. 2017

Baseline cut removes bias but adds excess noise



Patil et al. 2016

LOFAR-HBA NCP — Bias/Variance Tradeoff

Enforce smooth gains on >3MHz scales (w/ or /wo cut): problems disappear

Direction Dependent Calibration

Gains absorb diffuse structures including the 21-cm signal !!

This causes:

a. signal suppression if the gain solution are not spectrally smooth.
b. Excess noise if the sky model is incomplete.

Two solutions:

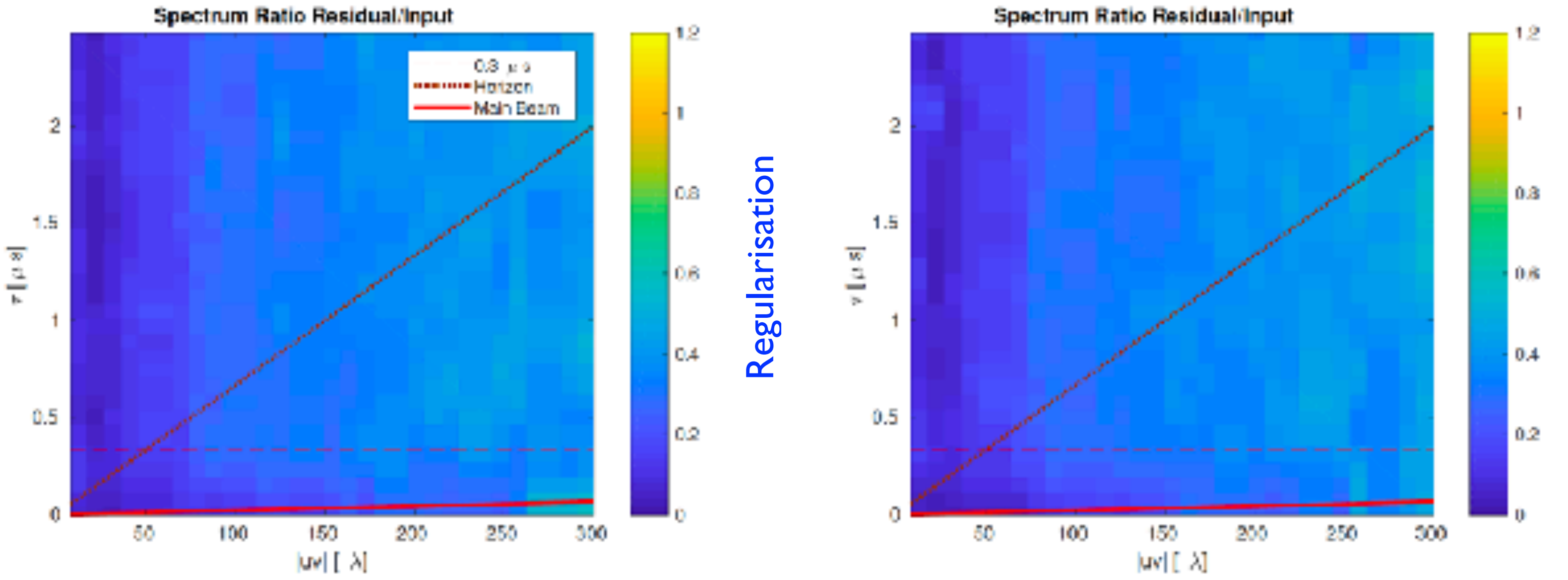
1. Optimal: Enforce spectrally smooth (>3MHz) gains.
2. Cheap: Introduce a baseline cut: no bias, but some excess power.

No baseline cut

Complete Sky

Incomplete Sky Model

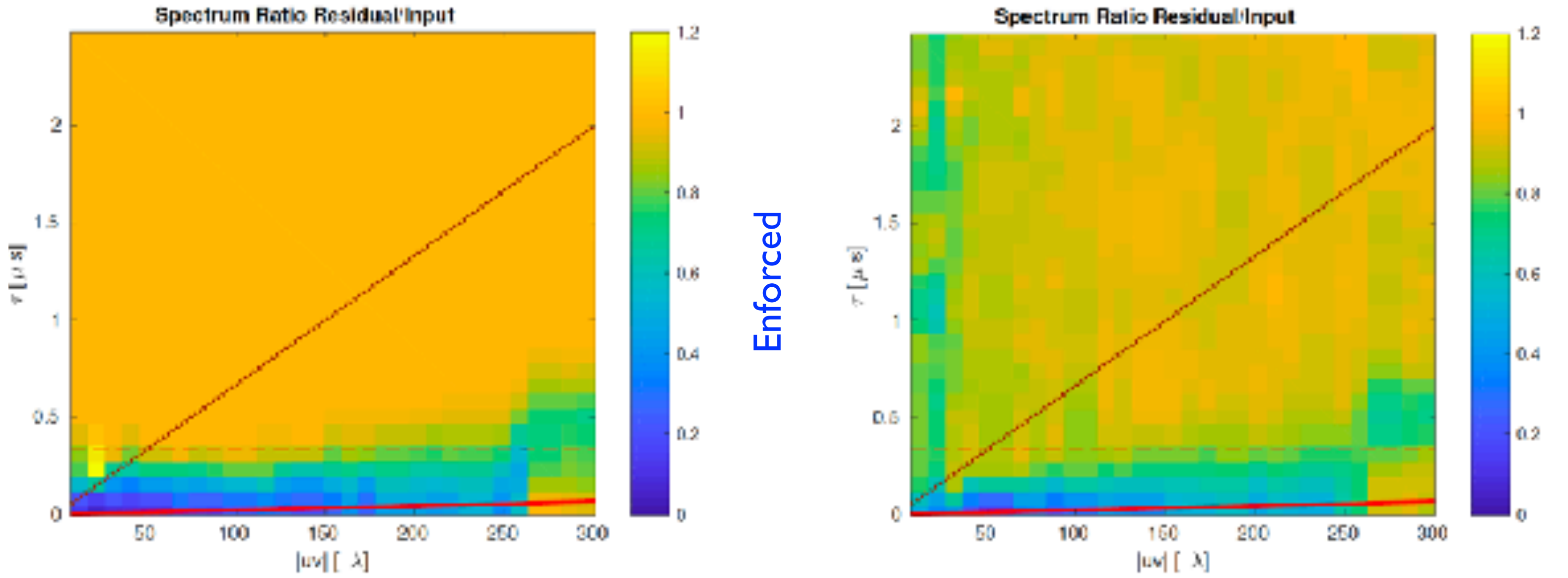
Regularisation



(a) Partially enforced smoothness.

(a) Scenario 2 the smoothness partially achieved.

Enforced



(b) Fully enforced smoothness.

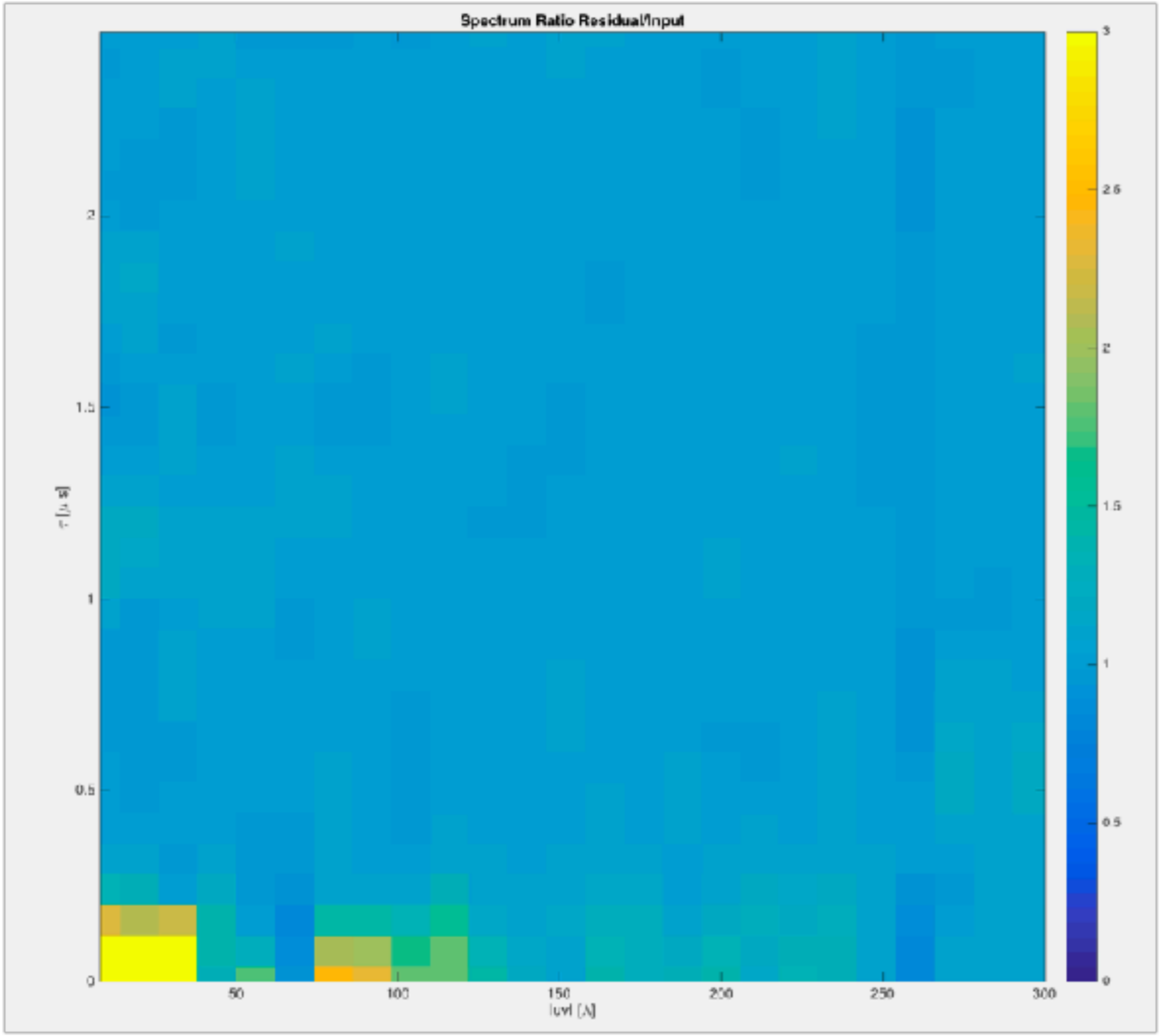
(b) Scenario 1 the smoothness is fully enforced

Sardarabadi & Koopmans, 2018; Mevius et al. in prep.

LOFAR-HBA NCP — Bias/Variance Tradeoff

Enforce smooth gains on >3MHz scales (w/ or /wo cut): problems disappear

Regularisation but now <u>with</u> baseline cut & incomplete sky model.



Sardarabadi & Koopmans, 2018; Mevius et al. in prep.

Direction Dependent Calibration

Gains absorb diffuse structures including the 21-cm signal !!

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2. Cheap: Introduce a baseline cut: no bias, but some excess power.

Global 21-cm Signal Experiments

Some exciting new results and prospects…!

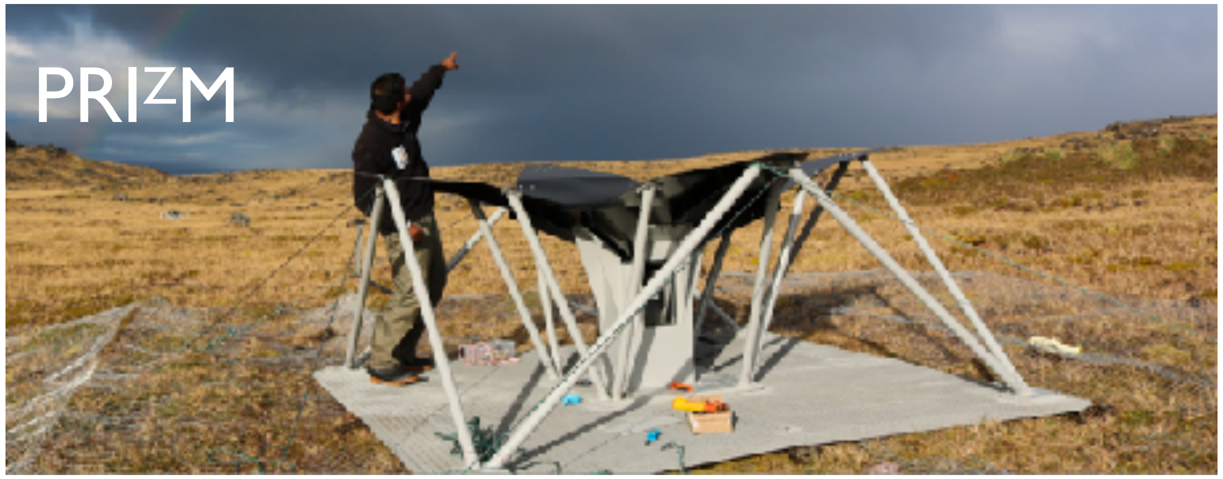
Current Global 21-cm Signal Experiments

Specs
- ~10-480 MHz, ~10-300 MHz (left, right)
- Western Australia

Sokolowski et al. 2015

Specs:
- 40-130 MHz
- Isla Guadalupe, Mexico

Peterson et al. 2014



Specs:
- 30-200 MHz
- Marion Island, SA

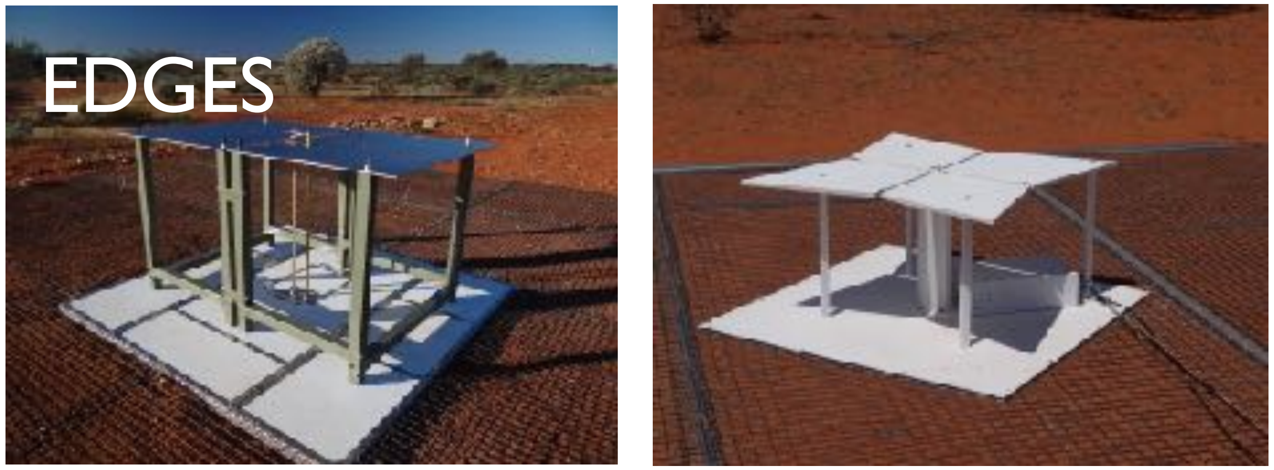
Peterson, Sievers, Chiang ++

Specs:
- 40-120 MHz
- Lunar orbit, 125km above lunar surface

Burns et al. 2017

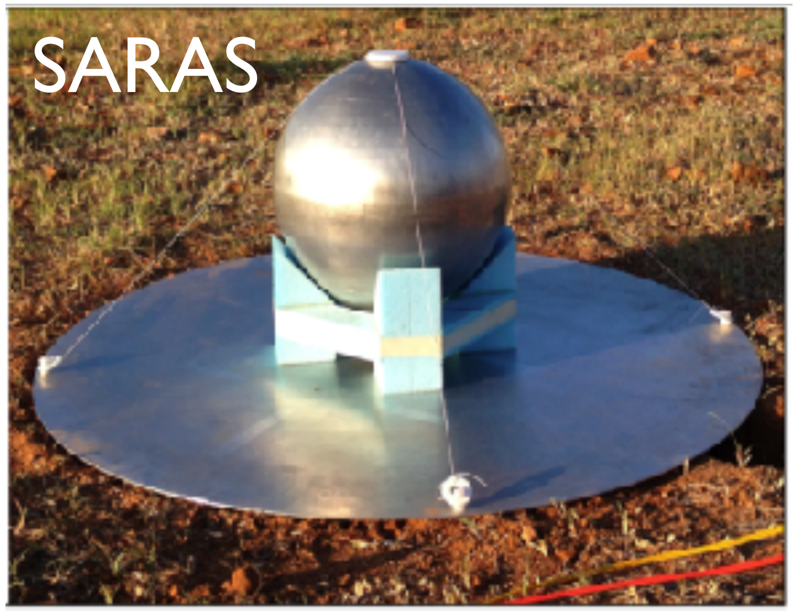
Current Global 21-cm Signal Experiments

Claimed detection (needs confirmation)



Specs
- 50-100, 100-200 MHz (left, right)
- Western Australia

Rogers & Bowman 2008, 2012; Bowman et al 2018



Specs:
- 50-100, 100-200 MHz (right, left)
- India (Timbaktu/ Himalayas)

Singh et al. 2017

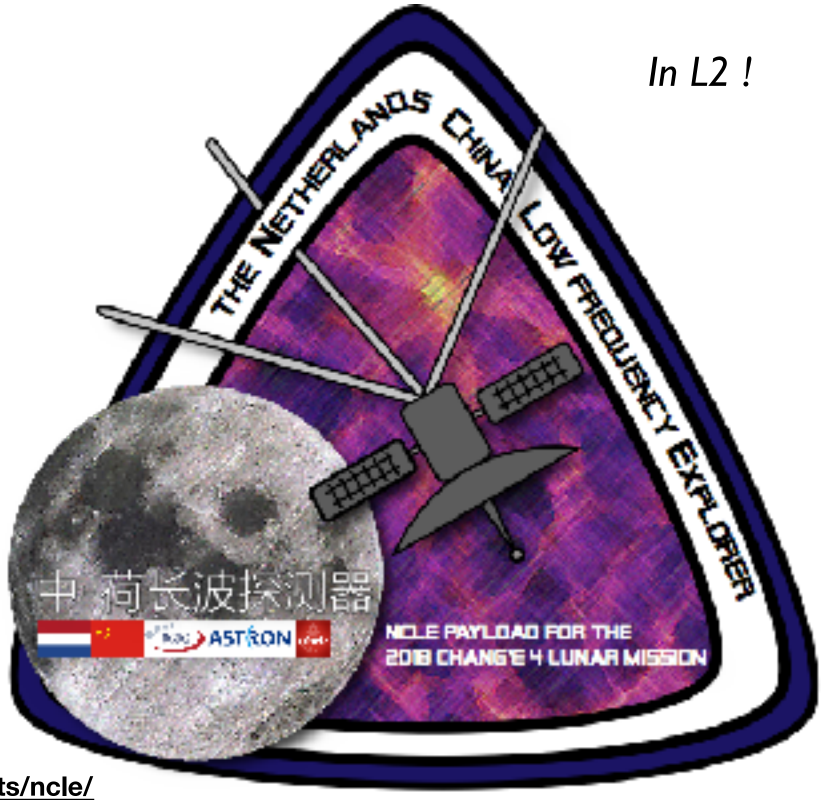
Specs:
- 30-88 MHz
- OVRO/California, US

Bernardi et al. 2016; Price et al. 2018

NCLE

Specs:
- 0.08-80MHz
- L2/Behind Moon

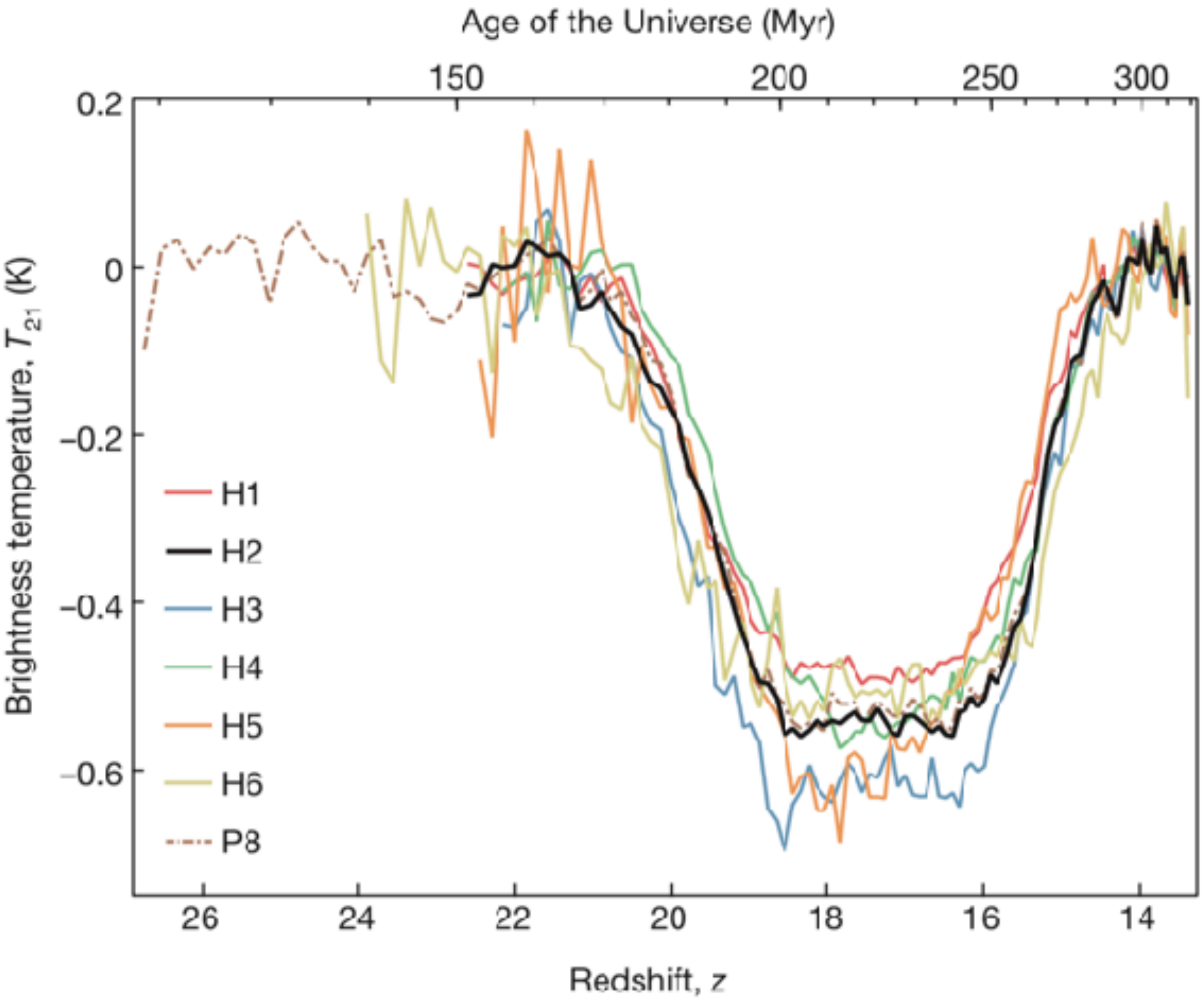
In L2 !

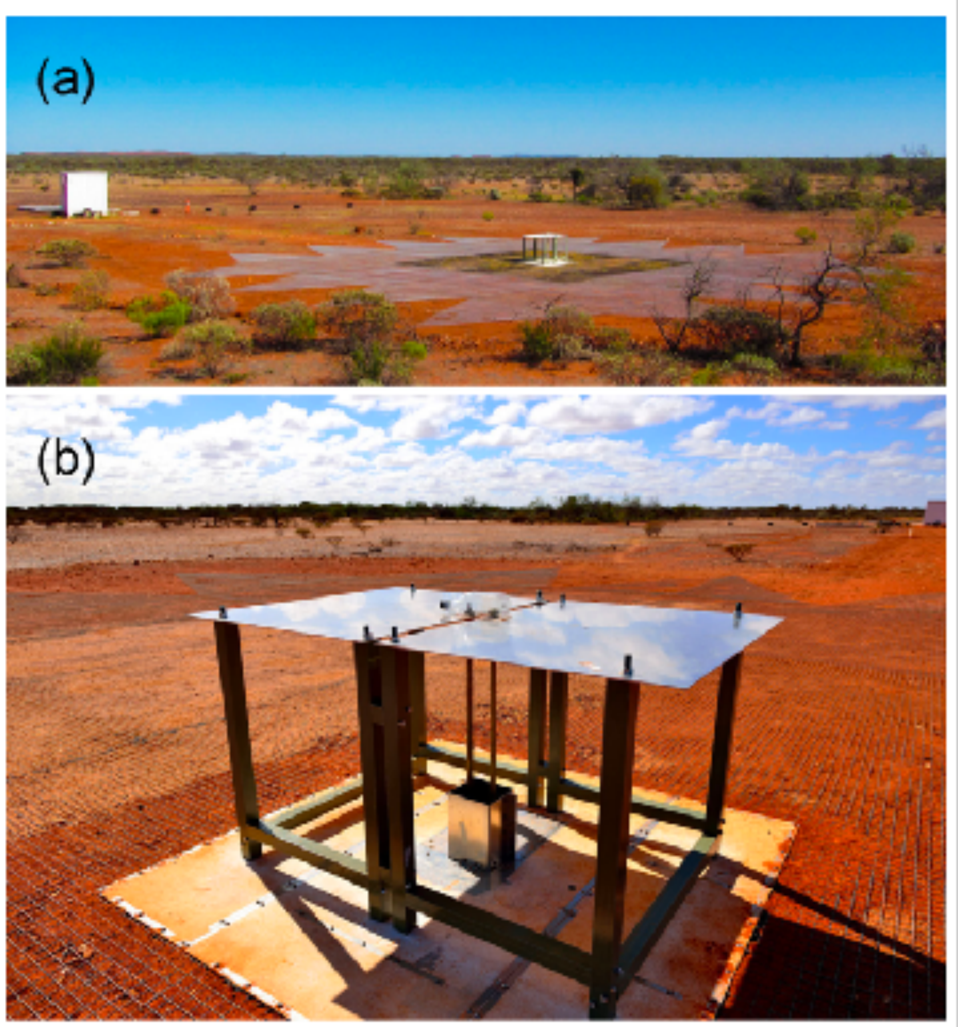


https://www.isispace.nl/projects/ncle/

EDGES2

In 2018 a detection of the global 21-cm signal of neutral hydrogen seen against the CMB was detected. But signal is too deep and too flat!

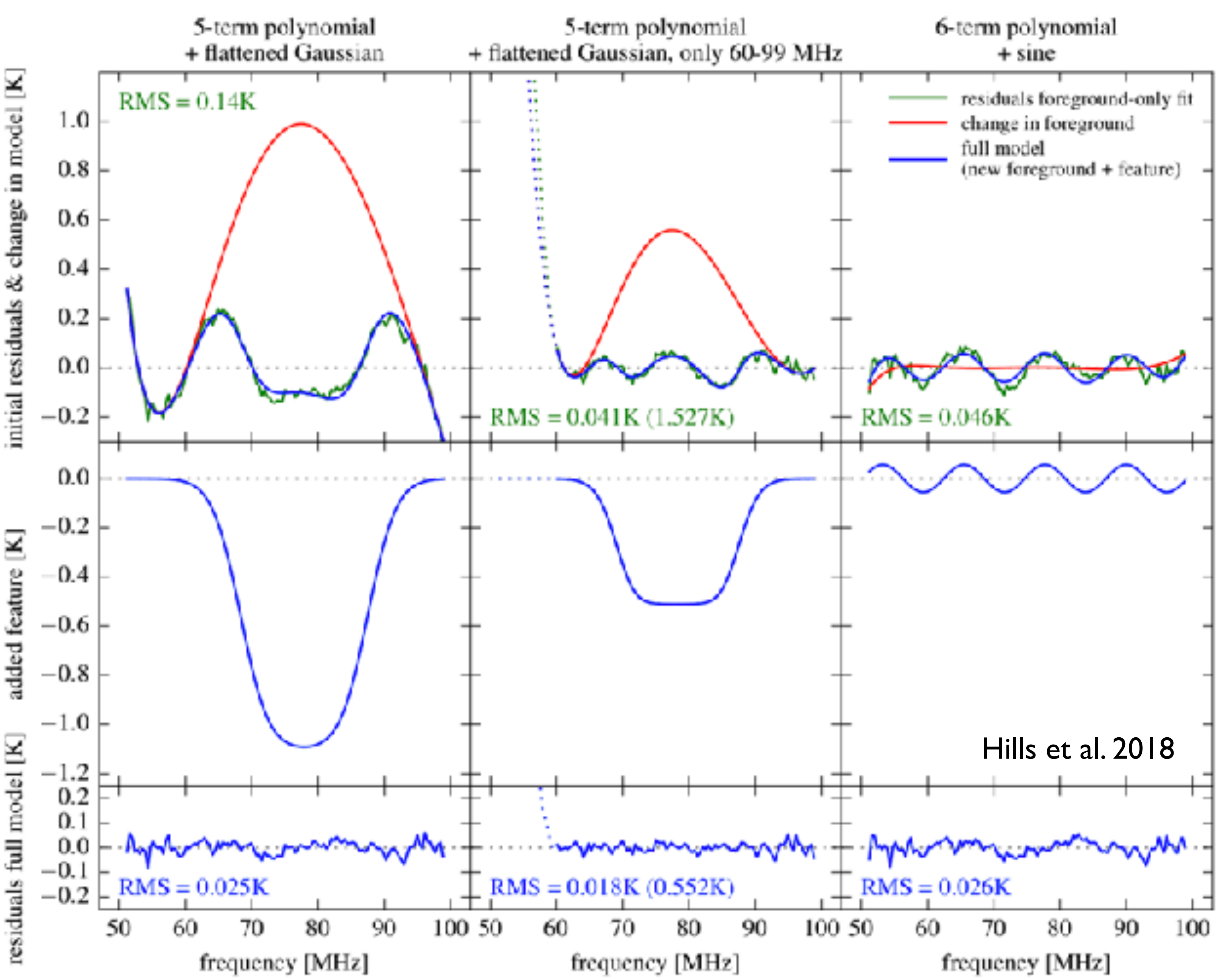




Bowman et al. 2018

EDGES2

But!! The signal however can be explained by many combinations of smooth foreground models and "21-cm signals" some clearly not physical.



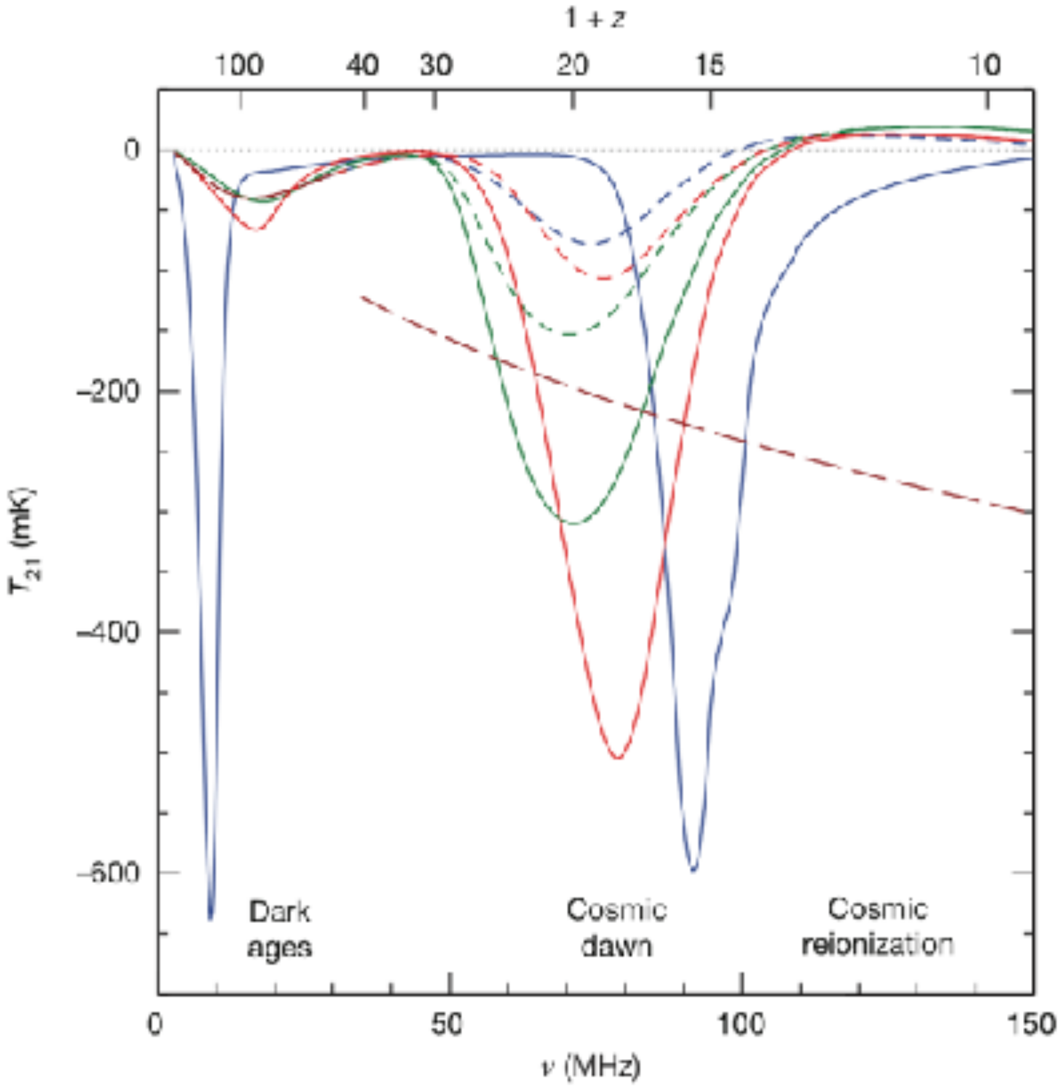
Hills et al. 2018

EDGES2 results needs confirmation by an independent instrument (e.g. SARAS3)

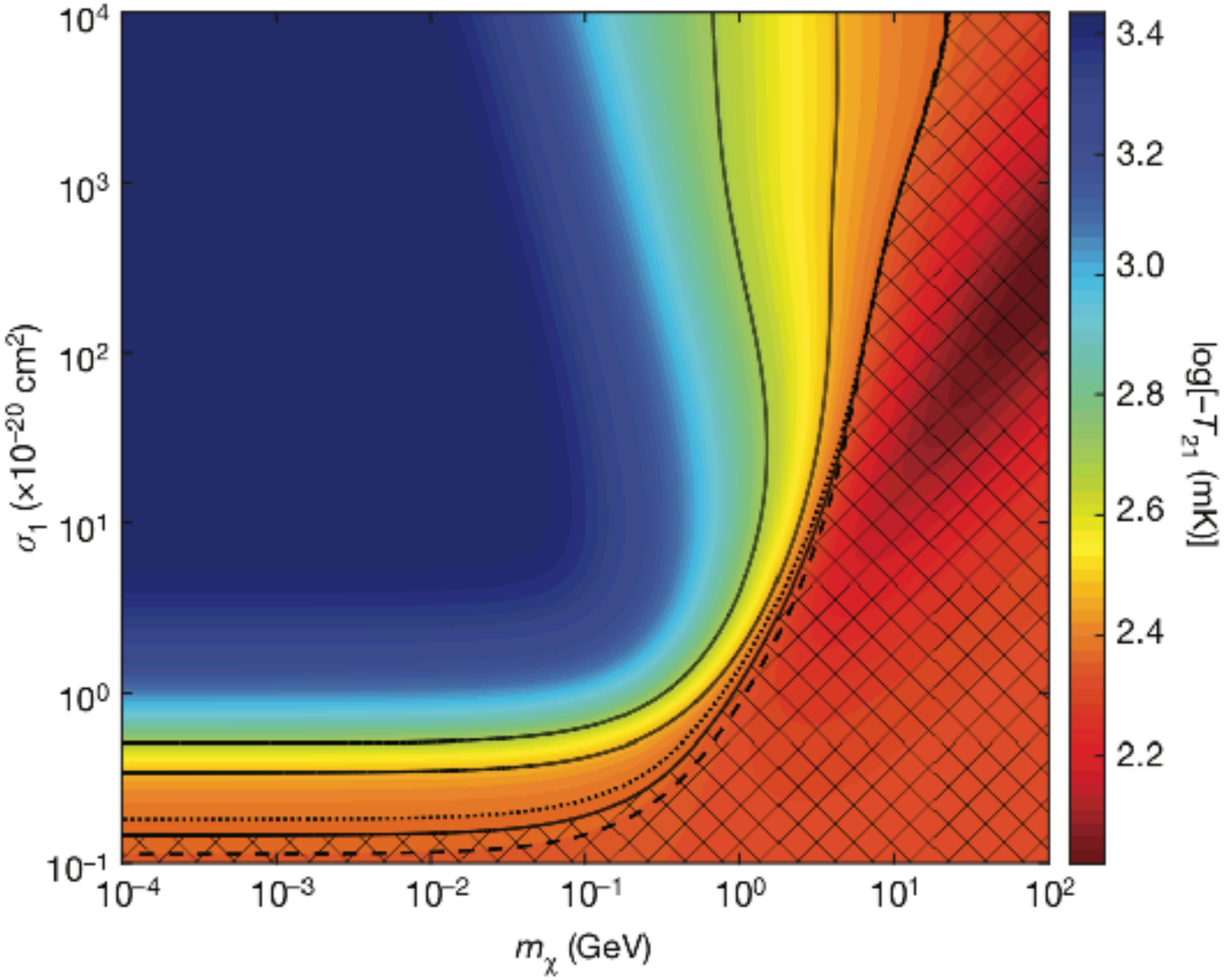
EDGES2

This result has generated an enormous interest. However, if true it requires some exotic physics such as the cooling of baryons by scattering off dark matter to explain the depth of the signal (-600mK).

Global-signal models; some affect the Dark Ages



Constraint on DM particle mass and cross-section



Barkana 2018

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kapteyn instituut

AARTFAAC Cosmic Explorer 'ACE'

All-Sky Imaging in the EDGES band

Joint Colloquium, Bologna, Feb. 14, 2019

AARTFAAC Cosmic Explorer (ACE) Program

EDGES2 results motivated the 1000-hr ACE program with LOFAR-LBA using AARTFAAC LBA-dipole-/HBA-tile-level correlator.

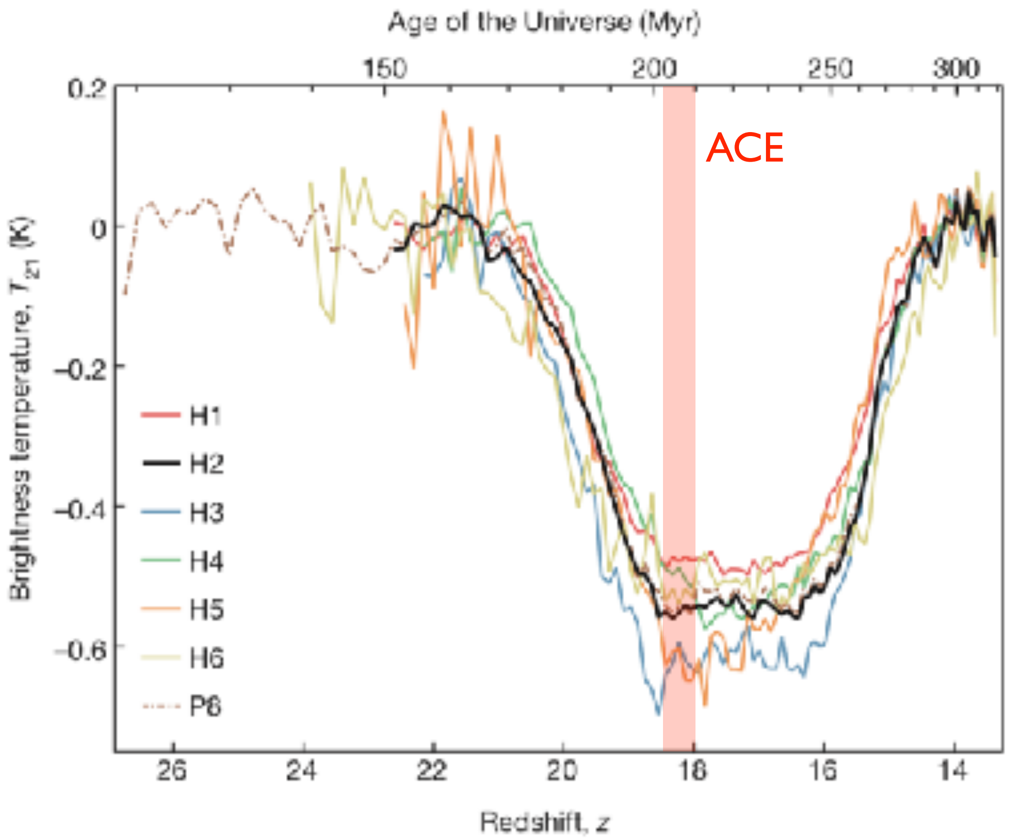
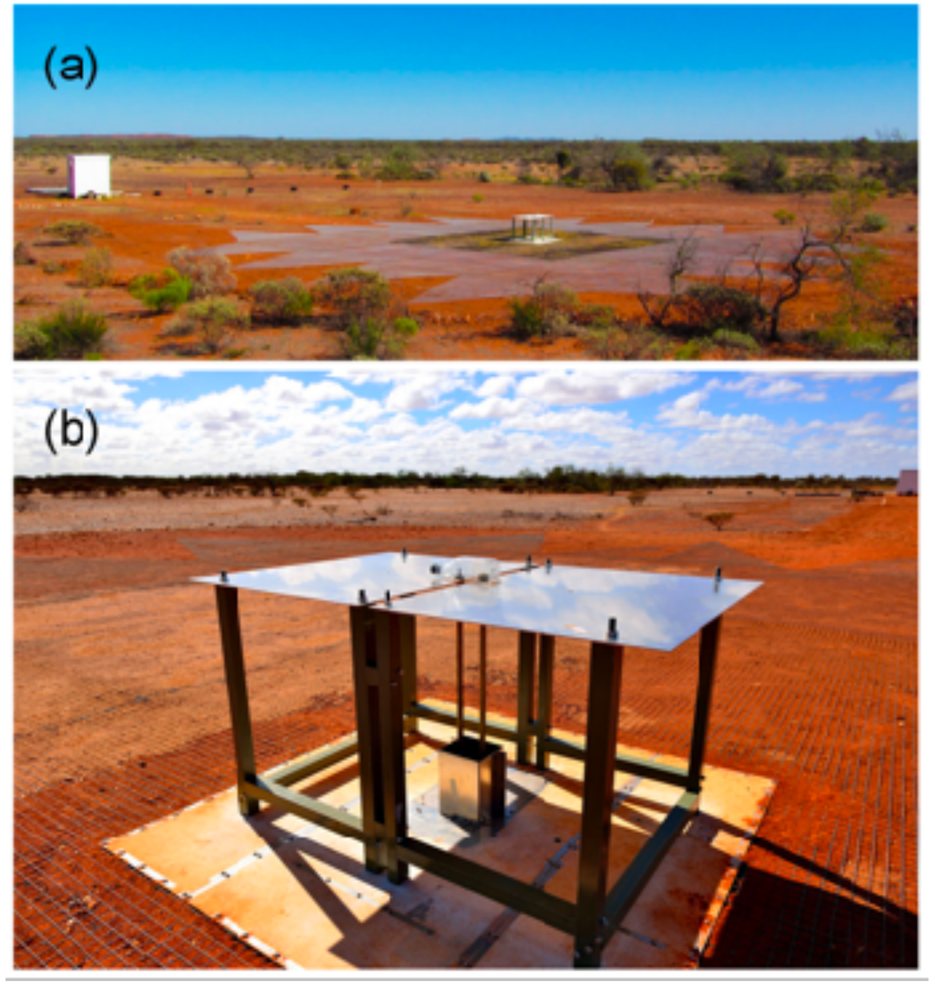


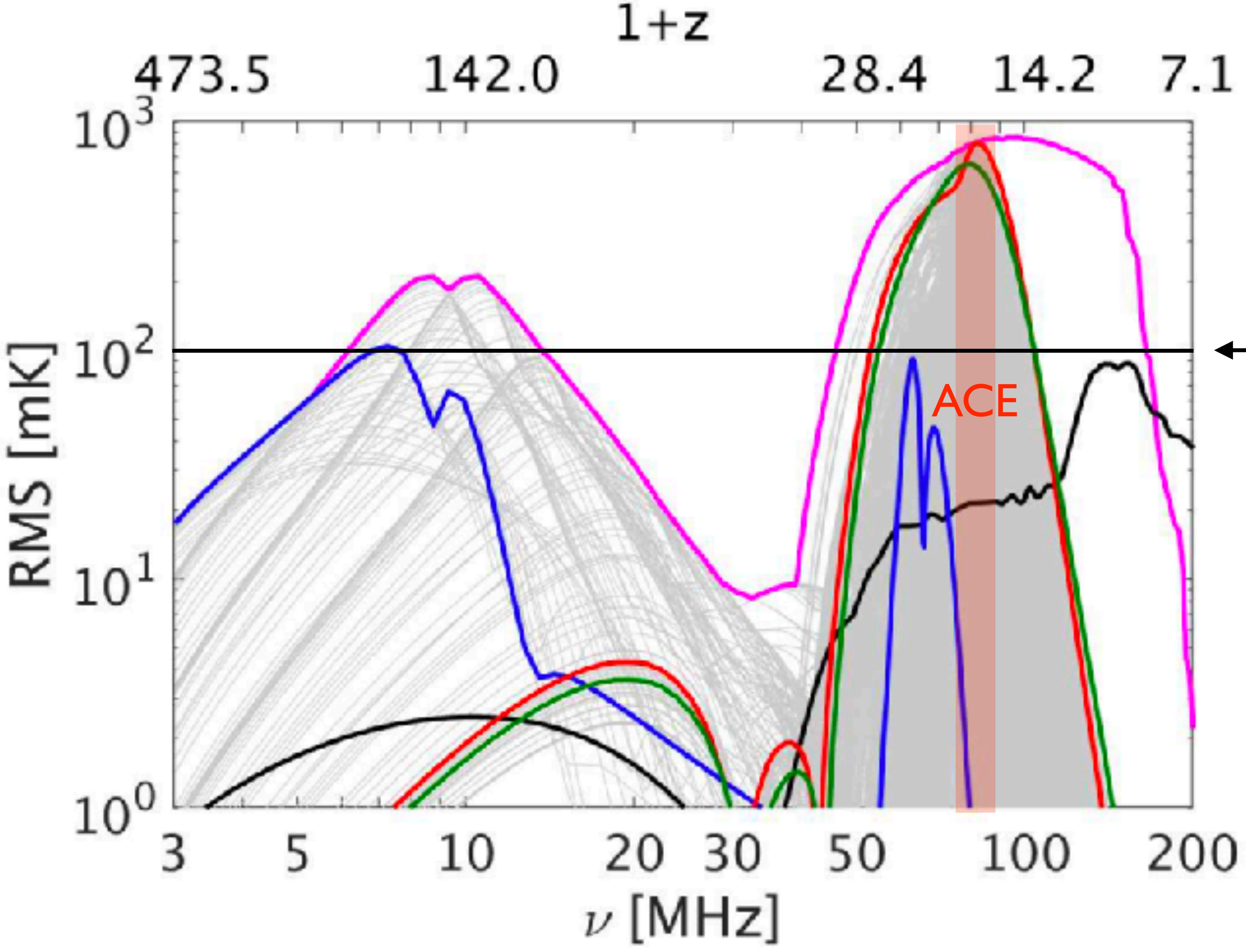
Figure 2 | Best-fitting 21-cm absorption profiles for each hardware case. Each profile for the brightness temperature T_{21} is added to its residuals and plotted against the redshift z and the corresponding age of the Universe. The thick black line is the model fit for the hardware and analysis configuration with the highest signal-to-noise ratio (equal to 52; H2; see Methods), processed using 60–99 MHz and a four-term polynomial (see equation (2) in Methods) for the foreground model. The thin solid lines are the best fits from each of the other hardware configurations (H1, H3–H6). The dash-dotted line (P8), which extends to $z > 26$, is reproduced from Fig. 1e and uses the same data as for the thick black line (H2), but a different foreground model and the full frequency band.



Bowman et al. 2018

AARTFAAC Cosmic Explorer (ACE) Program

Cross-correlate all 576 LOFAR LBA dipoles over ~2.5 MHz between 72.5-75MHz (z~18) using 42x61 kHz channels + two outrigger subbands.

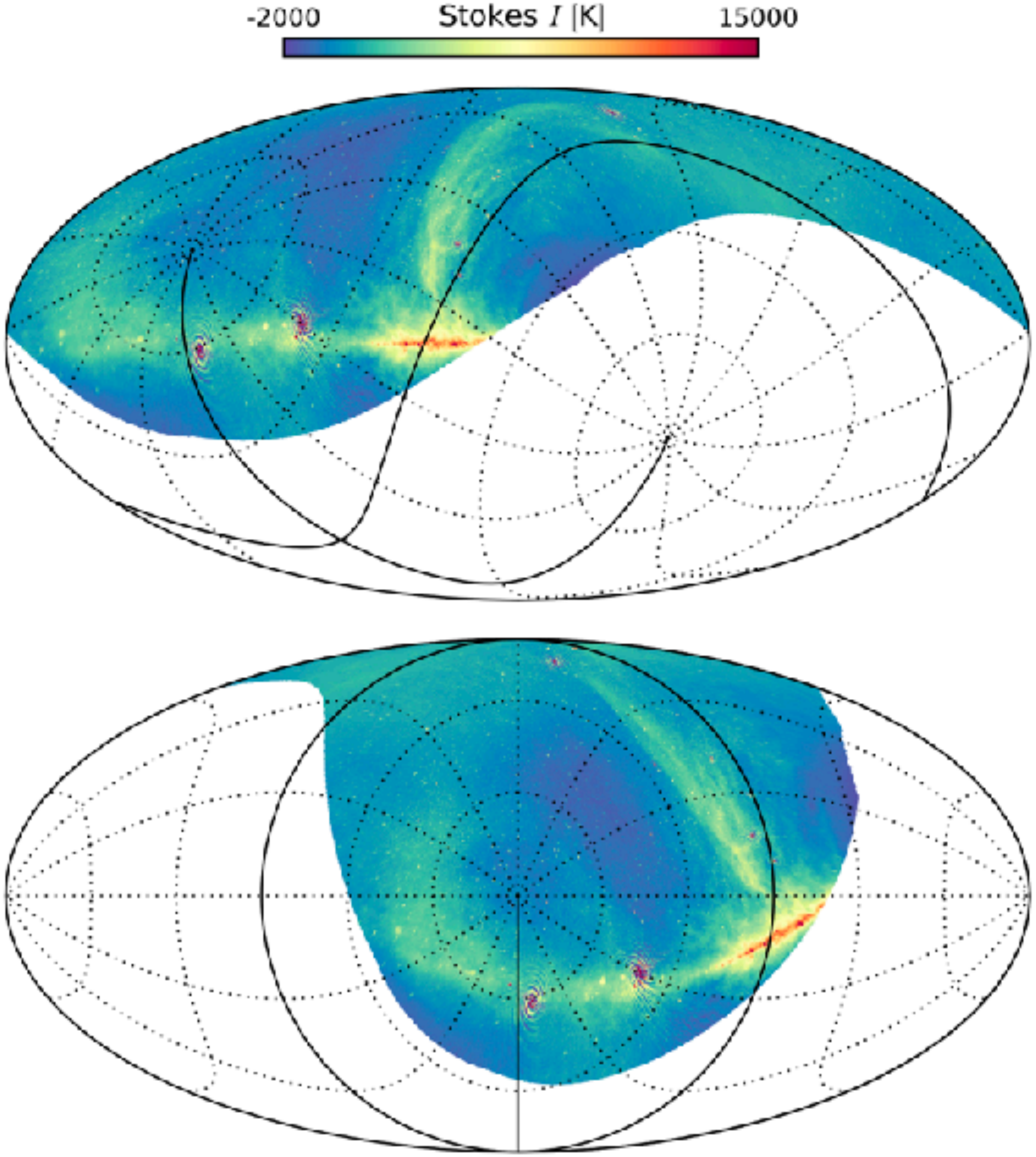


S/N expected in ~1000 hrs for typical signal as in Fialkov et al. (2018)

Fialkov et al. (2018)

AARTFAAC Cosmic Explorer (ACE) Program

Observations started in May 25 2018; continue for 4 Cycles until 2020.

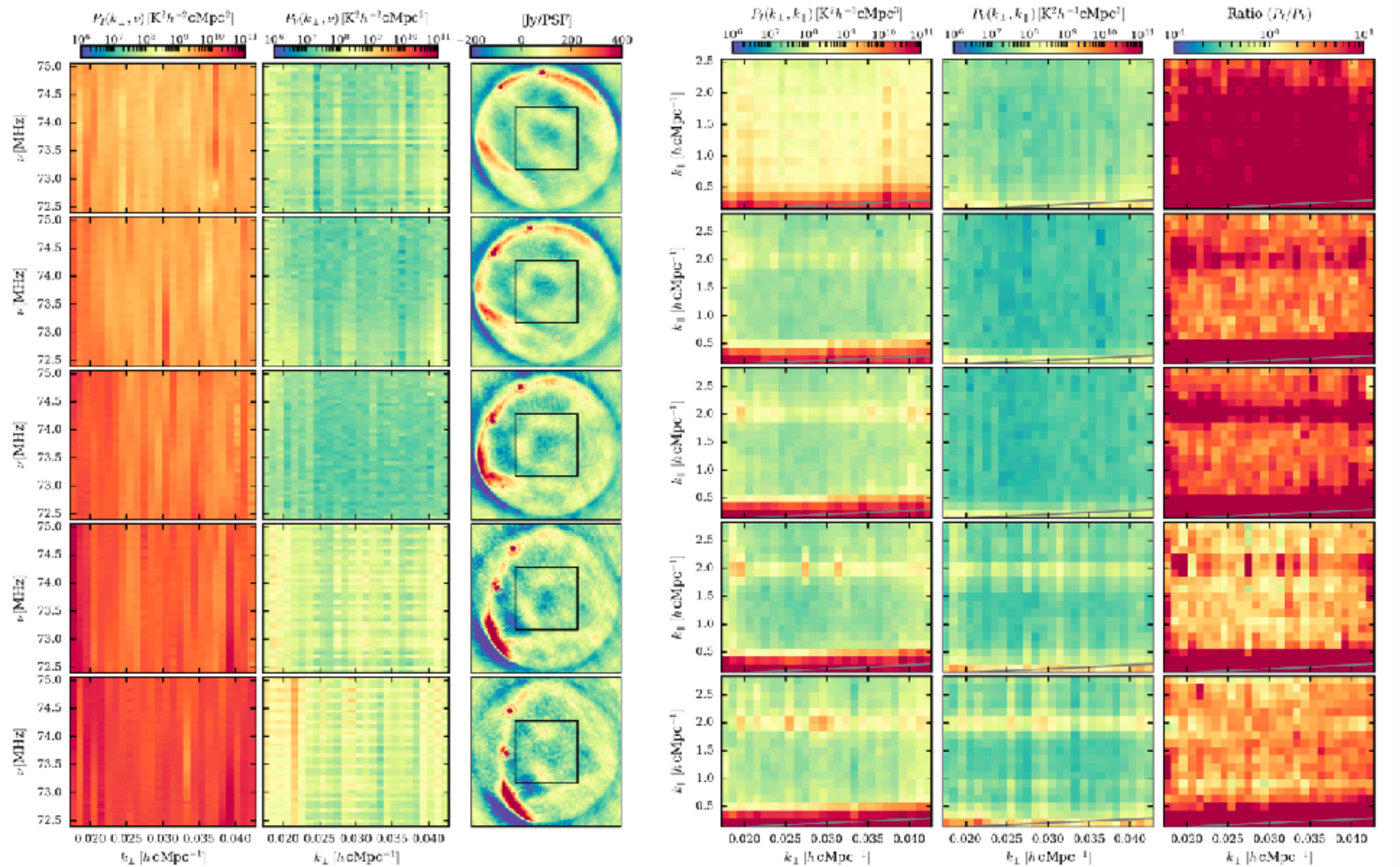


Single sub-band (@68MHz); 5.8hr integration; sliced and calibrated (NDPPP) per 10min with 20s/65kHz solution intervals). Sky model: Cas A, Cyg A, Vir A, 3C380, 3C196, 3C295

Gehlot et al. 2019

AARTFAAC Cosmic Explorer (ACE) Program

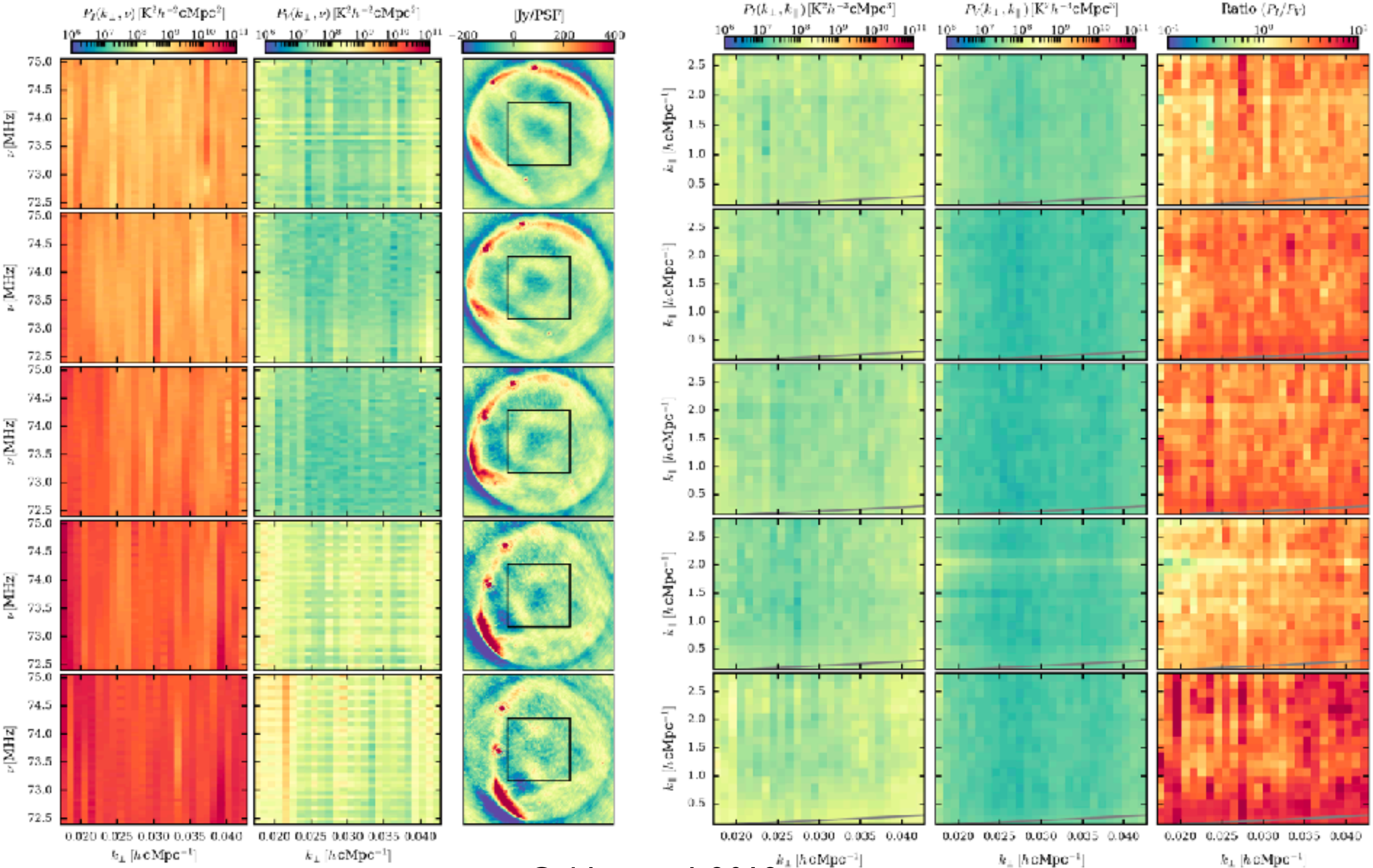
Cylindrical power spectra at z~18 before and after FG removal w/GPR



Gehlot et al. 2019

AARTFAAC Cosmic Explorer (ACE) Program

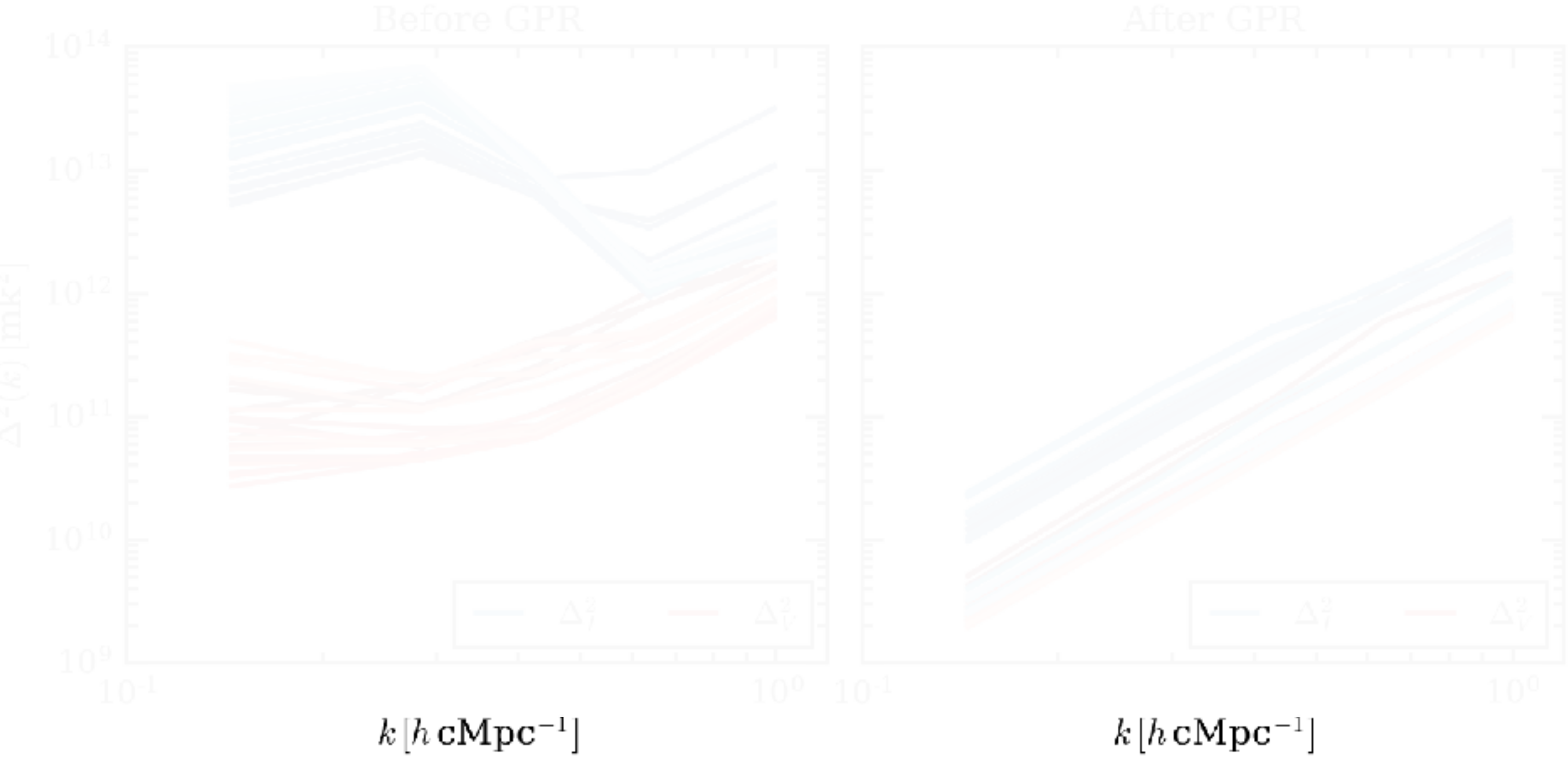
Cylindrical power spectra at z~18 before and after FG removal w/GPR



Gehlot et al. 2019

AARTFAAC Cosmic Explorer (ACE) Program

Spherical power spectra at z~18 before and after FG removal w/GPR



“Excess noise” remains that appear “white” and has a constant scaling w.r.t the thermal noise — origin not yet known.

Gehlot et al. 2019

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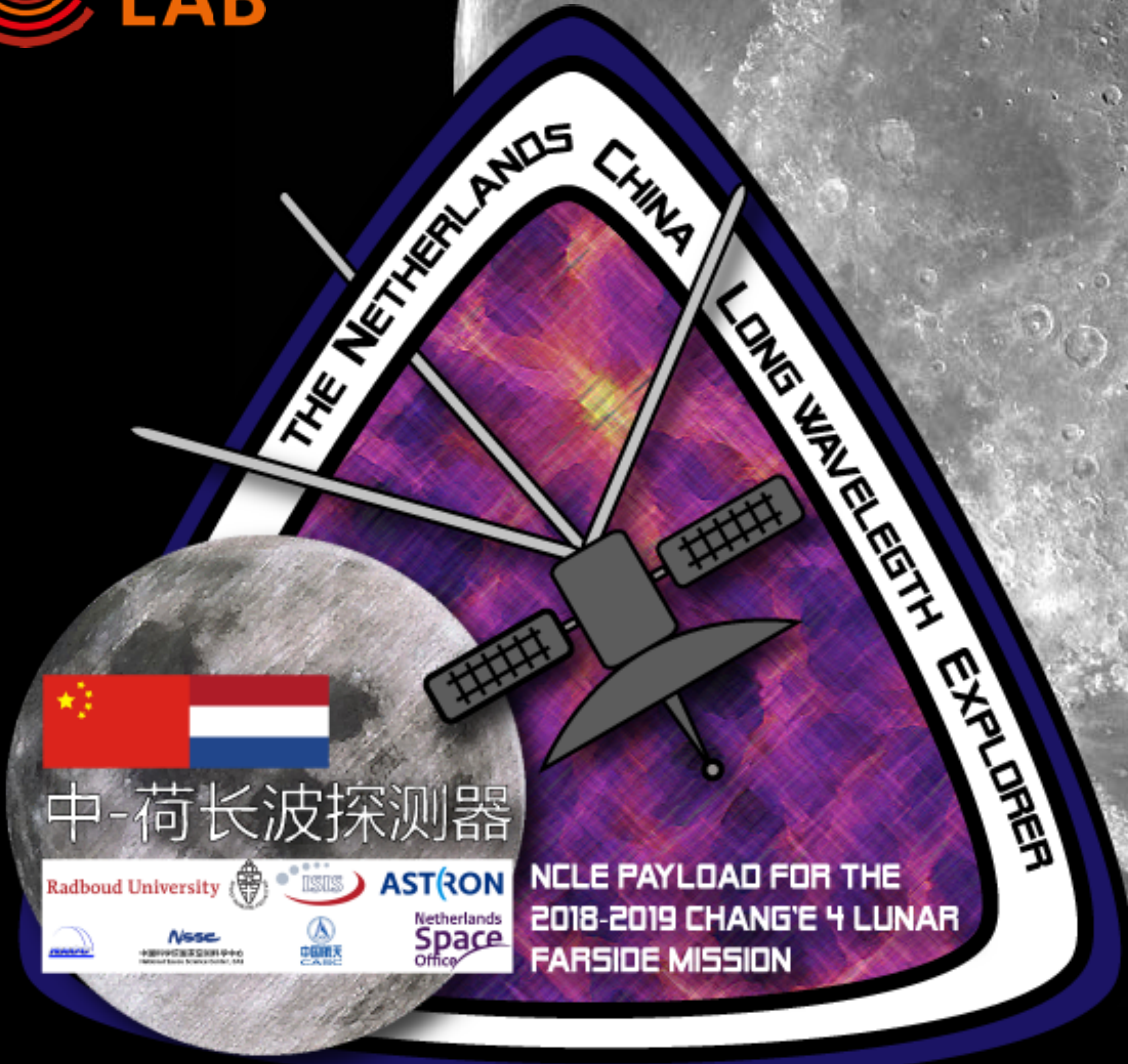
What about the Dark Ages signal?

Netherlands China Low-Frequency Explorer (NCLE)

Piggy-backing on to the Chines Chang'e 4 lunar lander mission…
Probing the Cosmic Dawn and the Dark Ages.

RADBOUD RADIO LAB



Radboud Universiteit Nijmegen

ASTRON
Netherlands Institute for Radio Astronomy

ISIS

NAOC

NSSC
中国科学院国家空间科学中心
National Space Science Center, CAS

CASC
中国航天
CASC

Netherlands Space Office

Science team member

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NCLE ON CHANG'E 4

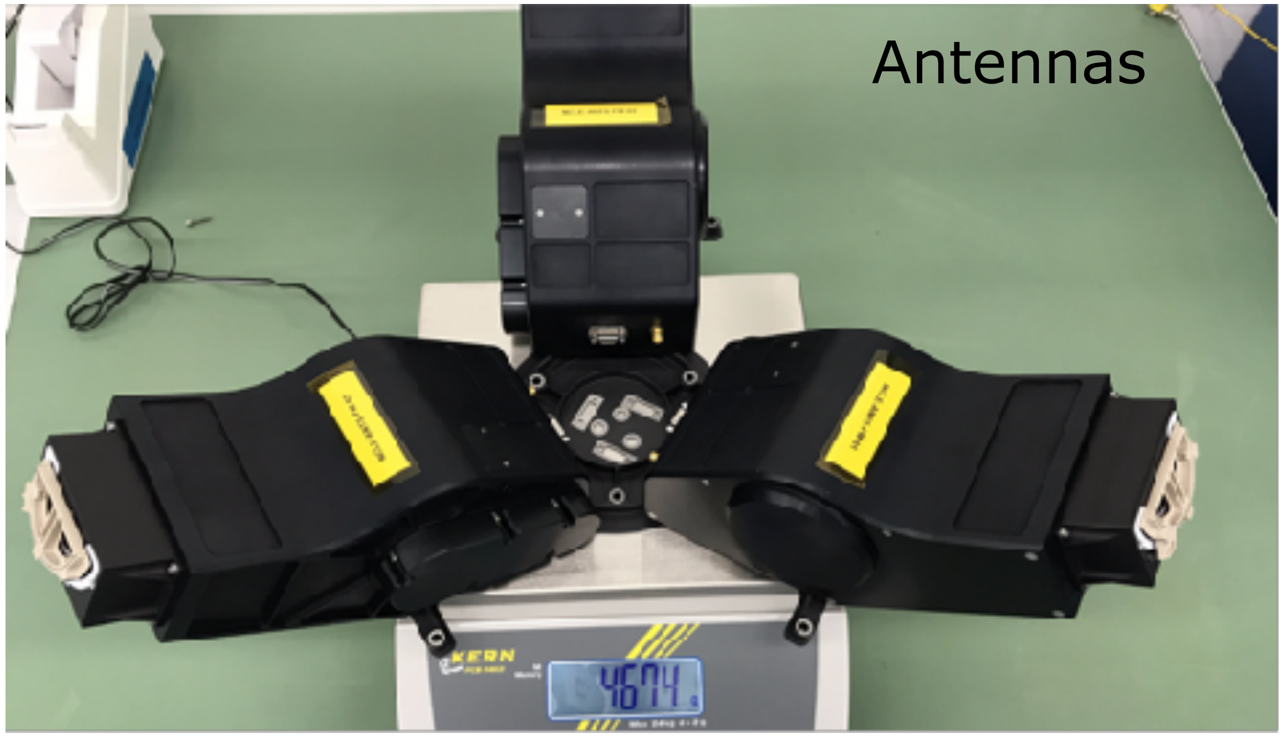
The first in many ways..

The first international payload on a Chinese mission, the first Dutch instrument to the moon and the first serious LF radio emission attempting to detect the redshifted 21-cm line emission from the Hydrogen in the very early Universe.

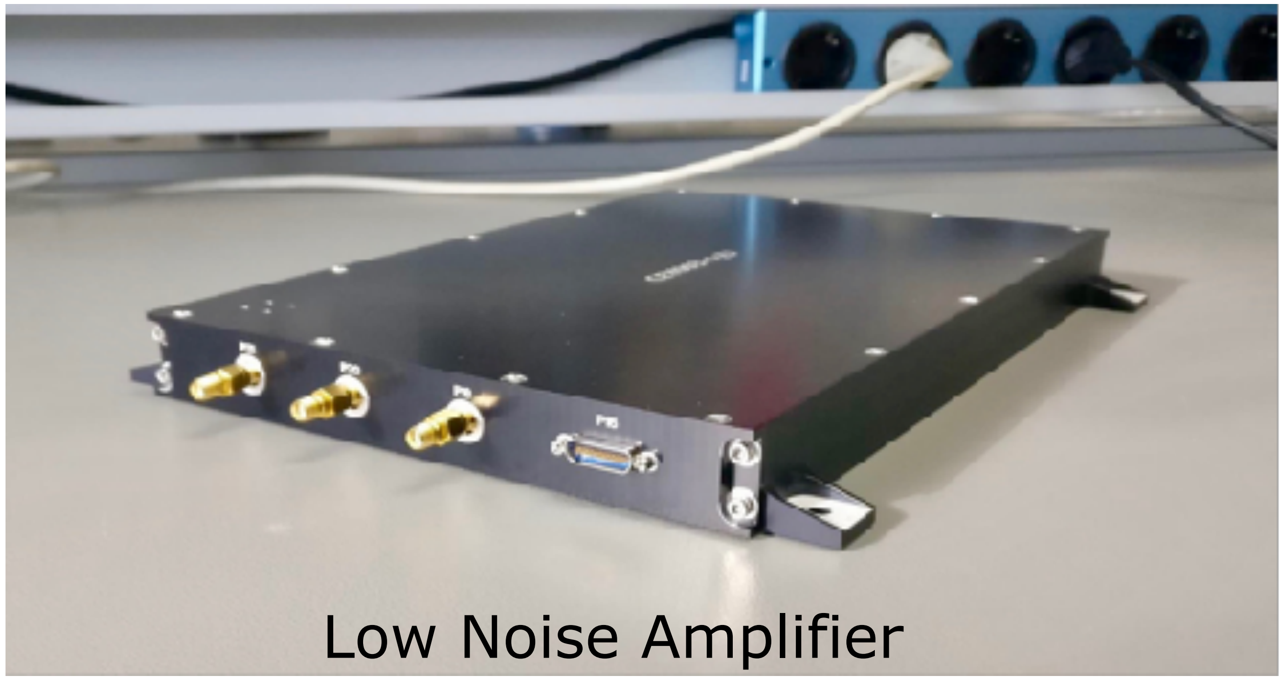
Netherlands China Low-frequency Explorer: NCLE

Components

- **Three Monopoles**, 5m each
- **3 bands**: <3 MHz, 1-60 MHz, 60-80 MHz
- **16k chan**, 7.5-0.9kHz, 100 ms dump time
- **Sky noise limited** for 2-50 MHz
- **Full polarization**: XX,YY, ZZ, XY,XZ,YZ
- **14 bit ADC**: 4x, 120 MHz
- on-board memory: **250 GB**
- Downlink: < **10Mbps**
- Power: < **25W**
- Mass: < **10Kg**
- mission life time: **3 years**
- Antenna deployment: **March 2019**

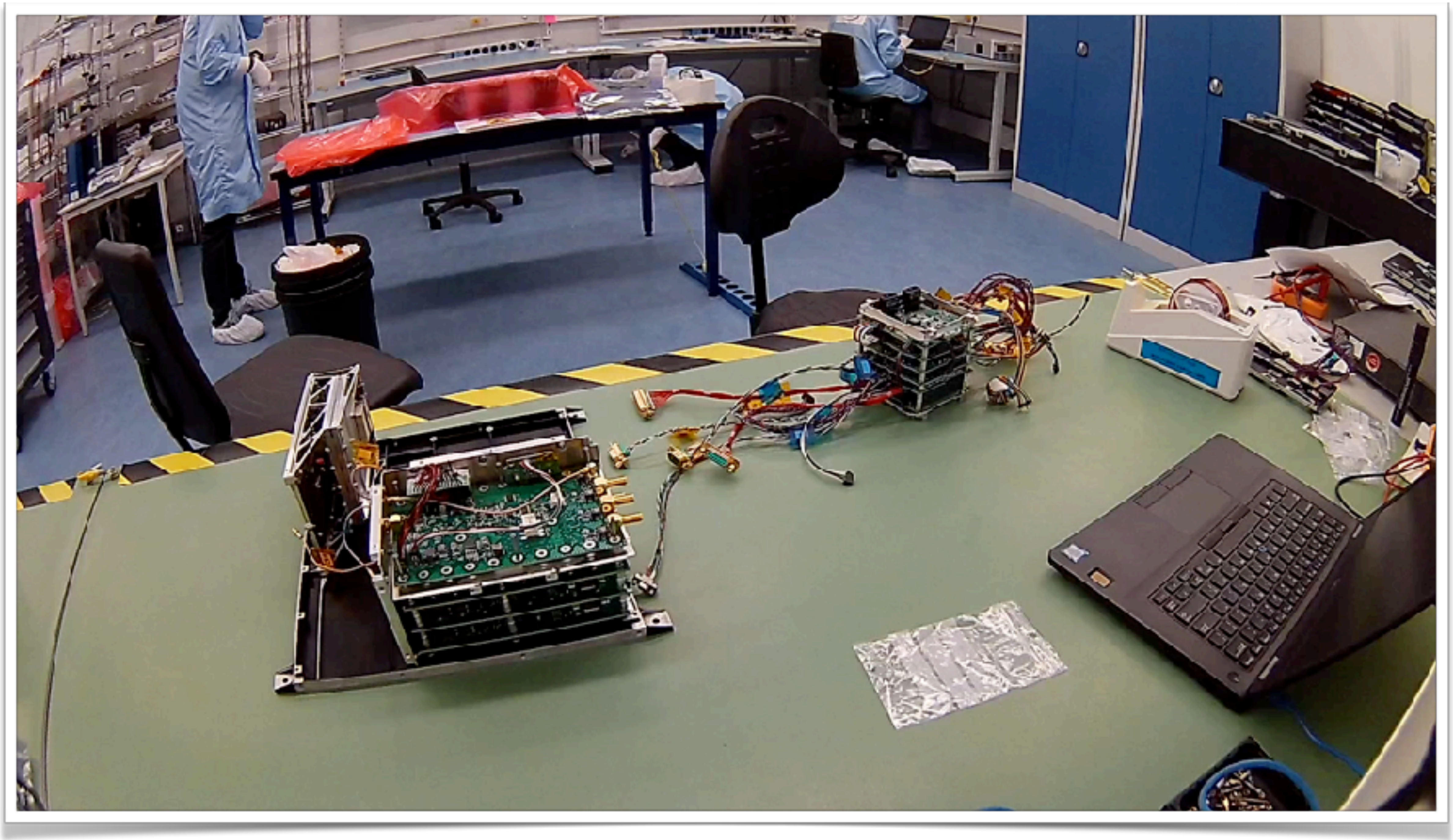

Antennas


Digital Receiver & Control


Low Noise Amplifier

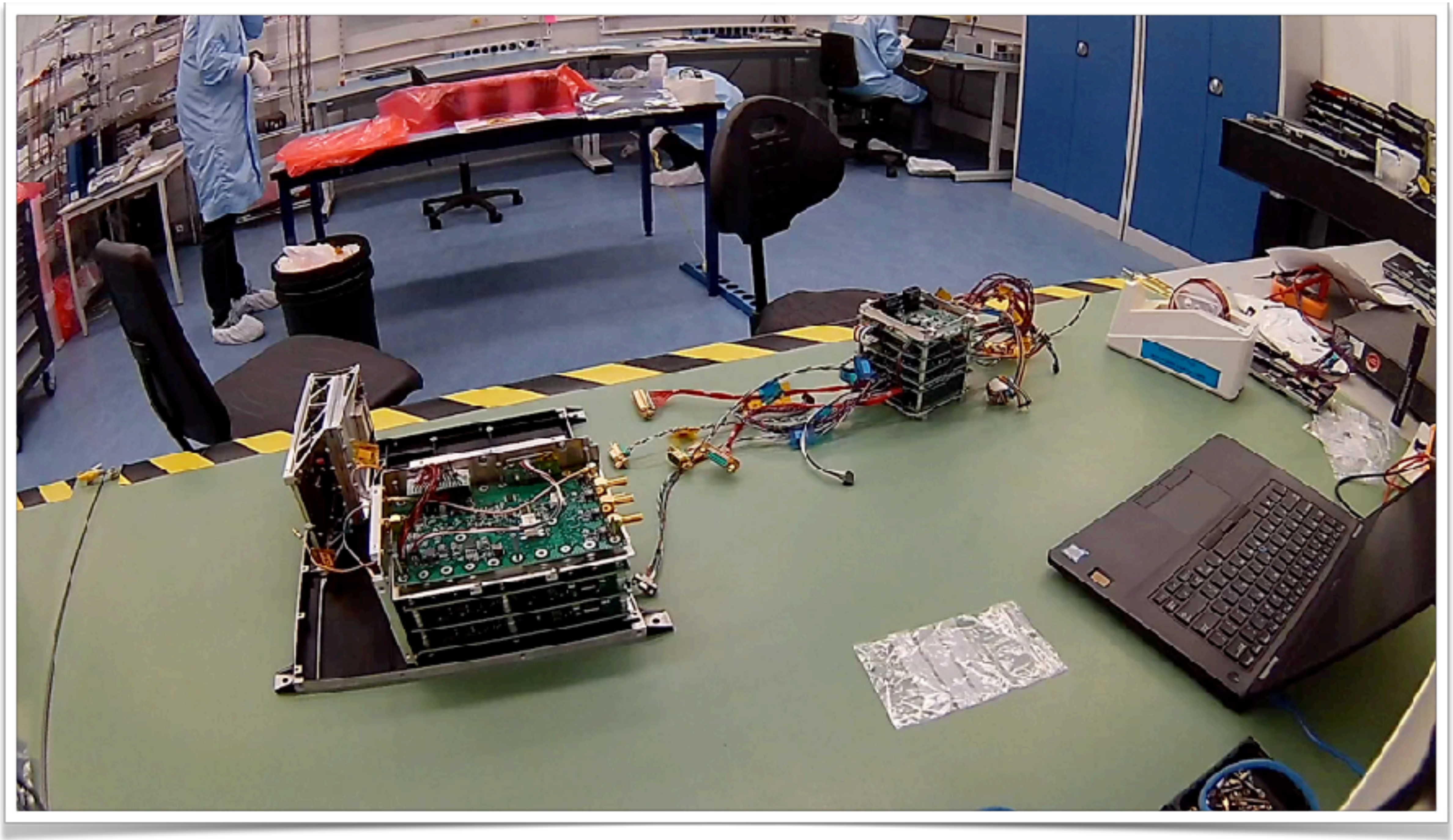
Netherlands China Low-frequency Explorer: NCLE

Integration time-lapse



Netherlands China Low-frequency Explorer: NCLE

Integration time-lapse



Netherlands China Low-frequency Explorer: NCLE

Unfolding of the tripoles (balloons compensate gravity)

Netherlands China Low-frequency Explorer: NCLE

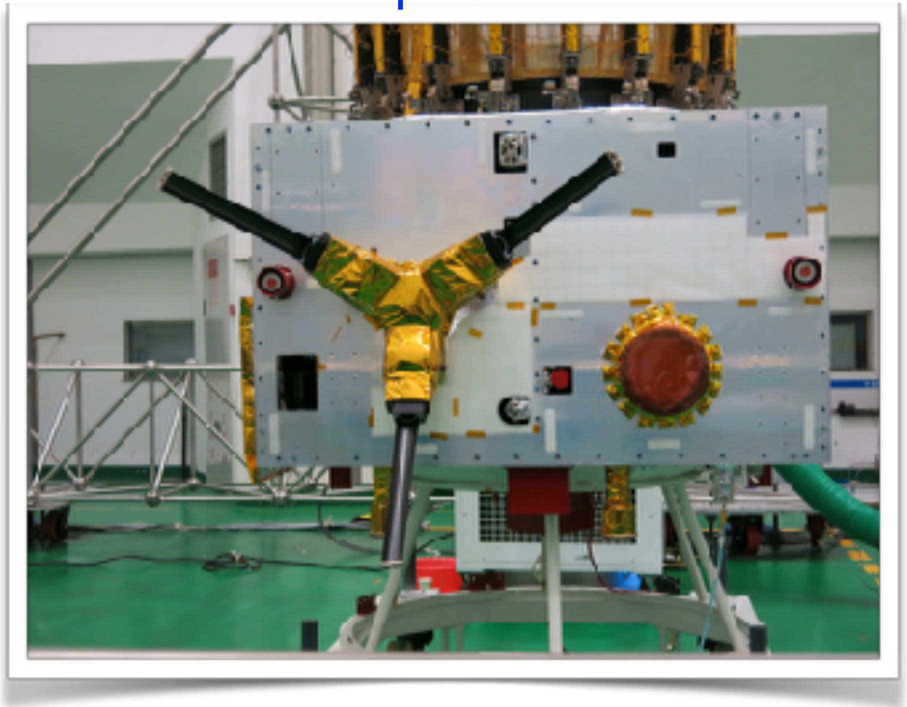
Unfolding of the tripoles (balloons compensate gravity)

Netherlands China Low-frequency Explorer: NCLE

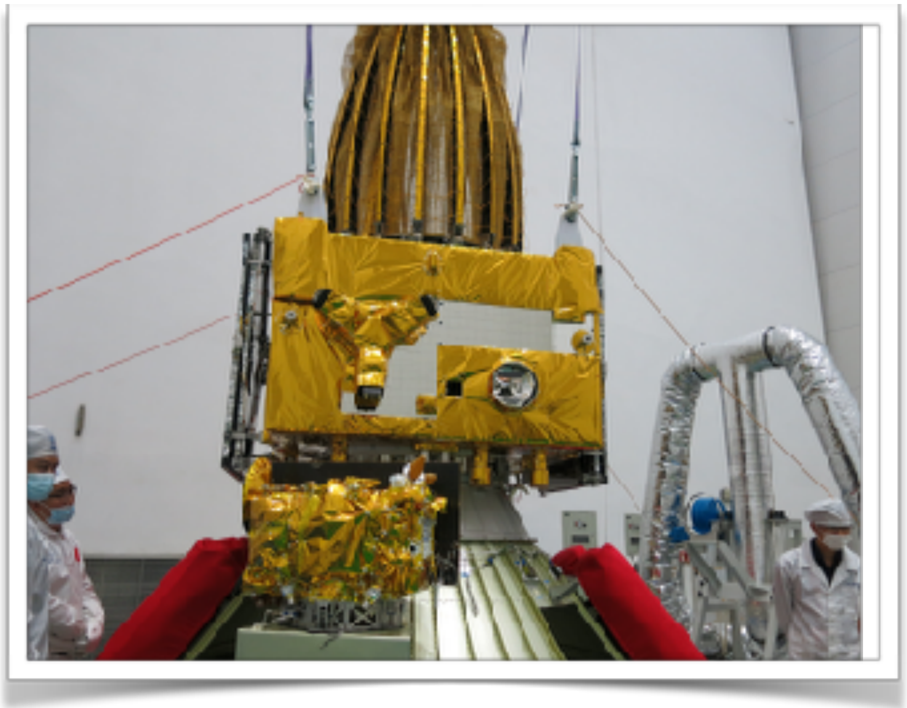
Unfolding of the tripoles (balloons compensate gravity)

Netherlands China Low-frequency Explorer: NCLE

Locations of the antennas elements on the spacecraft



Chang’e 4 Spacecraft at Xichang Launch base



Chang’e 4 Relay satellite with NCLE instrument in the cleanroom, April 2018

Detail of the receiver end

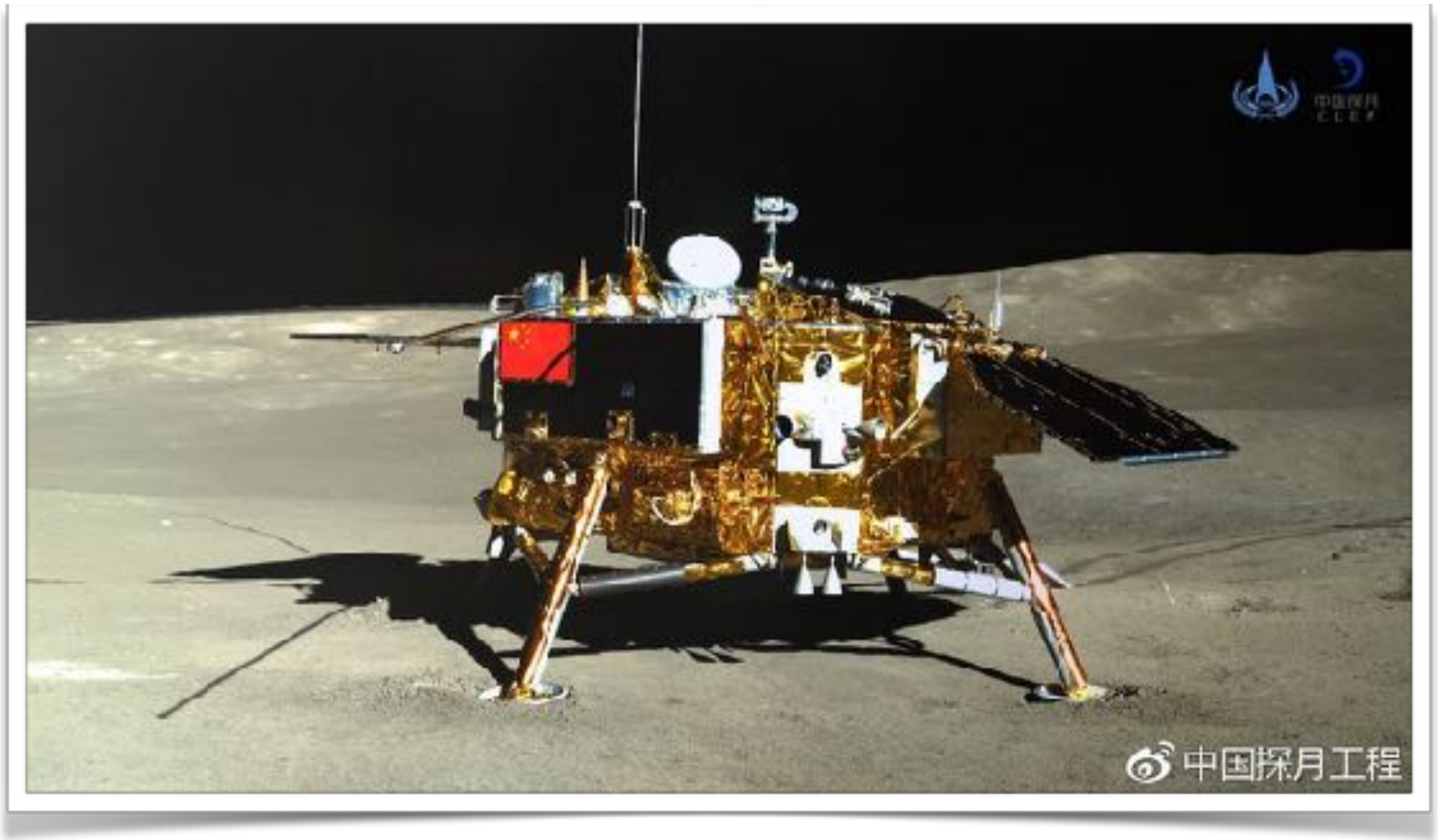
Netherlands China Low-frequency Explorer: NCLE

Successfully launched May 20/21 and deployed in L2.
Science operations will start spring 2019.

Netherlands China Low-frequency Explorer: NCLE

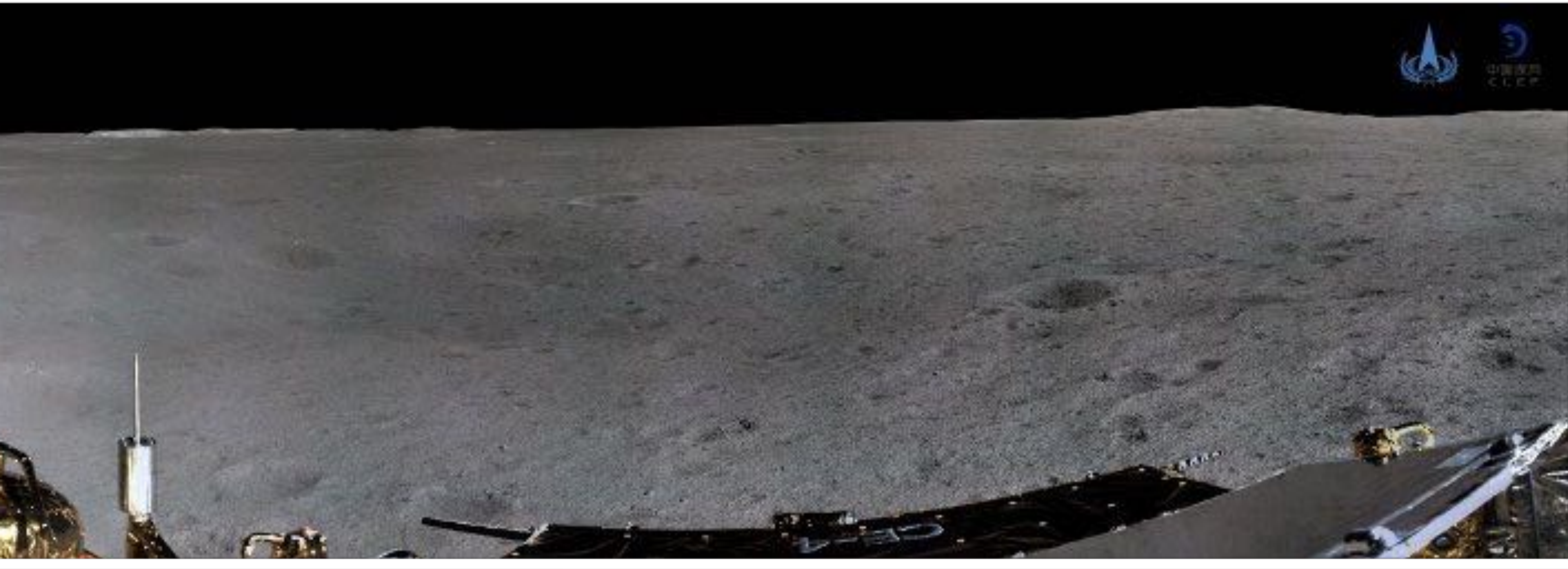
Lunar rover Yutu-2 deployed on the lunar surface, Jan 3rd 2019

Chang'e 4 Lunar lander - Dec 3rd, 2019, first ever landing on the lunar farside



Netherlands China Low-frequency Explorer: NCLE

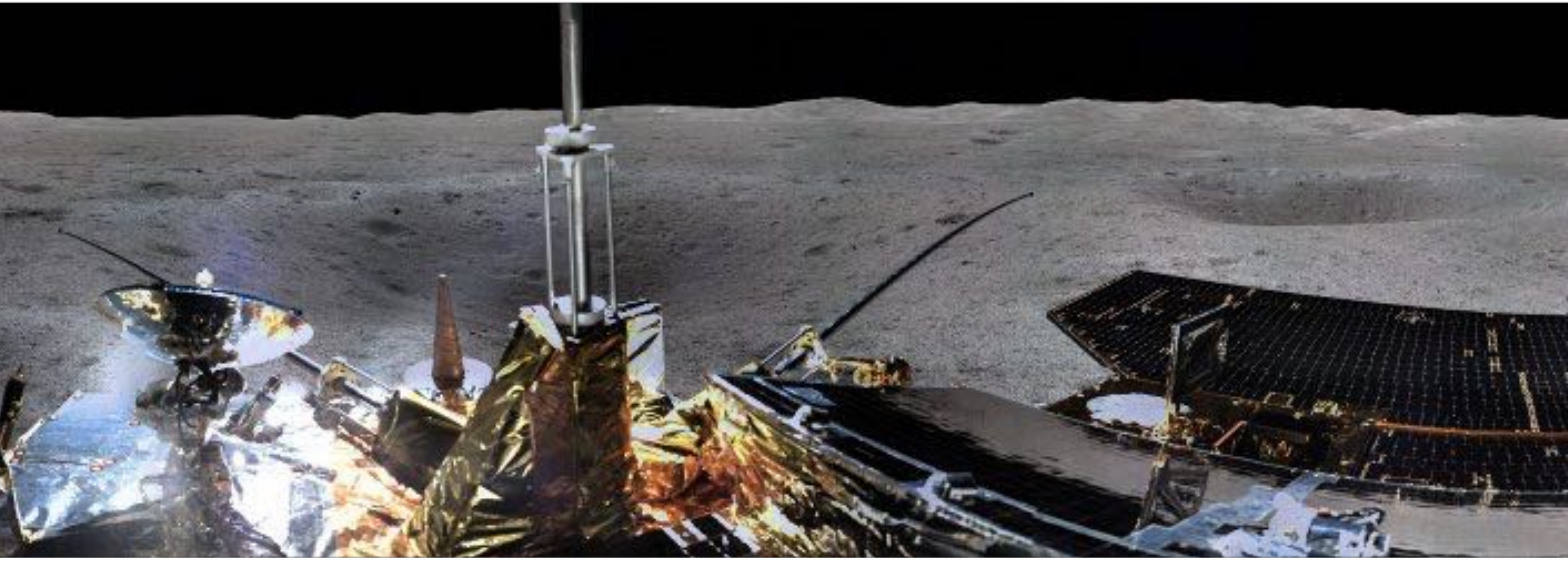
Chang’e 4 Lunar lander - View of the surroundings including the rover



Note the tripole on the lander! More data…

Netherlands China Low-frequency Explorer: NCLE

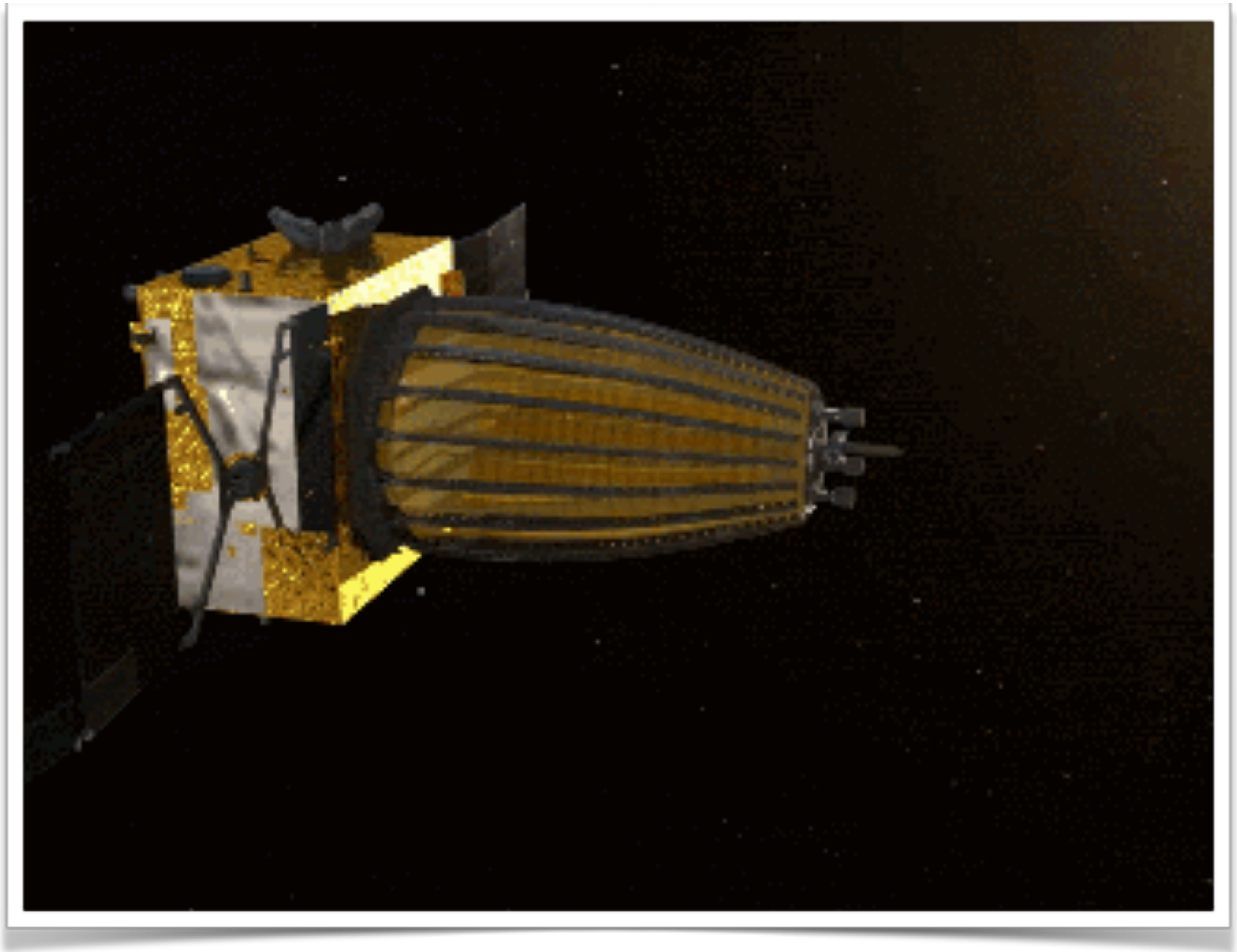
Chang’e 4 Lunar lander - View of the surroundings including the rover



Note the tripole on the lander! More data…

Netherlands China Low-frequency Explorer: NCLE

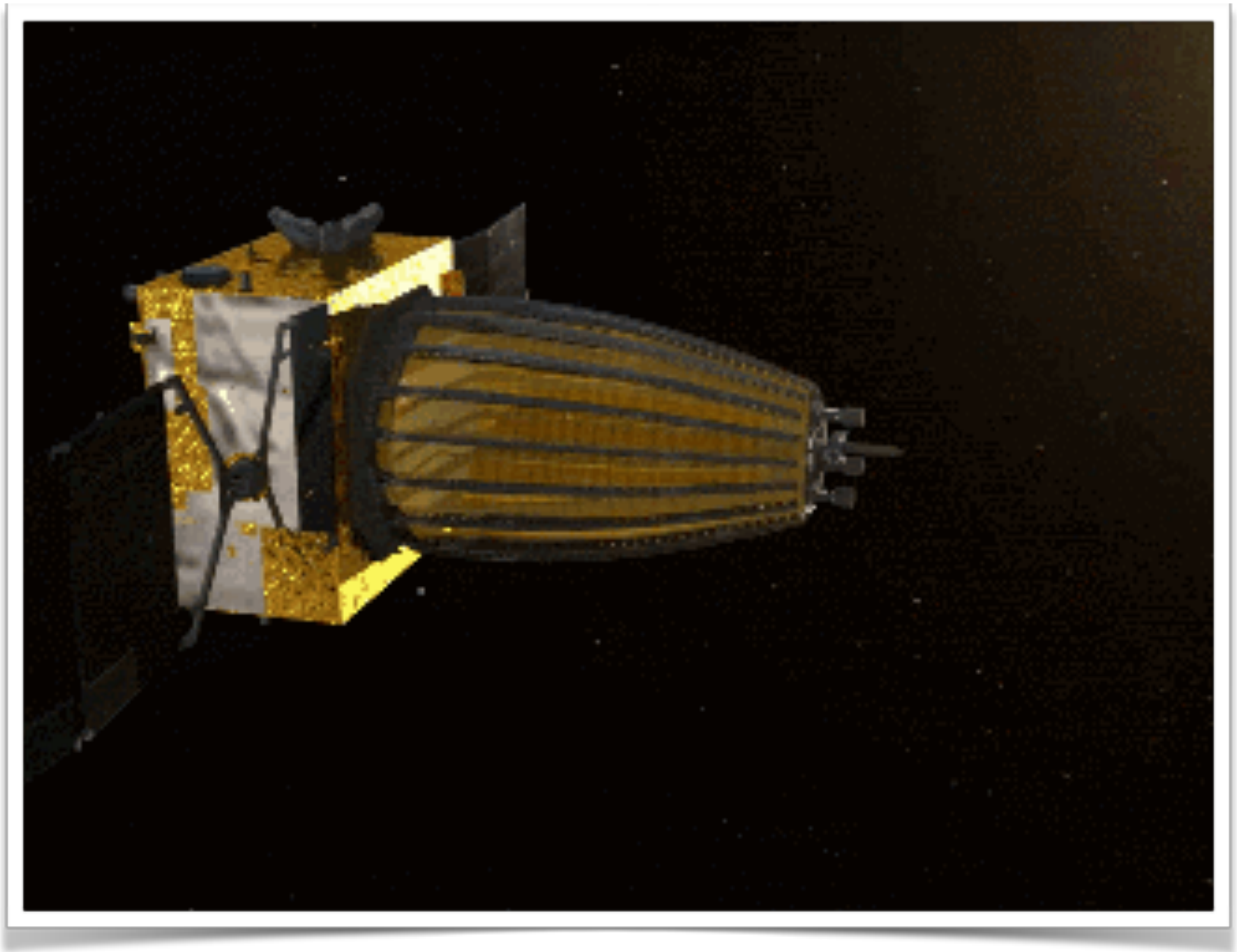
NCLE Antenna at Queqiao satellite, with Moon and Earth in the background



!! Maybe this week NCLE will start taking data with folded tripoles [1month];
then unfold: 0.5m [1months] =>1.5m(?) [1months] => 5m [>3 years]

Netherlands China Low-frequency Explorer: NCLE

NCLE Antenna at Queqiao satellite, with Moon and Earth in the background

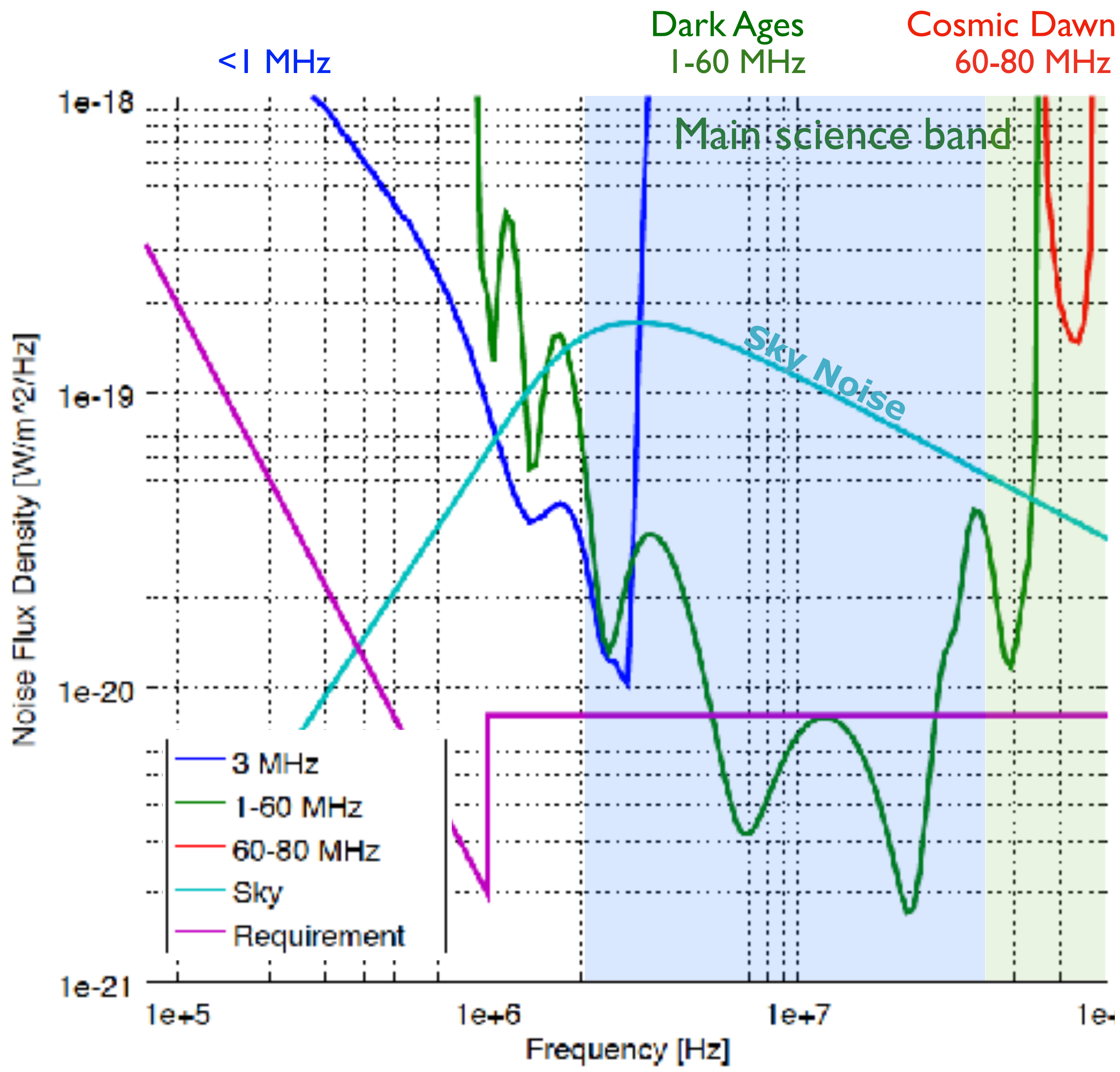


!! Maybe this week NCLE will start taking data with folded tripoles [1month];
then unfold: 0.5m [1months] =>1.5m(?) [1months] => 5m [>3 years]

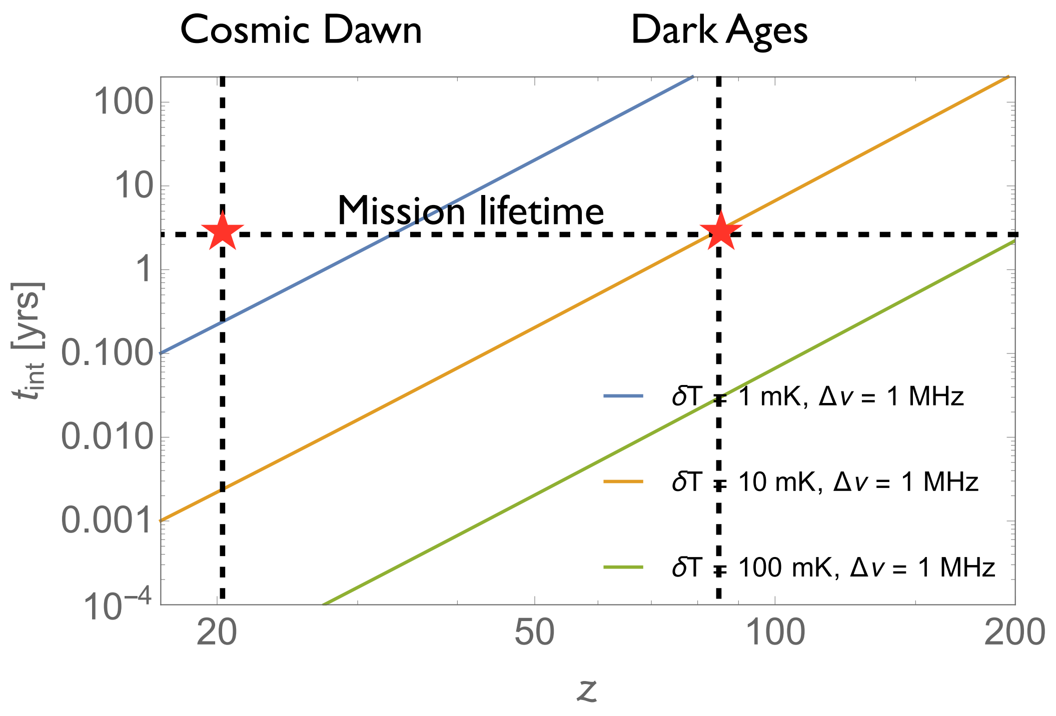
Netherlands China Low-frequency Explorer

NCLE can detect EDGES -600mK Dark Ages signal in ~1 week (>6-sigma level per MHz BW). For the nominal (-60mK) signal it requires the entire mission lifetime of several years.

This assumes limited systematics/RFI, etc.



- Sky noise dominated from 2-60MHz
- First light to be expected in spring
- Proof of principle: pilot project
- if successful, other experiments in the pipeline (DSL)



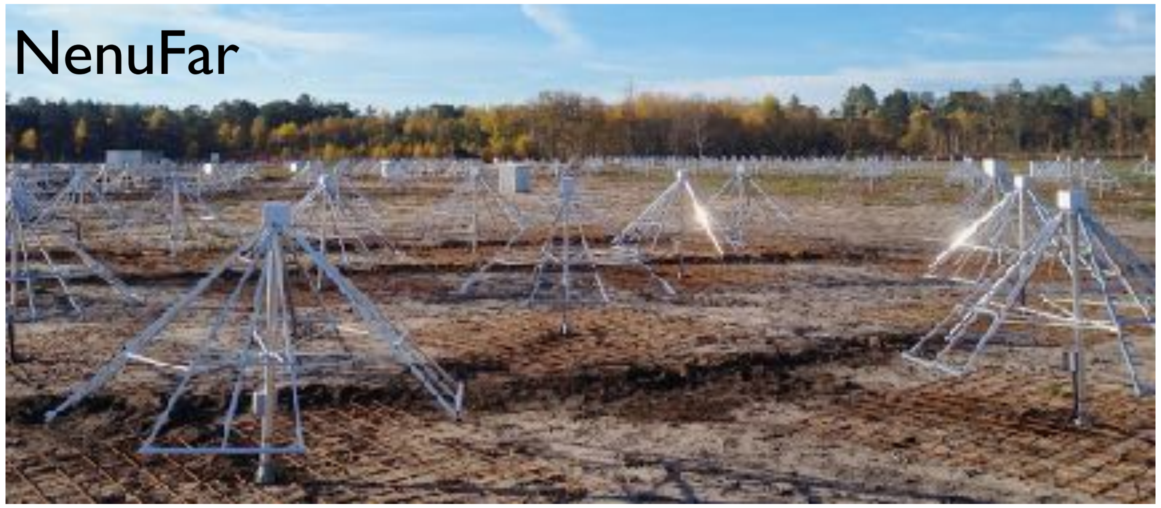
Slide Credits to Heino Falcke, Radio Lab Nijmegen, ISIS, ASTRON

Other Future Prospects

*New instruments on the horizon! SKA, HERA, NenuFar, DSL, NCLE2, …
many new ideas and instruments are being designed and build.*

Exciting new 21-cm Power-Spectrum/Tomography Instruments

2019



Specs:

- 10-80 MHz/FoV ~ 20°
- 52-96 mini-stations of 19 low-freq. dipoles each
- Baselines: ~10 m - 400 m (plus outriggers)

~2020

Specs:

- 50-250 MHz/FoV ~ 9°
- 331x14m wide-band dishes
- Baselines: few m to ~1 km

Paciga et al. 2013

~2025

Specs:

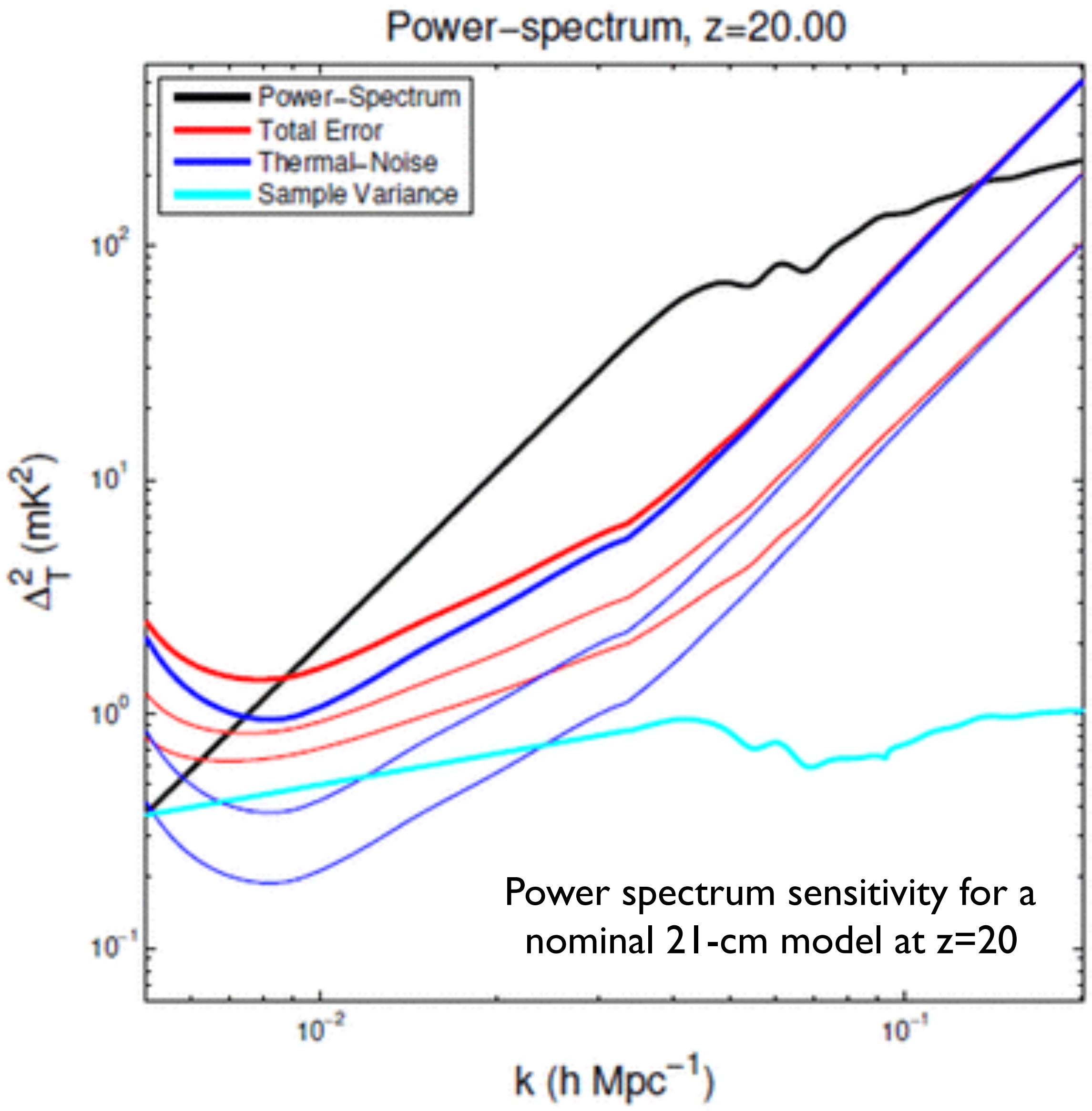
- 50-350 MHz/FoV ~ 4°
- 512 stations of 256 wide-band dipoles each
- Baselines: few m to 65 km

Dillon et al. 2015

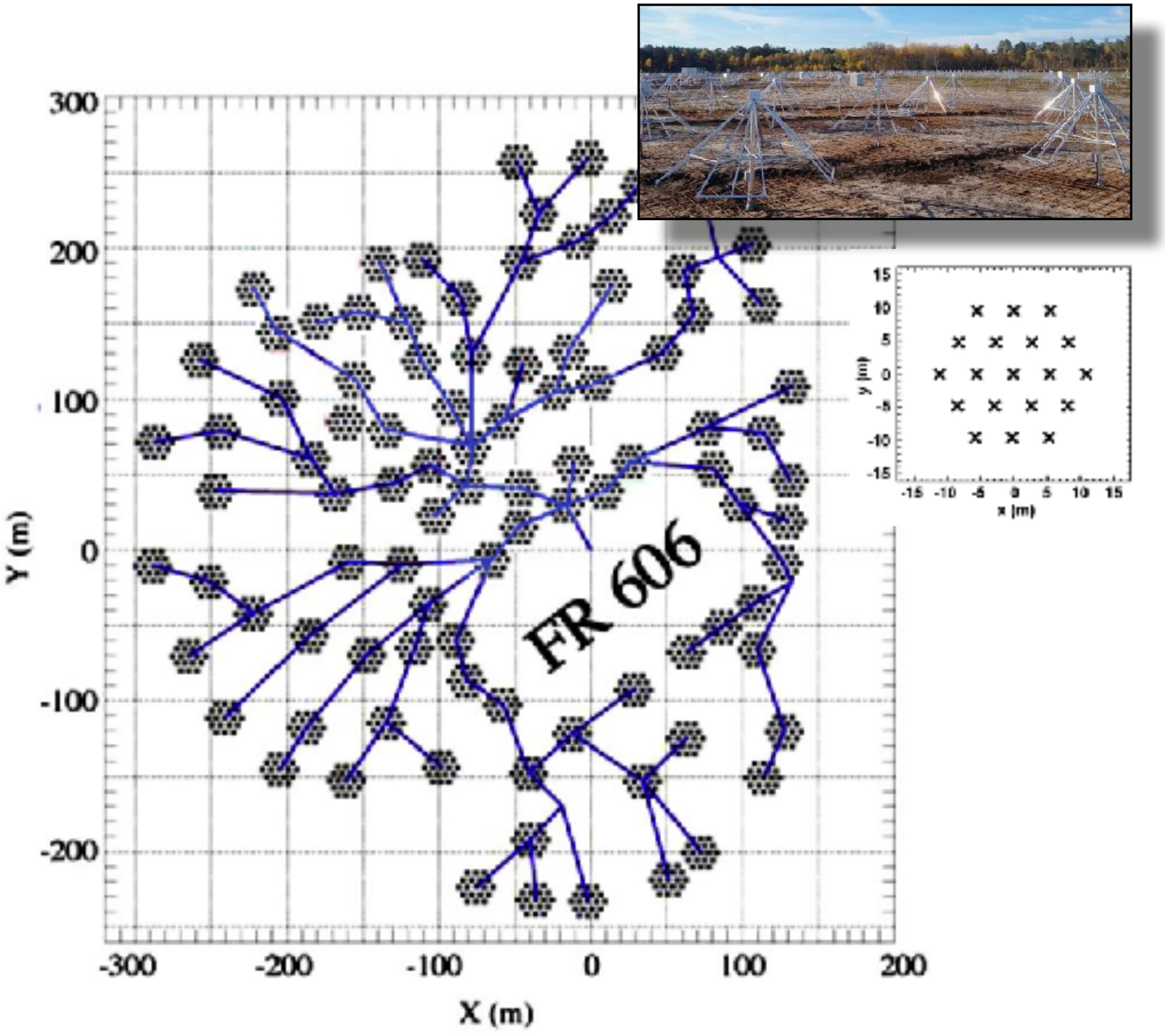
New Extension in Nançay Upgrading LOFAR: NenuFar

New Extension in Nançay Upgrading LOFAR: NenuFar

Starting a new Key Science Project: 21-cm signal from the Cosmic Dawn!



Power spectrum sensitivity for a nominal 21-cm model at z=20



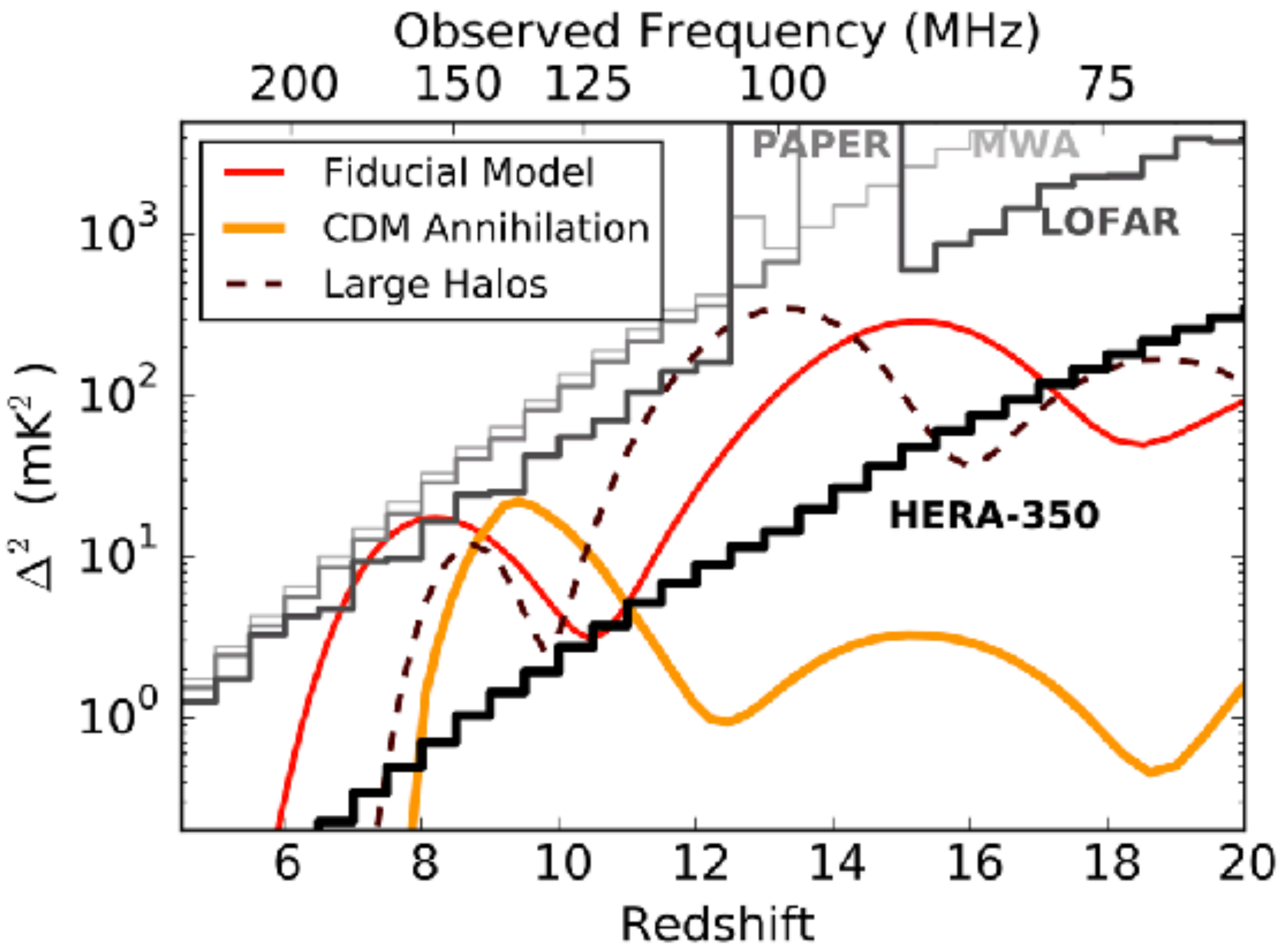
Large number of dipole receivers (96x19 = 1824) leads to extremely high sensitivity at low frequencies (f~1 @ 30MHz); Nançay, France)

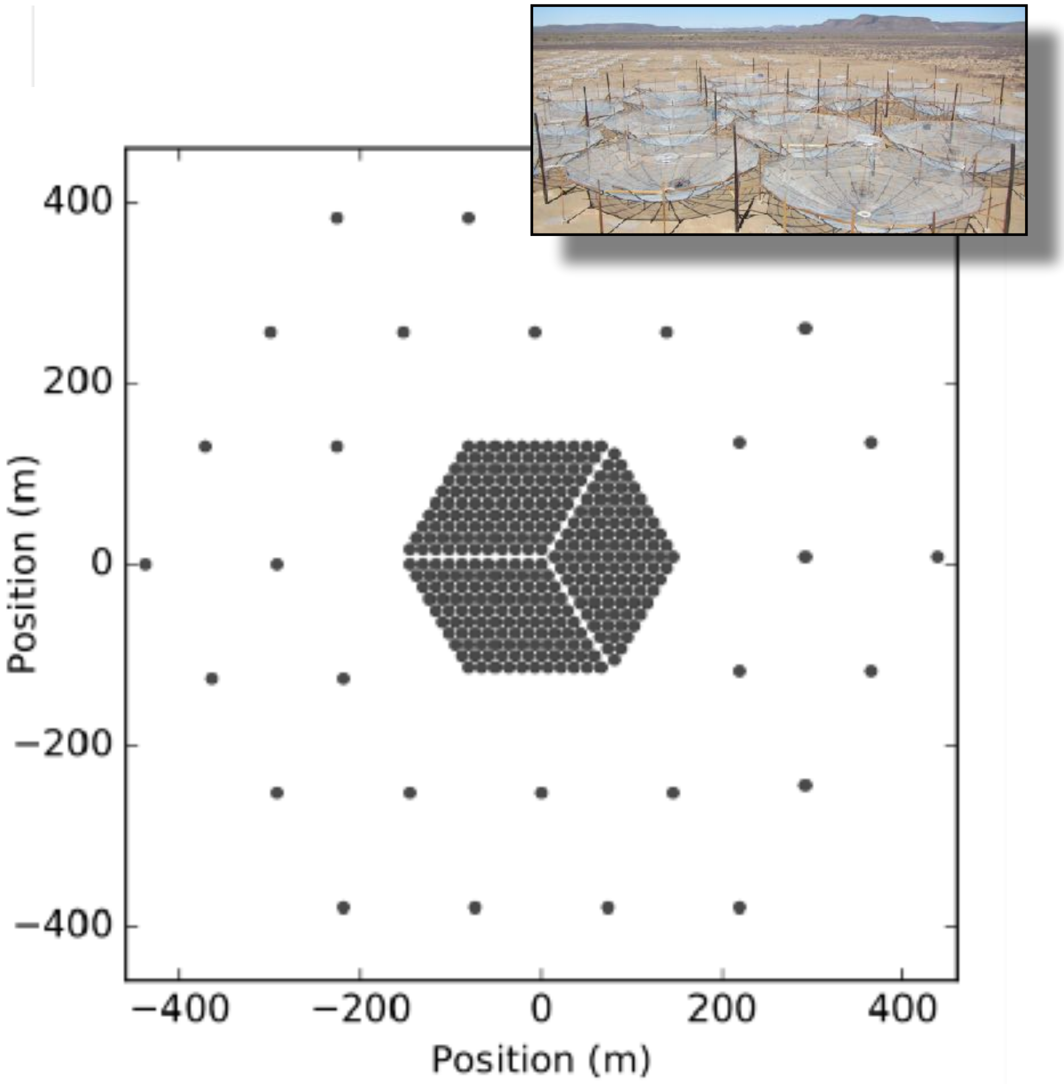
Zarka et al. 2015

Hydrogen Epoch of Reionization Array: HERA

Hydrogen Epoch of Reionization Array: HERA

Going deep very fast with a redundant array, some risks…





Large number of ~13m dish receivers (up to ~350) in a redundant hexagonal configuration but reduced field of view (Karoo, South Africa).

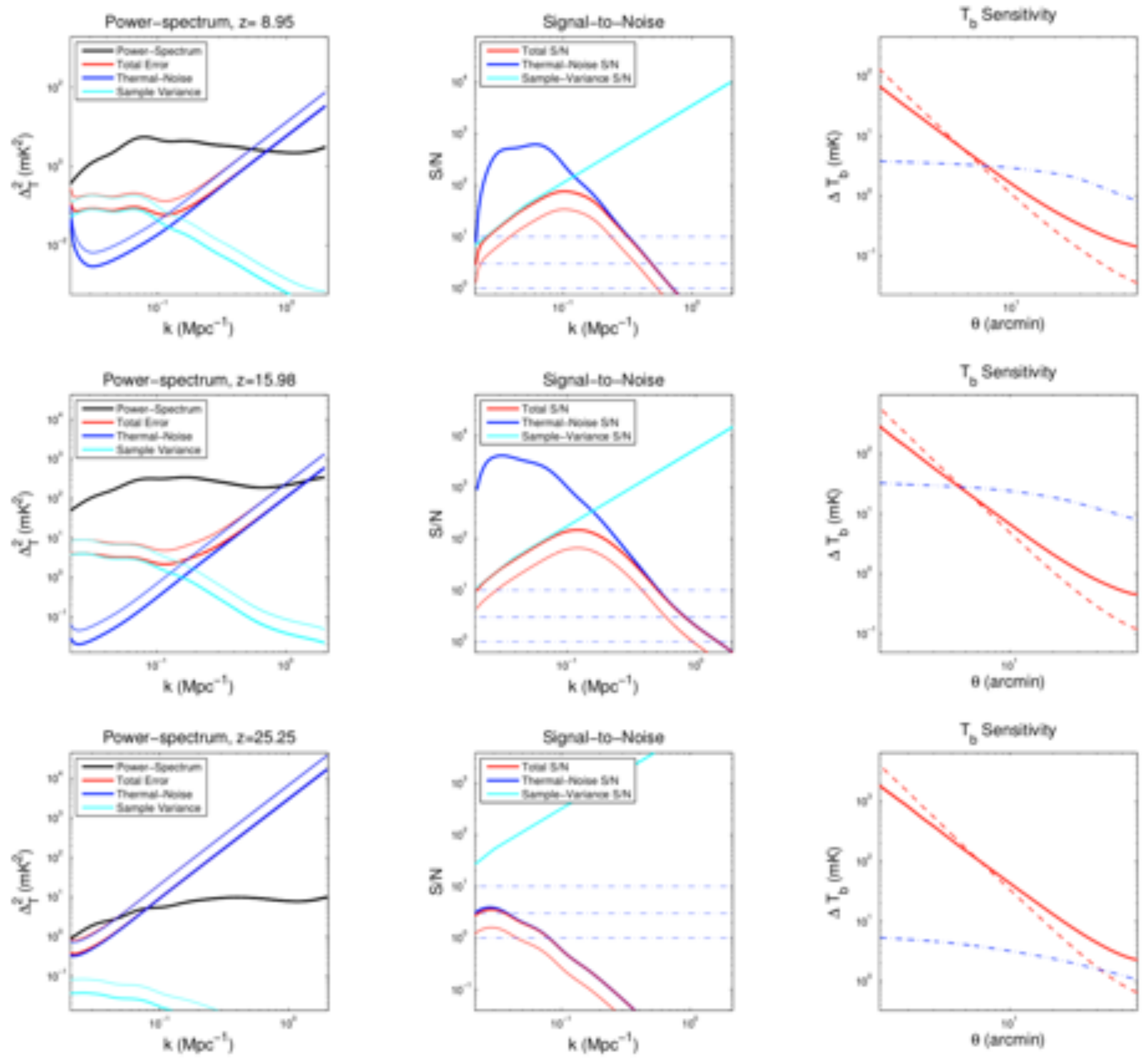
deBoer et al. 2016

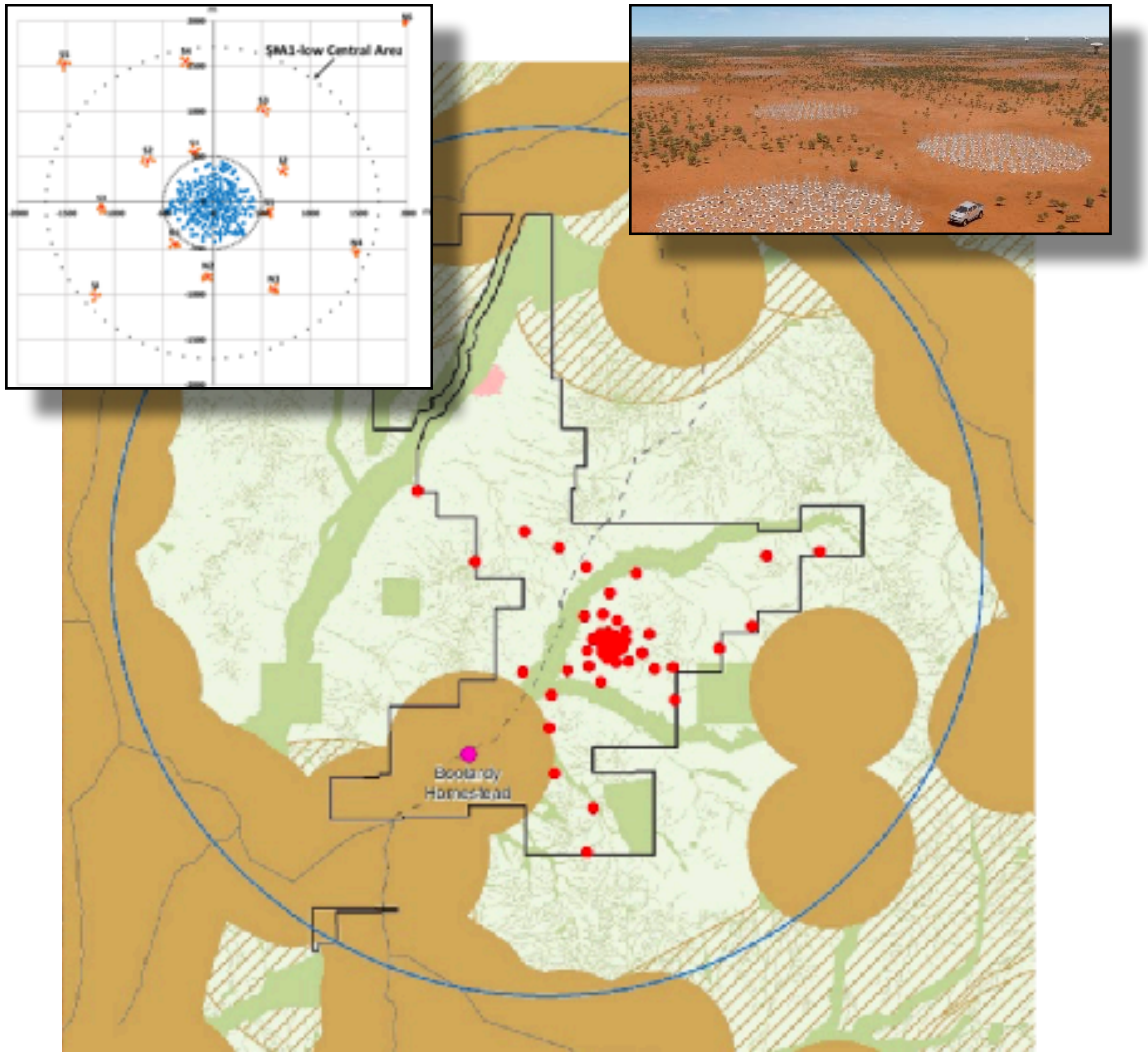
Square Kilometre Array: SKA(-low)

Square Kilometre Array: SKA(-low)

The Square Kilometre Array: SKA(1)-Low

Going deep very fast with a non-redundant array, most flexible system.





Large number of cross-dipole receivers grouped in ~512 stations (w/256 receivers) in a non-redundant configuration with reduced field of view (Western AU).

Koopmans et al. 2015; Labate et al. 2017

The Square Kilometre Array: SKA(1)-Low

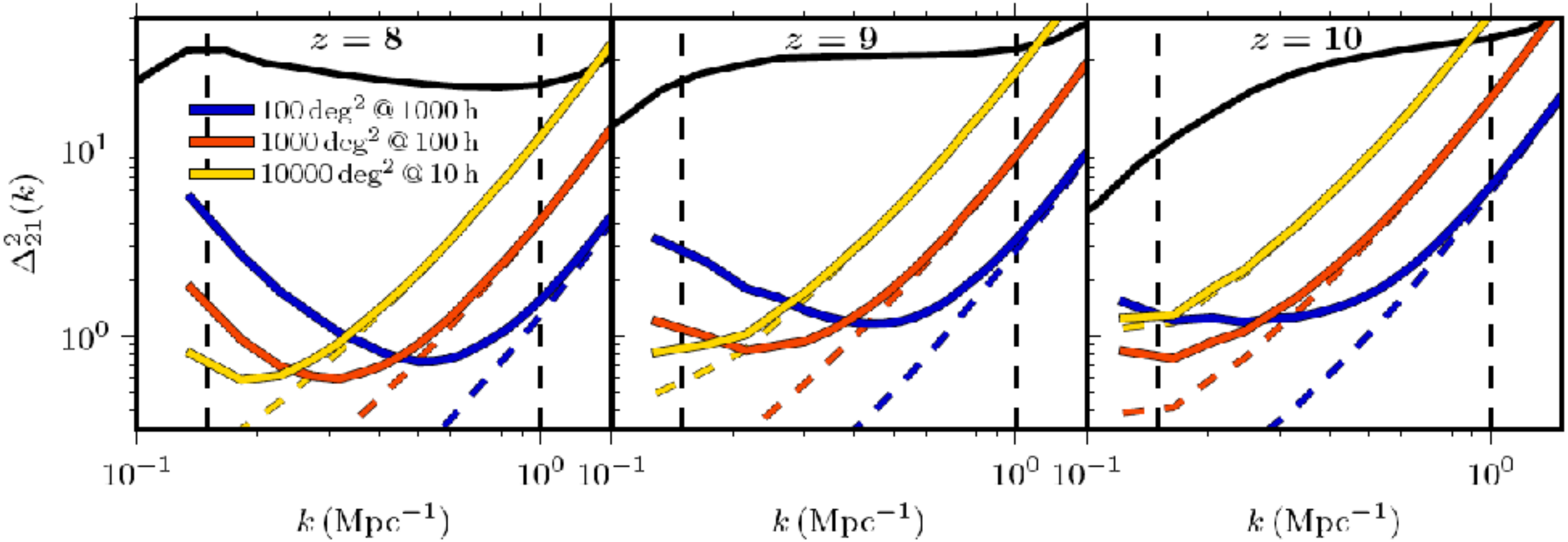
A three tiered-survey (3x5,000hrs):

- DEEP: 100sdq with 1000hr/pointing
- MEDIUM: 1000sqd with 100hr/pointing
- SHALLOW: 10000sqd with 10hr/pointing

Deeper is better on small scales (less thermal noise; bubbles)

Wider is better on large scales (less sample variance)

Both are needed (PS+Tomography)

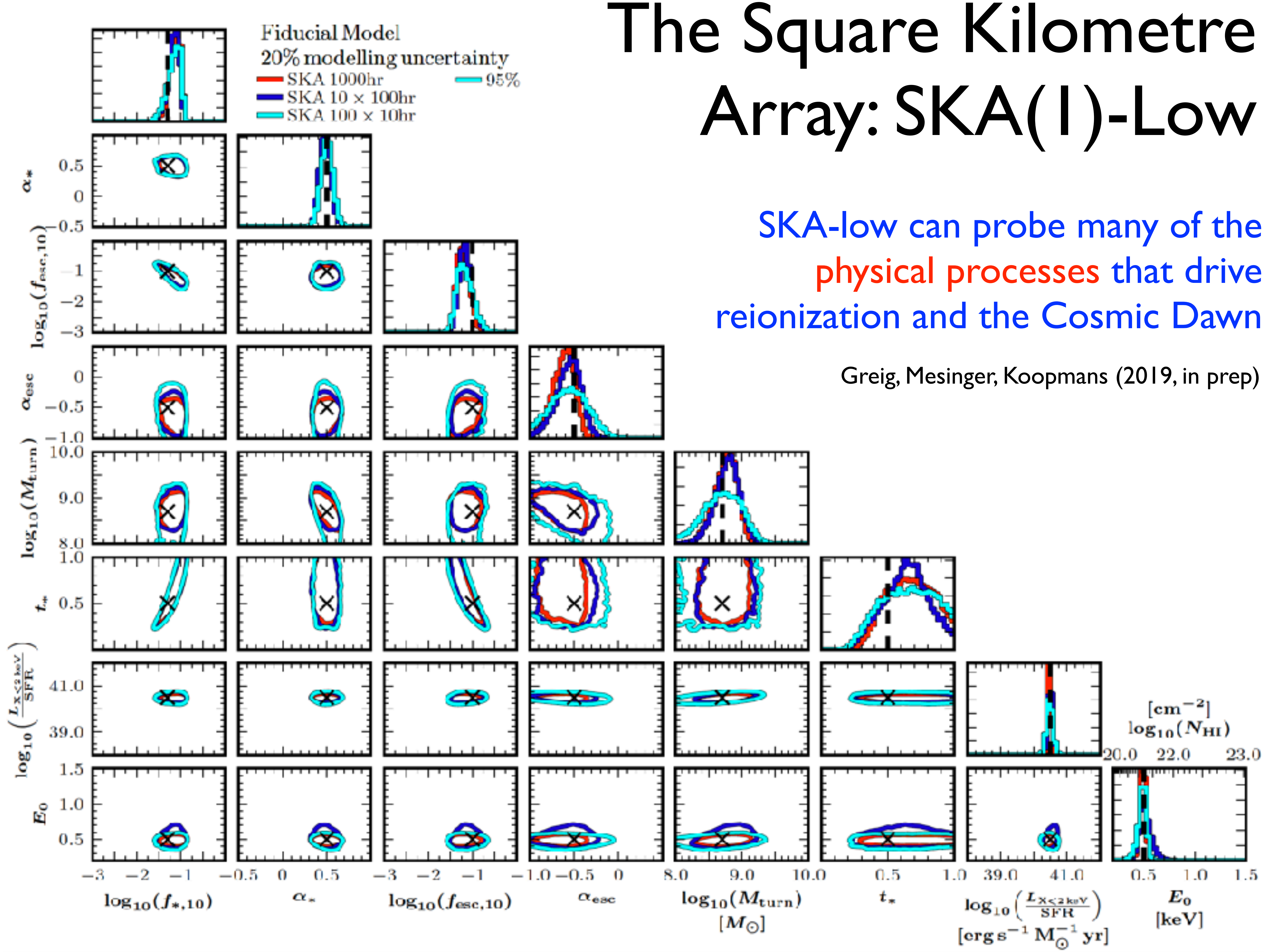


Greig, Mesinger & Koopmans (2015)

The Square Kilometre Array: SKA(1)-Low

SKA-low can probe many of the physical processes that drive reionization and the Cosmic Dawn

Greig, Mesinger, Koopmans (2019, in prep)



The Square Kilometre Array: SKA(1)-Low

Ending with an artist impression of SKA1-low in Western Australia in ~2025

Dutch ministry has just agreed on a contribution of 30M€ to SKA1

The Square Kilometre Array: SKA(1)-Low

Ending with an artist impression of SKA1-low in Western Australia in ~2025

Dutch ministry has just agreed on a contribution of 30M€ to SKA1

General Summary

- The 21-cm signal from the Dark Ages, Cosmic Dawn and Reionization promises a new and unique probe of the 1st billion year of the Universe.

- Many ongoing/planned global and interferometric experiments
  - All experiments are extremely difficult (technically, (astro)physically, signal processing)
  - Steady progress on all fronts, but requires long-term investments
  - Ground and now also space-based experiments (e.g. NCLE)

- Current Status (selected)
  - ‣ Only upper limits on the 21-cm signal, but …
  - ‣ EDGES2 claimed detection of the global signal (-600mK @ z~17)
  - ‣ LOFAR: obtained the deepest upper limits on PS @ k=0.1, z=8-10, 20-25

- Future promises
  - ‣ Important for the field: confirm EDGES result w/e.g. SARAS3/LEDA…
  - ‣ Detect EoR/CD 21-cm signal power spectra w/e.g. LOFAR/MWA/…
  - ‣ Building of SKA, HERA, NenuFar: tomography of the 21-cm signal
  - ‣ Going in to space: NCLE/… and going for the Dark Ages.