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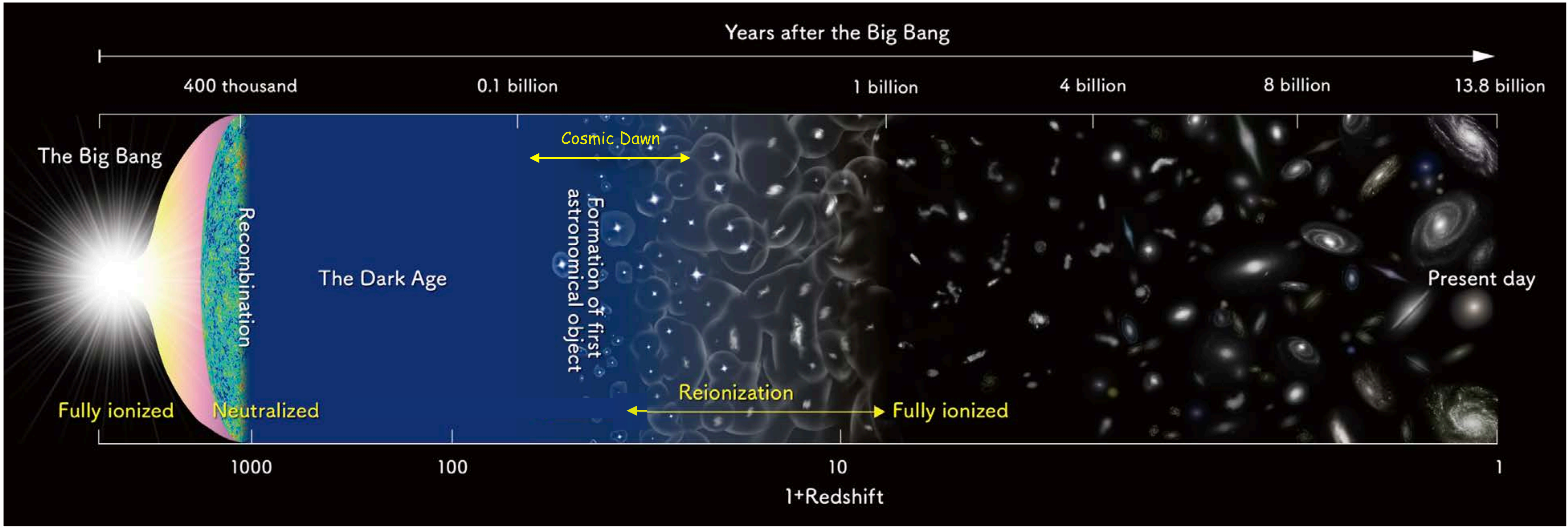
The Epoch of Reionization

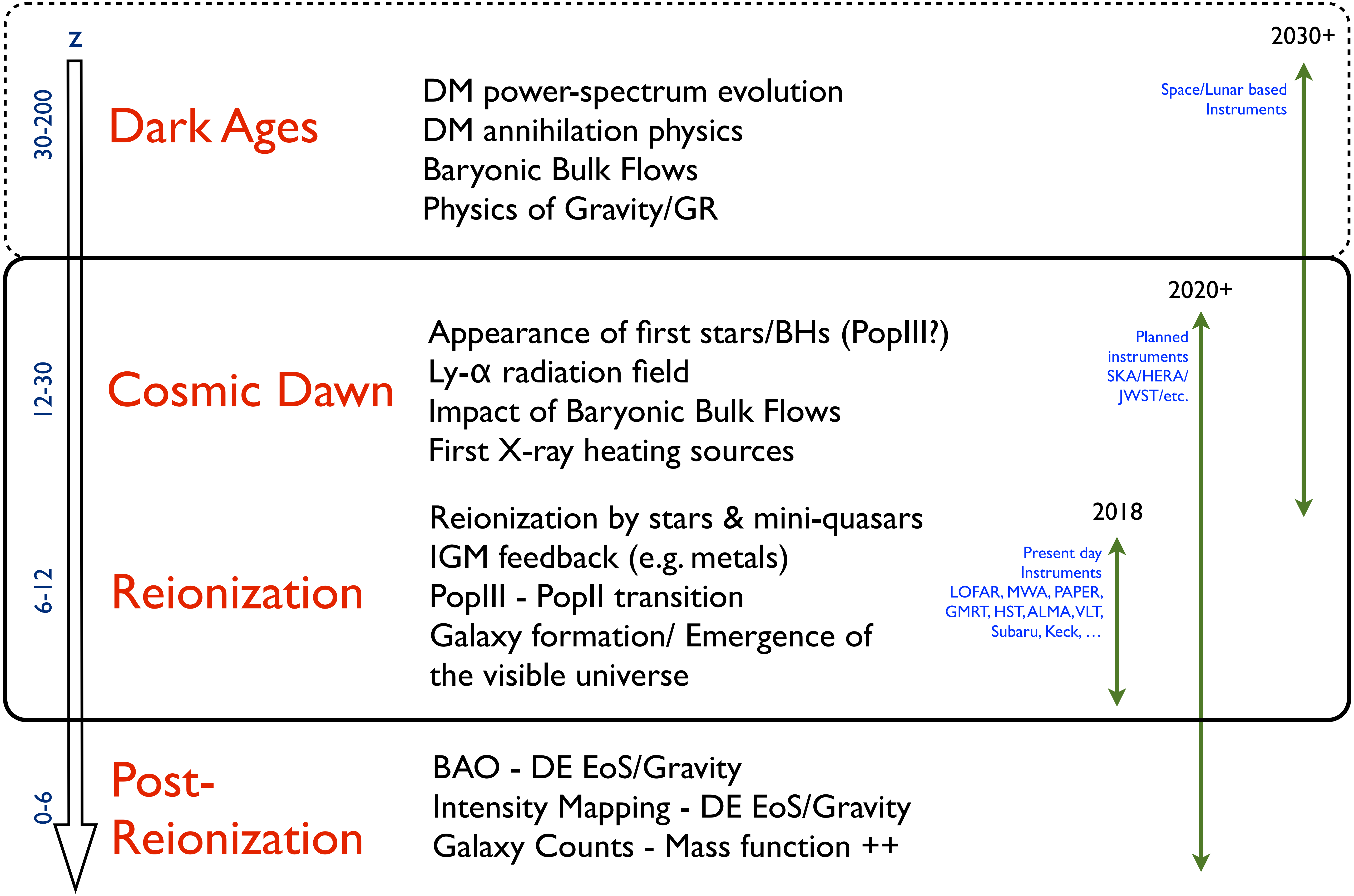
Léon V.E. Koopmans (Kapteyn Astronomical Institute)

*“We know more about recombination than about reionization,
but it forms the foundation of the present-day Universe.”*



IAU, 2018

Why Study the Universe’s First Gyr?



z

30-200

Dark Ages

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

2030+
Space/Lunar based Instruments

12-30

Cosmic Dawn

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

2020+
Planned instruments SKA/HERA/JWST/etc.

6-12

Reionization

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

2018
Present day Instruments
LOFAR, MWA, PAPER, GMRT, HST, ALMA, VLT, Subaru, Keck, …

0-6

Post-Reionization

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

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Mounting Evidence for Reionization

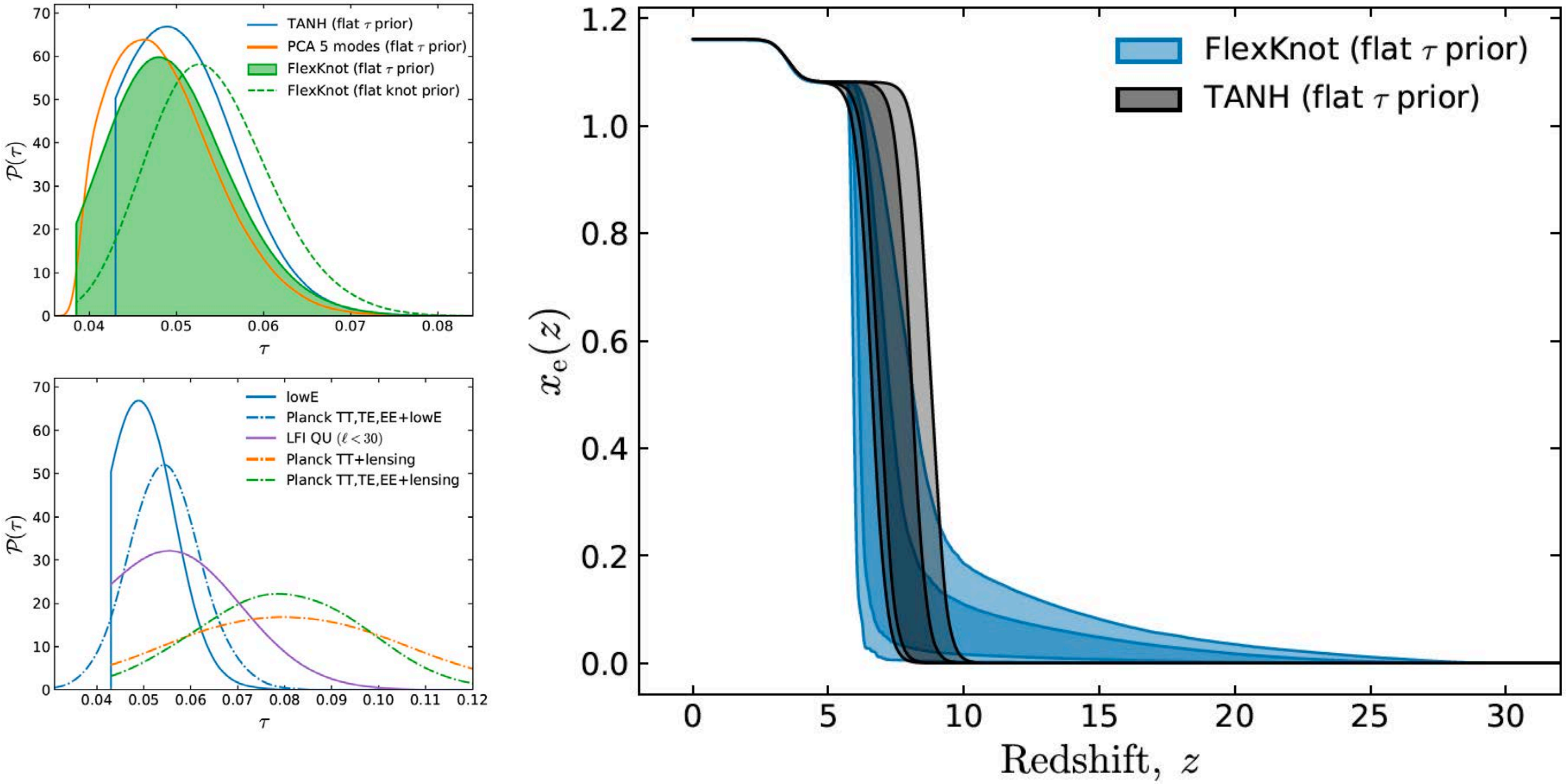
The last decade has witnessed an enormous growth in observational evidence for reionization happening rapidly at relatively low redshifts (z<10) thanks so many new instrument (HST-WFC, WMAP/Planck, Subaru-HSC, ALMA, etc.).

But the hydrogen itself has not yet been detected … or has it?

IAU, 2018

Some Selected Observations of the CD/EoR

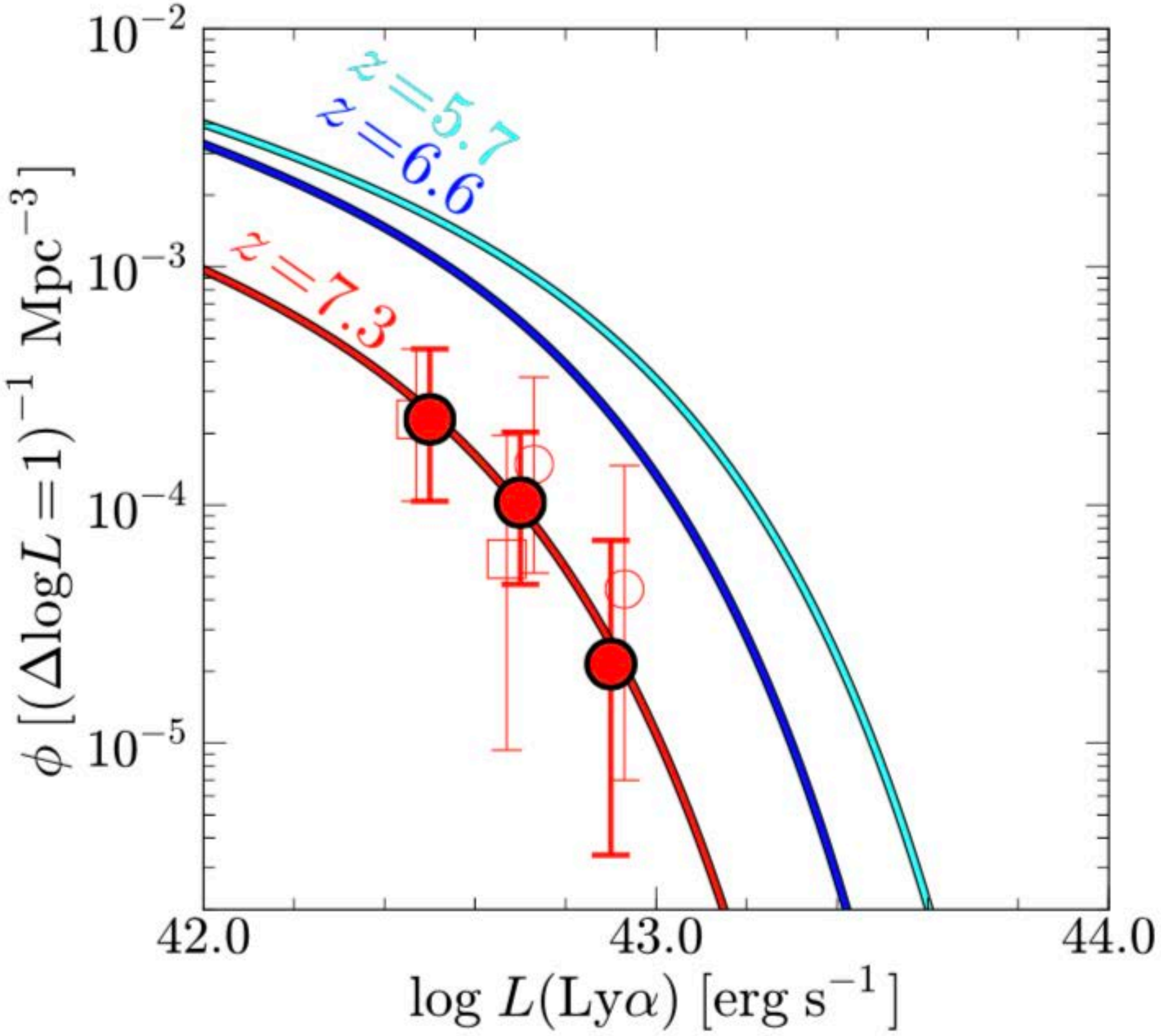
Observations by Planck (2018) suggest a low Thomson optical depth and hence a low electron density: i.e. the bulk of reionization occurs at low redshifts (z~8) when the volume of the Universe was already larger.

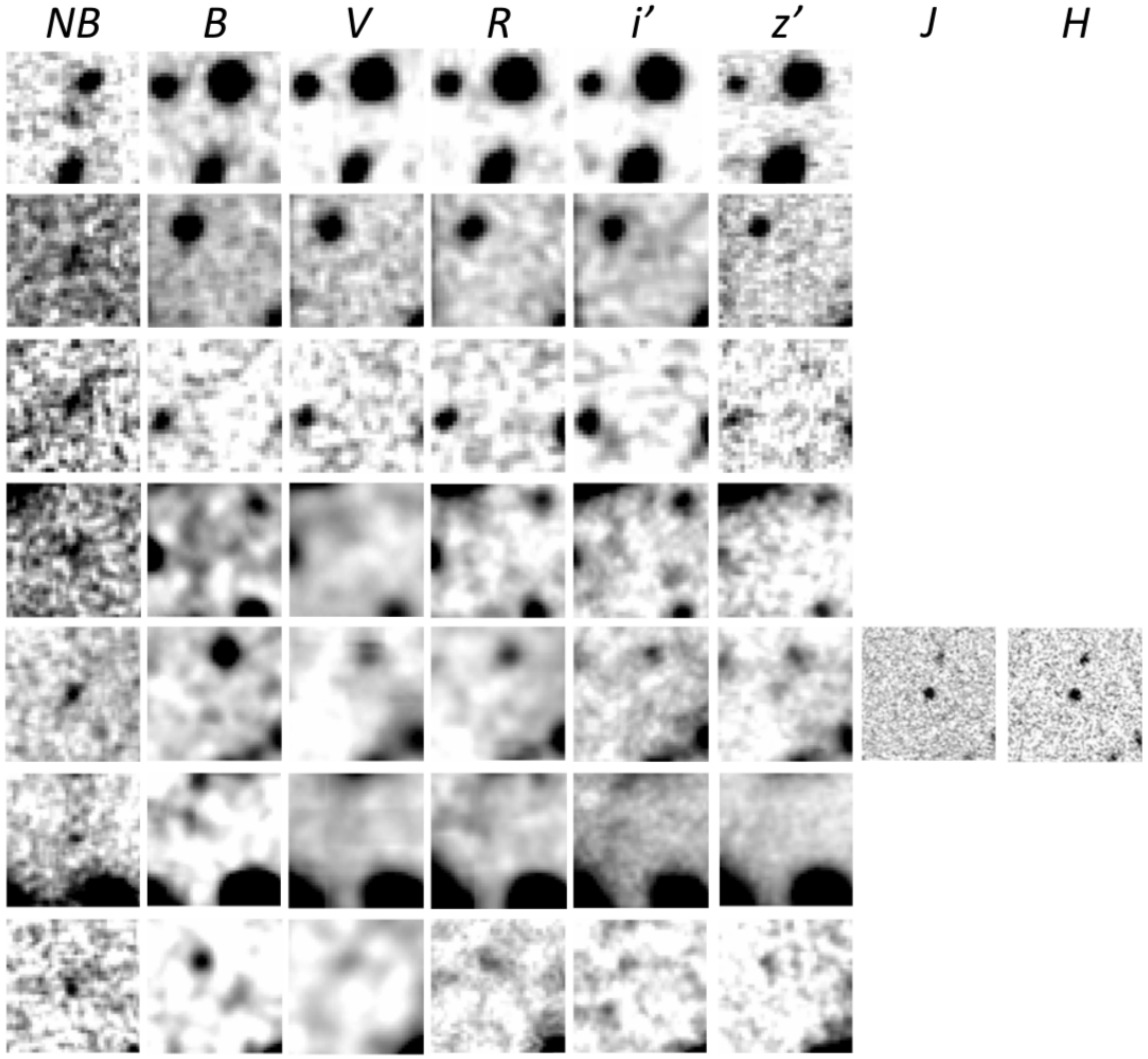


Planck+18

Some Selected Observations of the CD/EoR

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



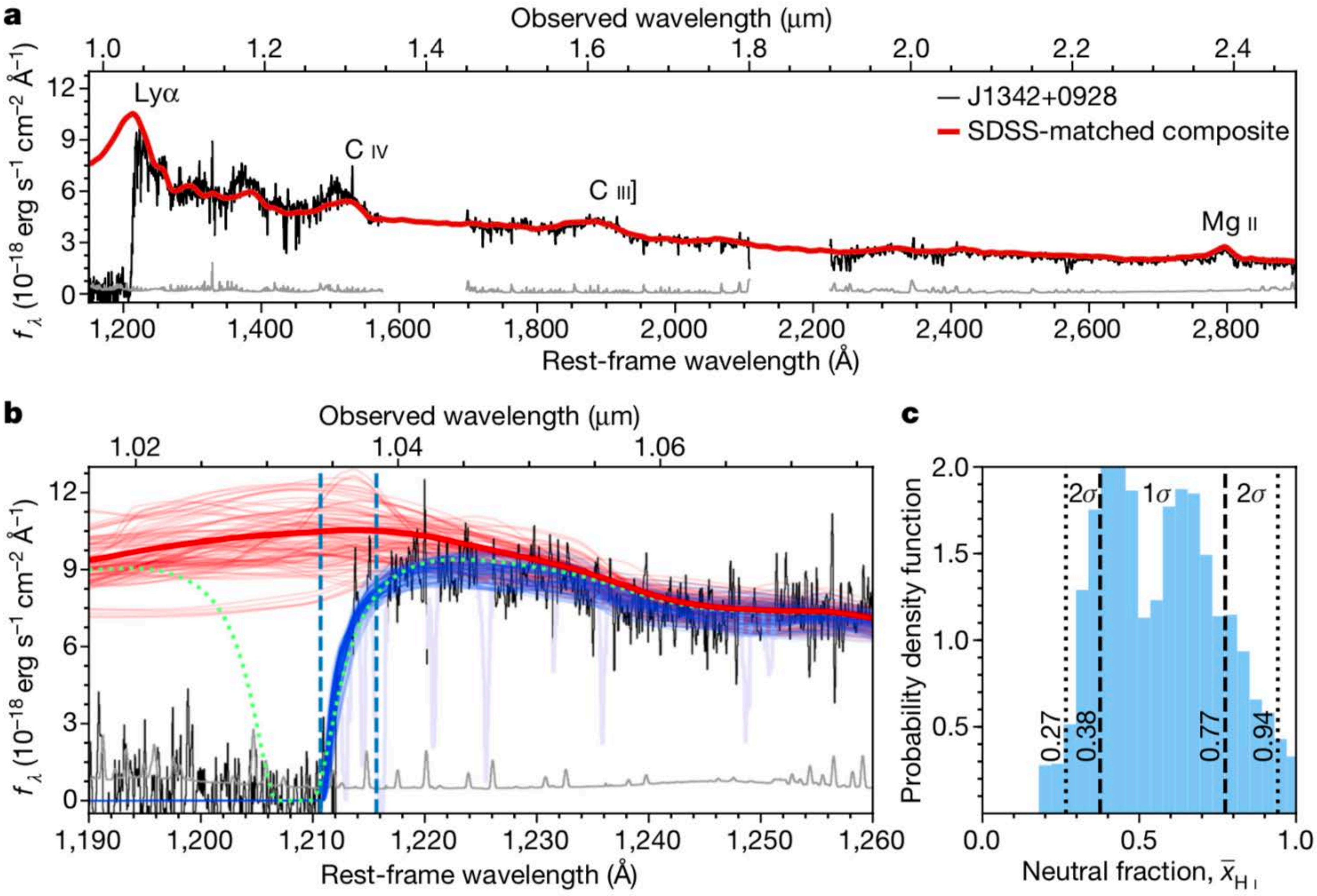


No continuum but strong narrow-band emission at z~7.3

Konno+14

Some Selected Observations of the CD/EoR

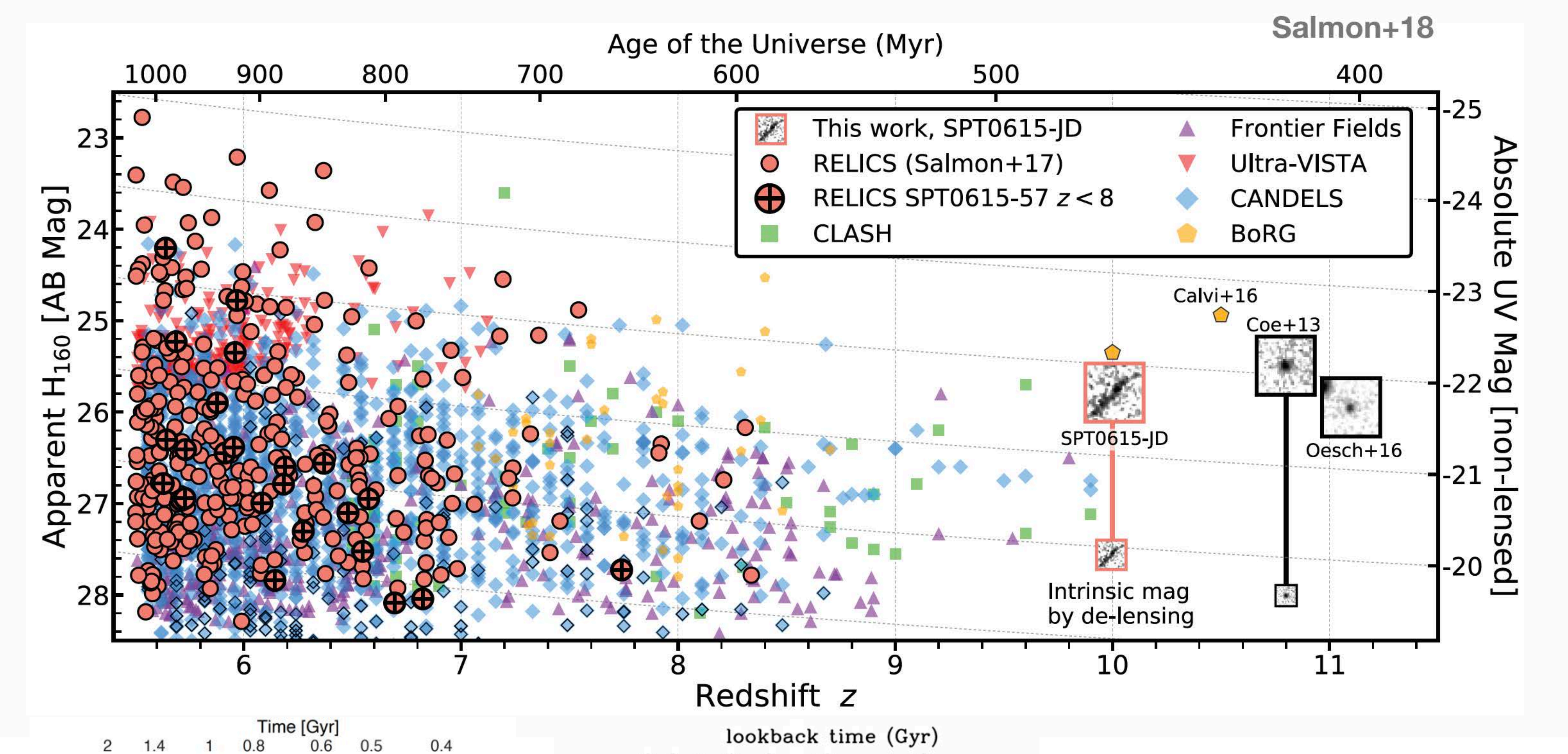
High redshift QSO's (rare) also suggest a high neutral fraction >0.27 (2-sigma) at z=7.5.

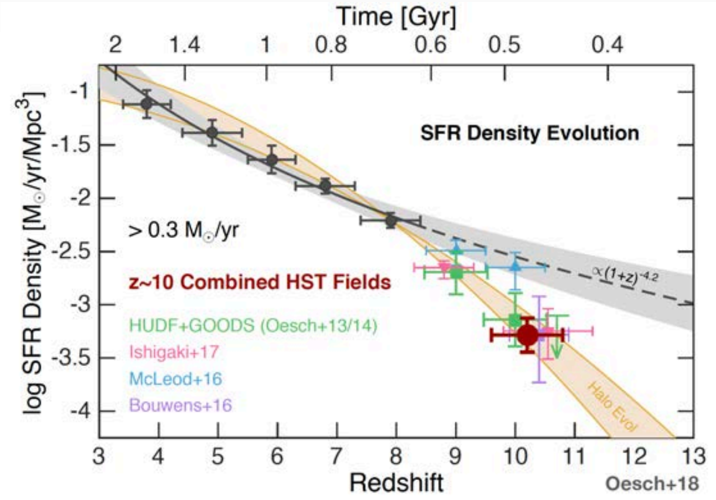


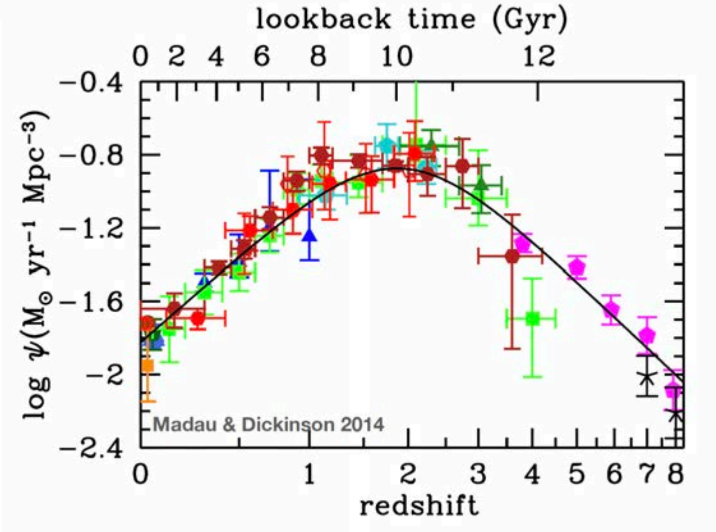
Banados et al. 2017

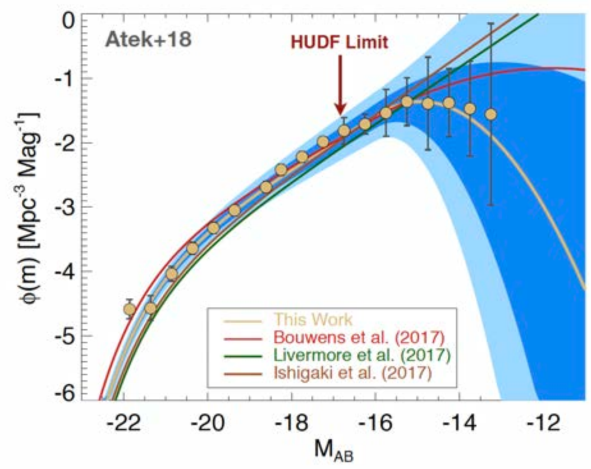
Some Selected Observations of the CD/EoR

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. using HST).









Summary of Current Constraints on the CD/EoR

- Scattering optical depths from CMB observations

  Ionised medium causes CMB polarisation: z_{eor} ~ 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 ???

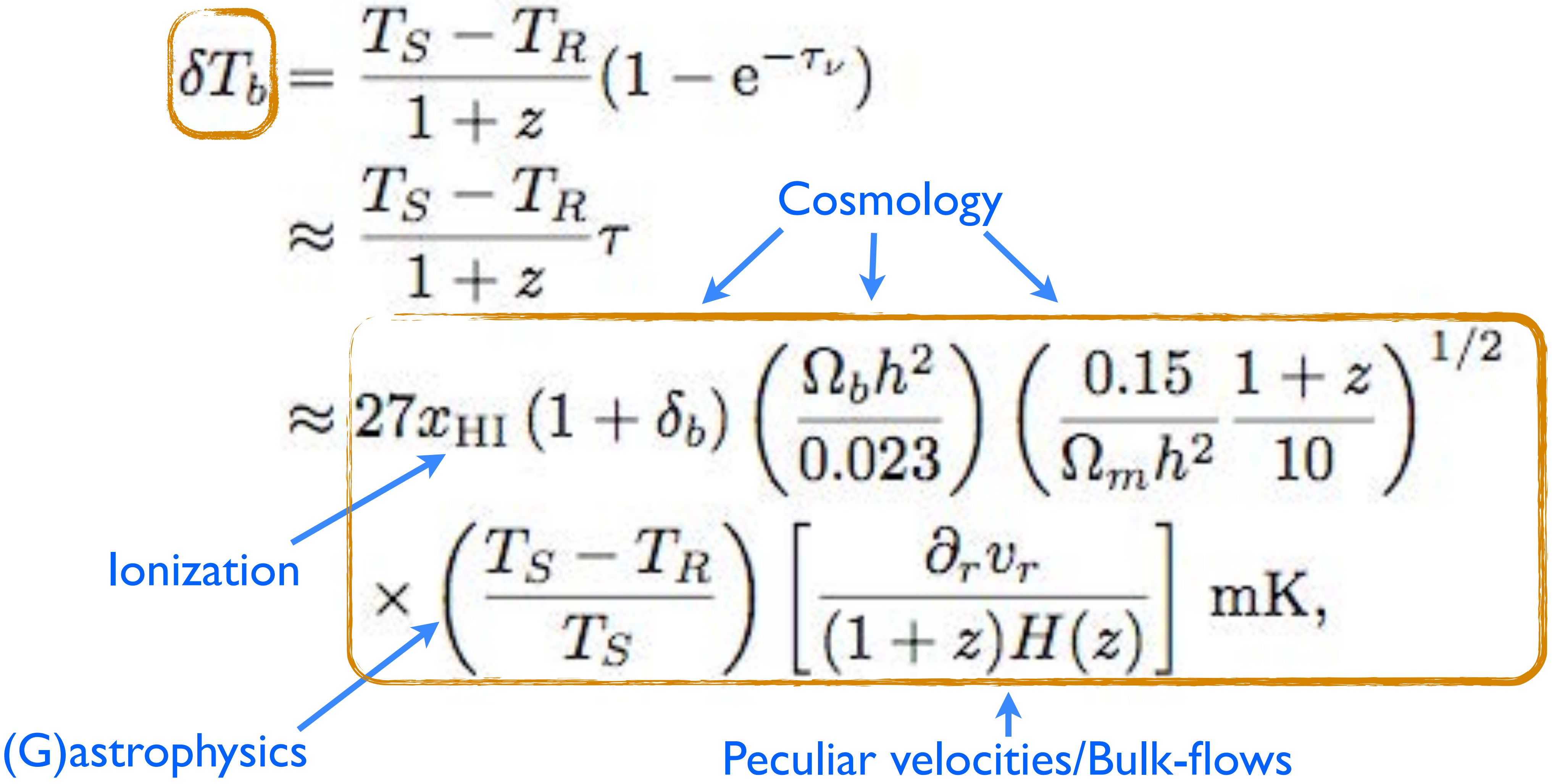
The 21-cm Signal of Neutral Hydrogen

Most evidence points at substantial reionization occurring at $z<10$, being halfway around $z\sim8$ and ending around $z\sim6$.

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)

Hydrogen Brightness Temperature

The quantity that is measured with radio telescopes along a given line of sight is given by:



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

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

Studying HI Through Cosmic Time

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

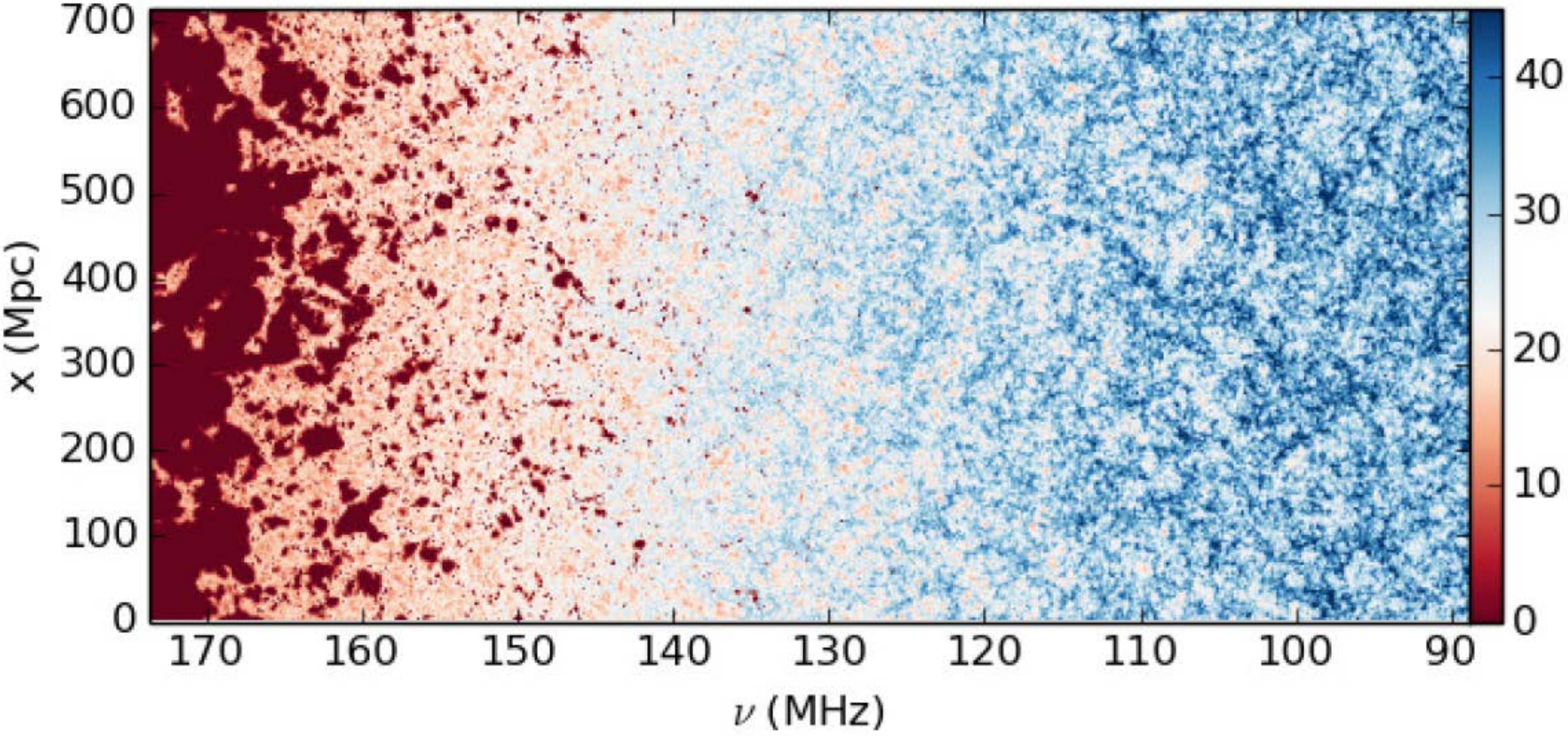
Post-Reionization

HI is found largely in galaxies

Dark Ages/Cosmic Dawn/Reionization

HI has a filling factor of order unity

←



Credit: Dixon, Illiev et al.

Hydrogen Brightness Temperature

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

- Globally-averaged 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, …

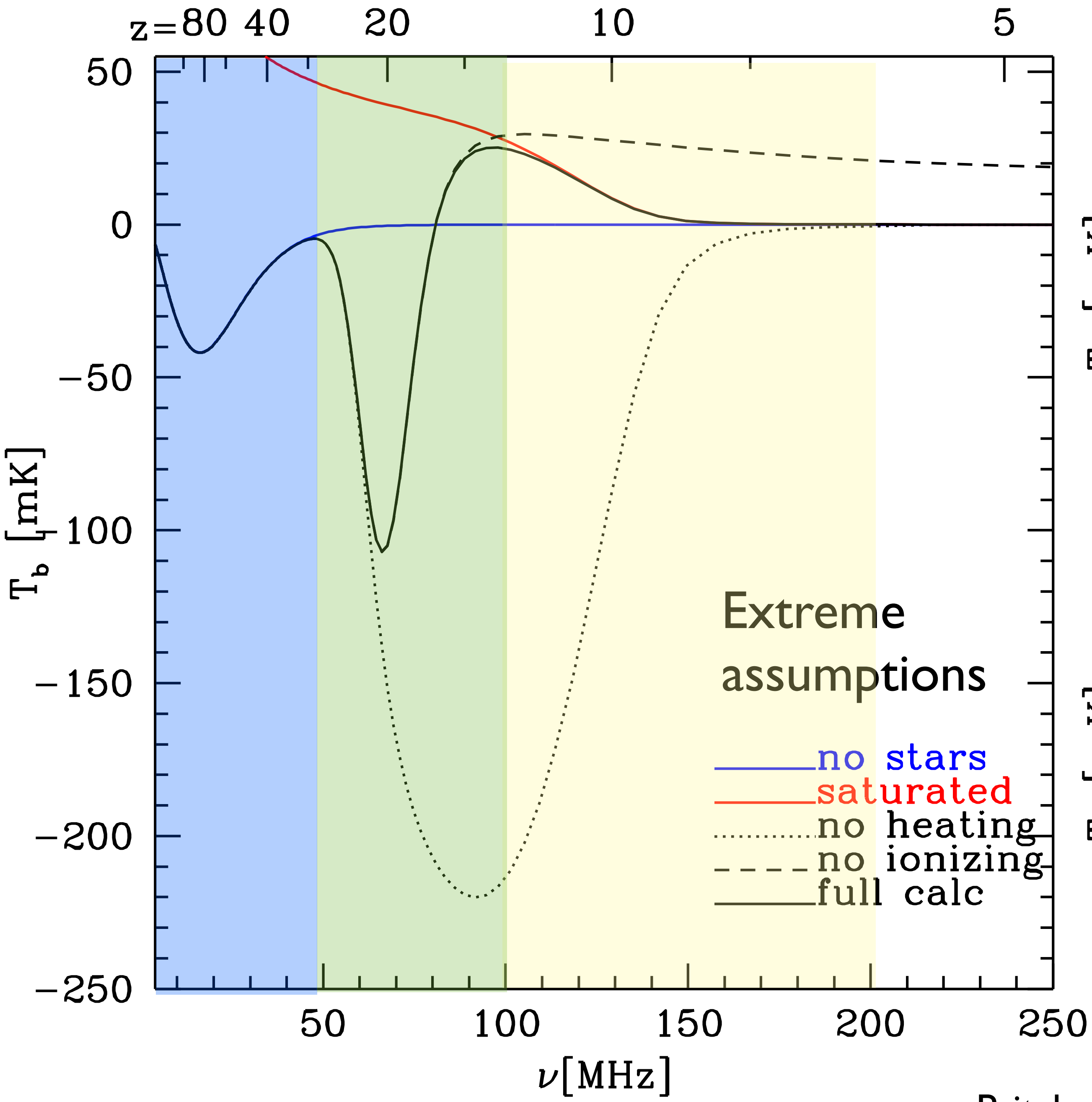
- Spatial/spectral 21-cm signal intensity fluctuations:
  - Expensive, using multiple (cross-correlation) receivers (needs large A_{eff}/FoV)
  - Power-spectra, bi-spectra, moments, etc.
  - LOFAR/AARTFAAC, MWA, PAPER, GMRT, LEDA, NenuFar, HERA, SKA, …

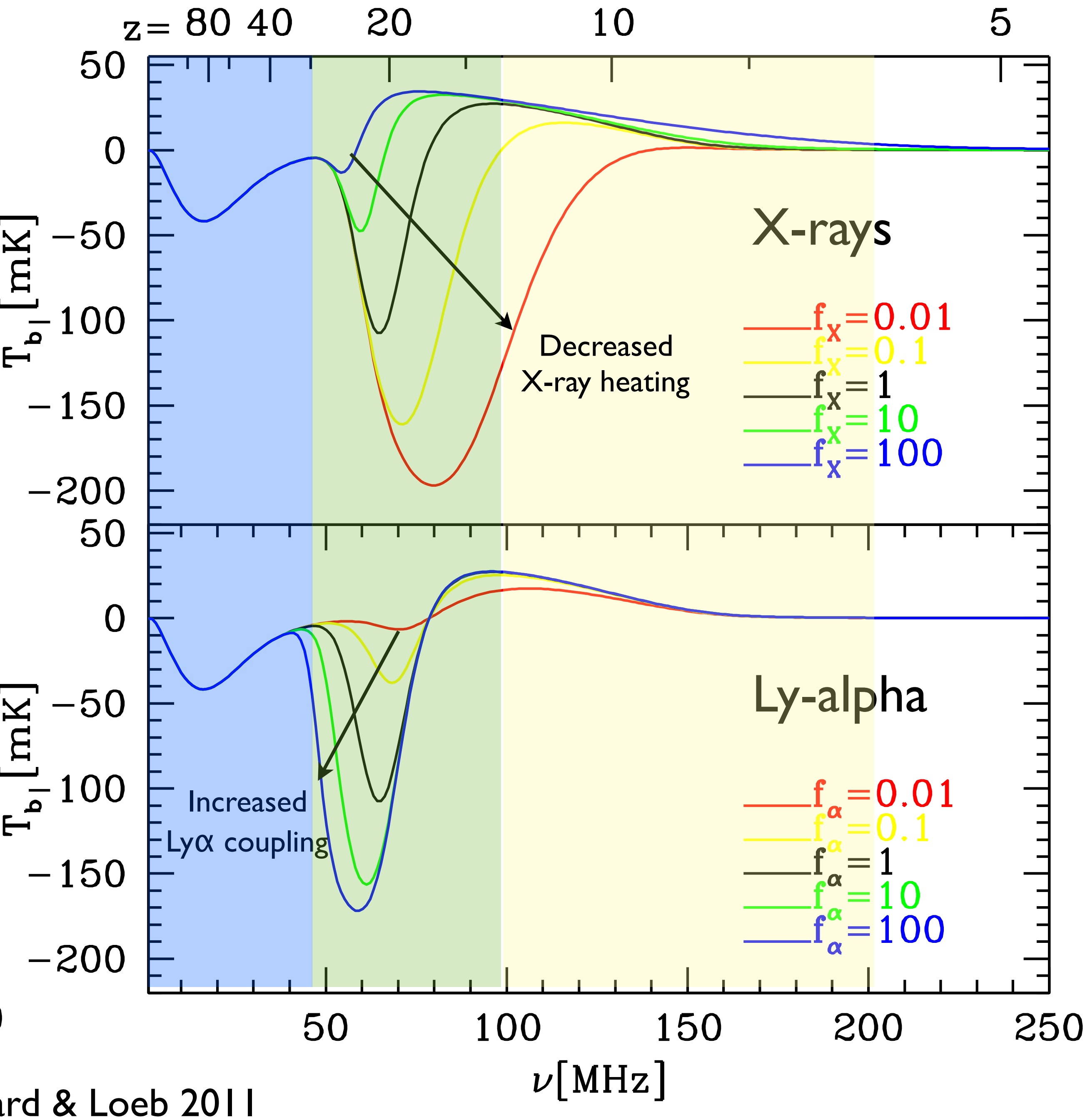
- Tomography/Imaging
  - Retains all information (if above the noise)
  - SKA (on few to tens of arcmin scales), HERA (on degree scales)

Hydrogen Brightness Temperature

Global Signal

The history of T_b can vary; hence measuring T_b as function of redshift/time, provides a handle on star formation, Ly-α coupling, (X-ray) heating, etc.



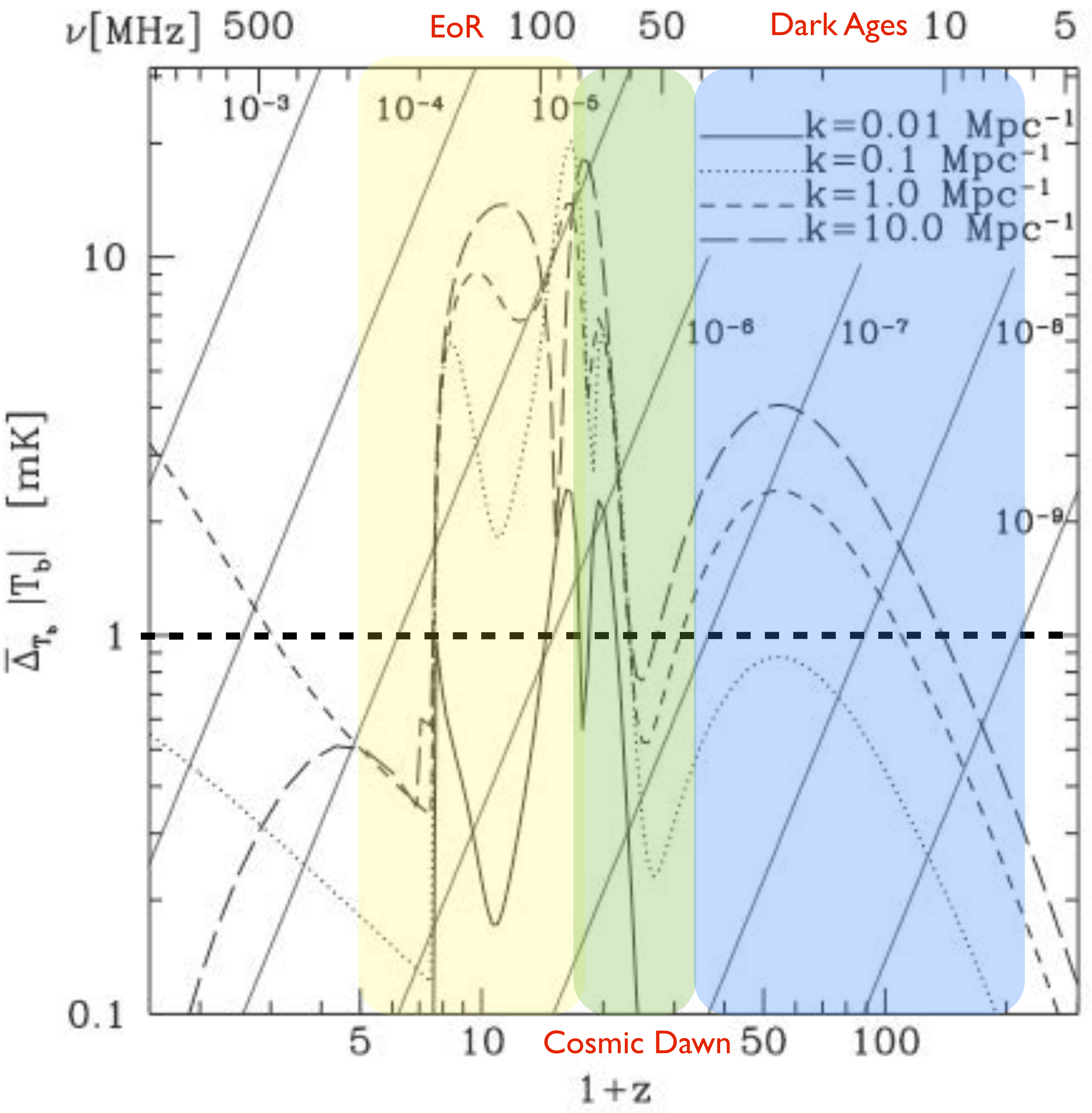


Pritchard & Loeb 2011

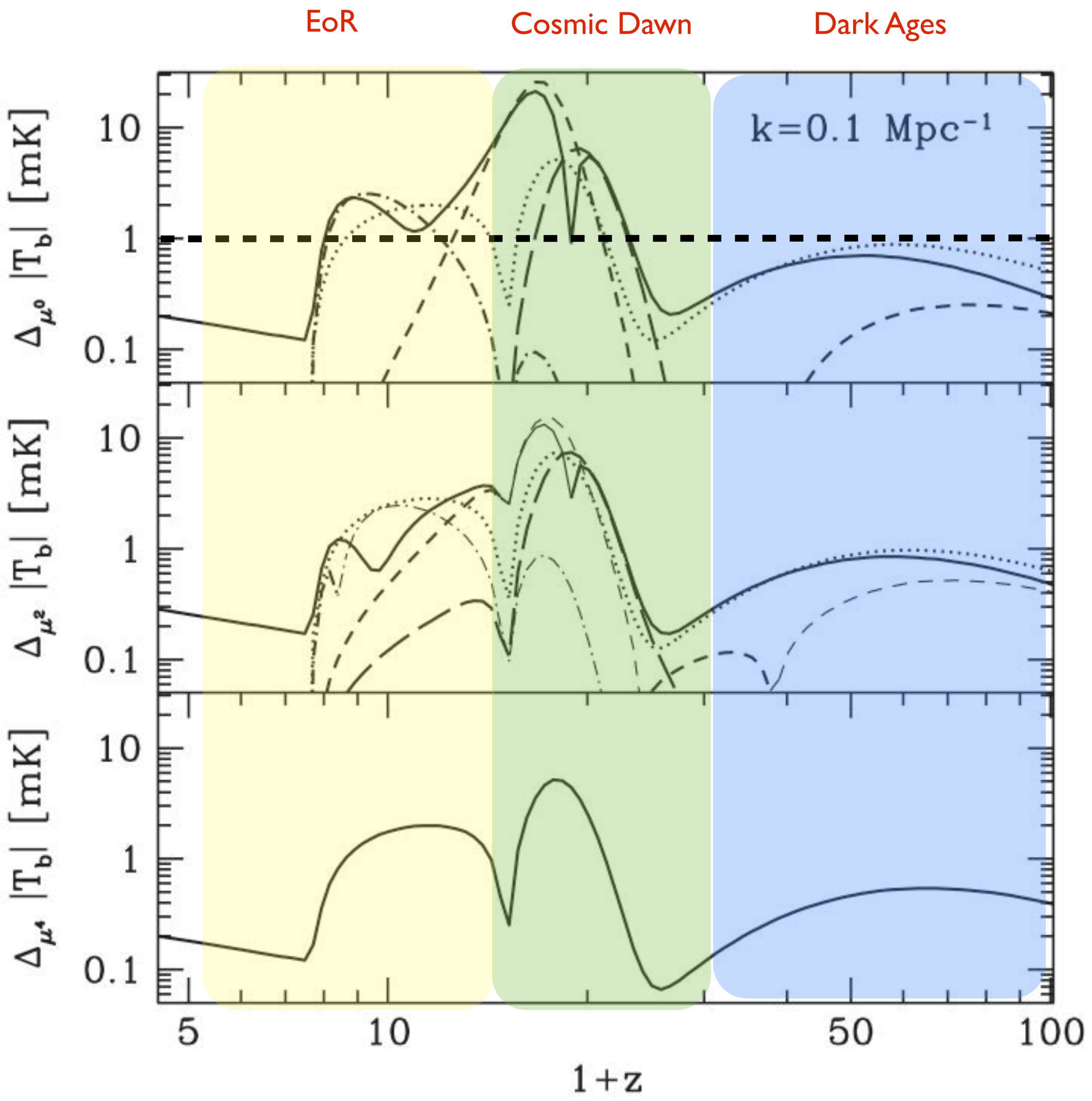
Hydrogen Brightness Temperature

Power-Spectrum

Intensity Fluctuations



Intensity Fluctuations

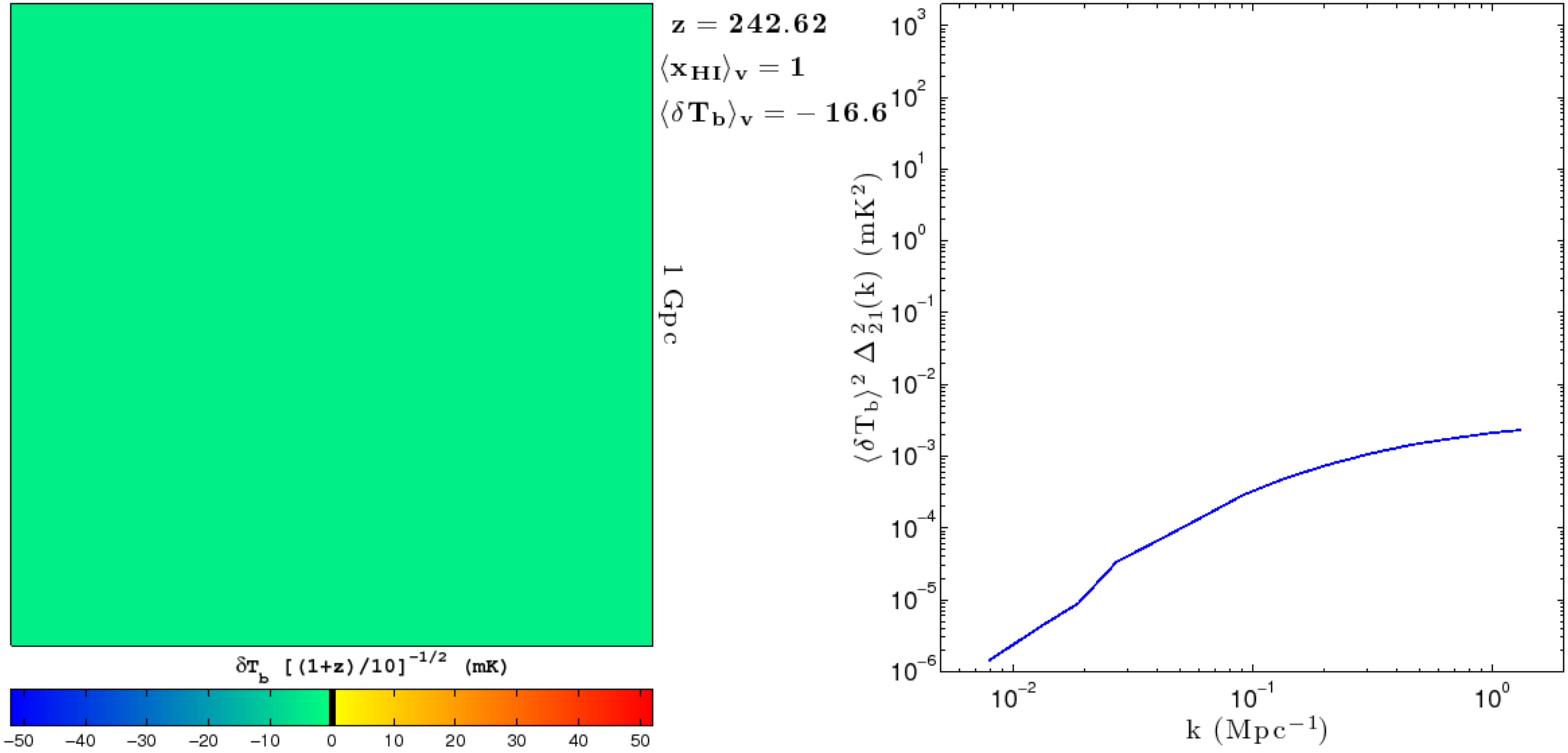


Pritchard & Loeb 2009; see also Santos et al. 2008, 2010, 2011

Hydrogen Brightness Temperature

Power-spectrum

Credit: Mesinger

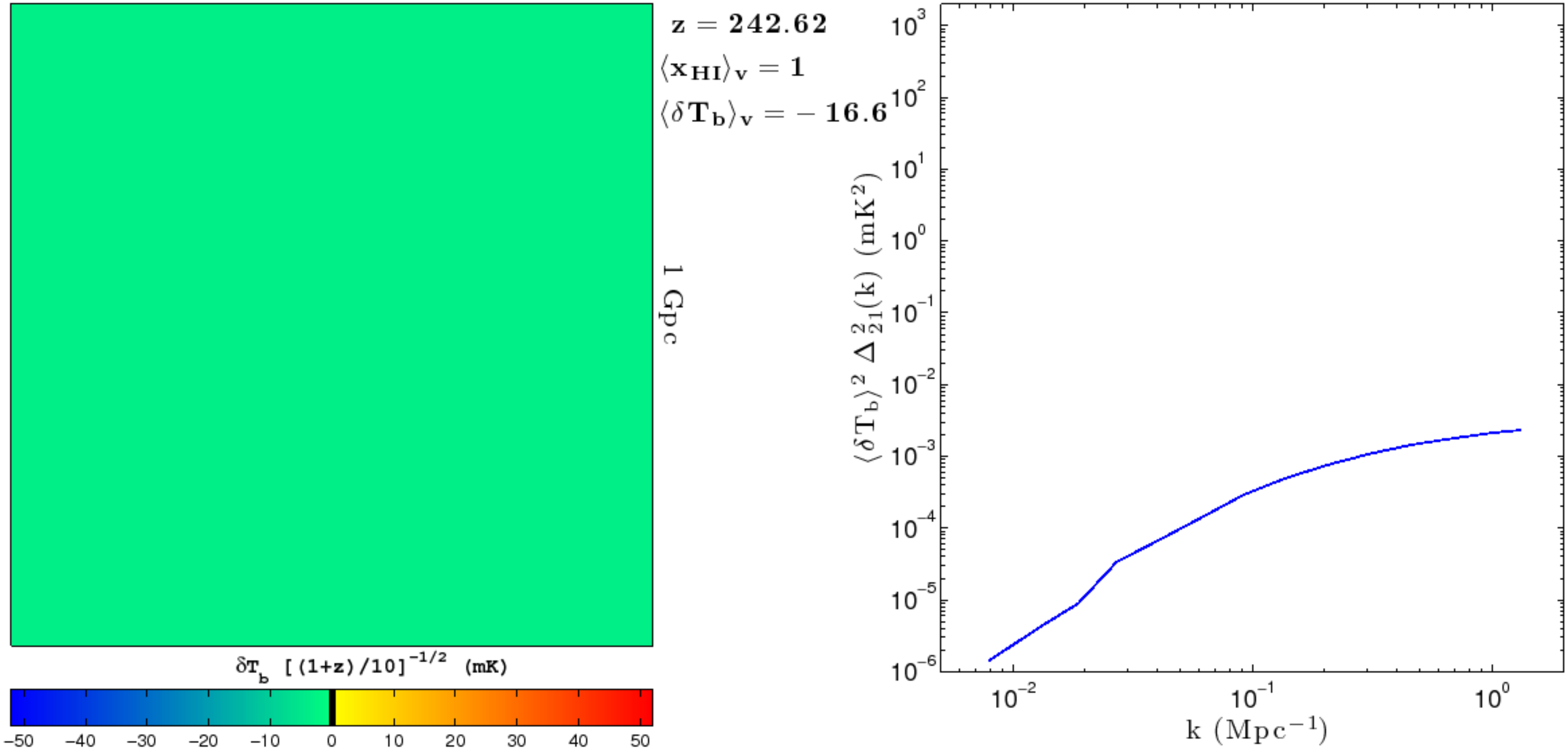


Sensitivity limits are scale dependent but Δ^2_{noise}~few mK^2 is where current instruments aim for in ~1000 hrs. SKA can go to Δ^2_{noise}~0.1 mK^2

Hydrogen Brightness Temperature

Power-spectrum

Credit: Mesinger



Sensitivity limits are scale dependent but Δ^2_{noise}~few mK^2 is where current instruments aim for in ~1000 hrs. SKA can go to Δ^2_{noise}~0.1 mK^2

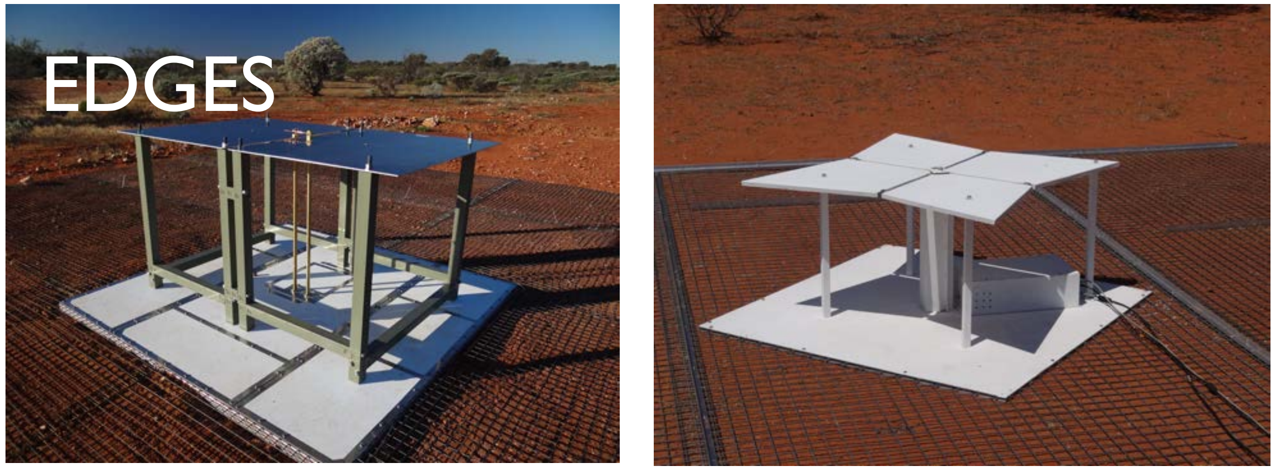
Global 21-cm Signal Experiments

Some exciting new results… Remember the year 2018!

IAU, 2018

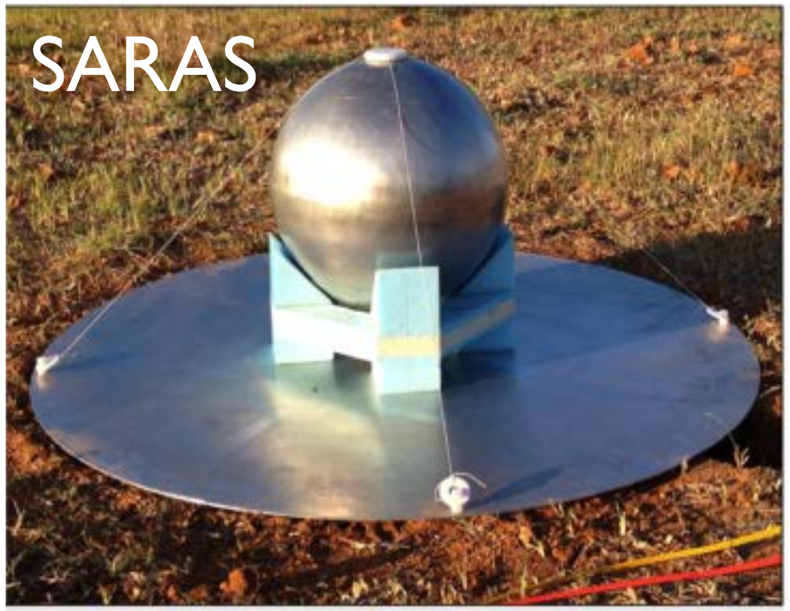
Current Global 21-cm Signal Experiments

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

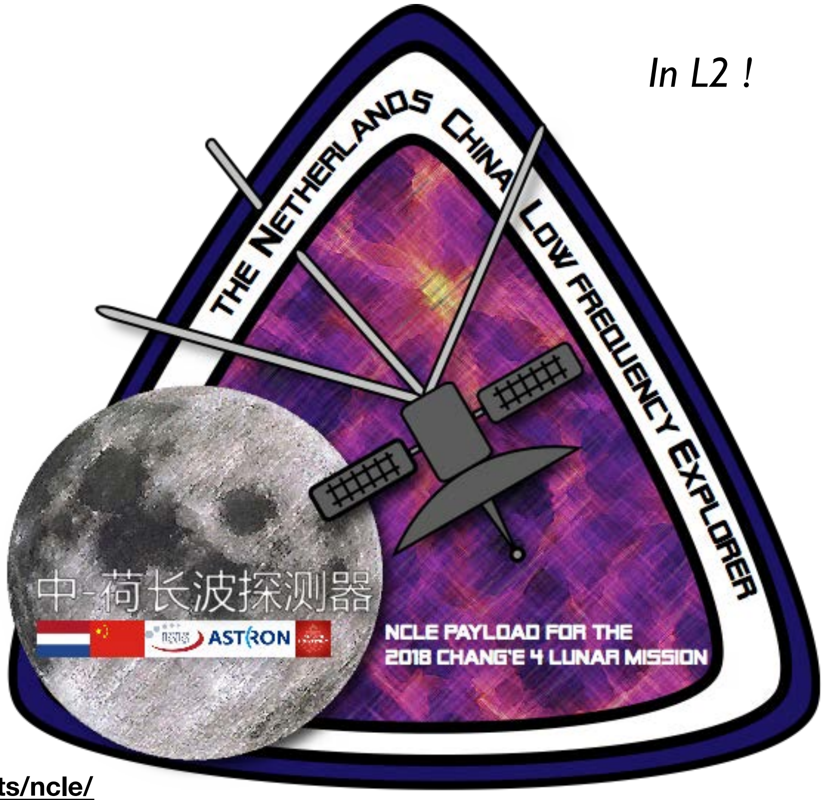
Specs:
- 30-88 MHz
- OVRO/California, US

Bernardi et al. 2016; Price et al. 2018

NCLE

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

In L2 !



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

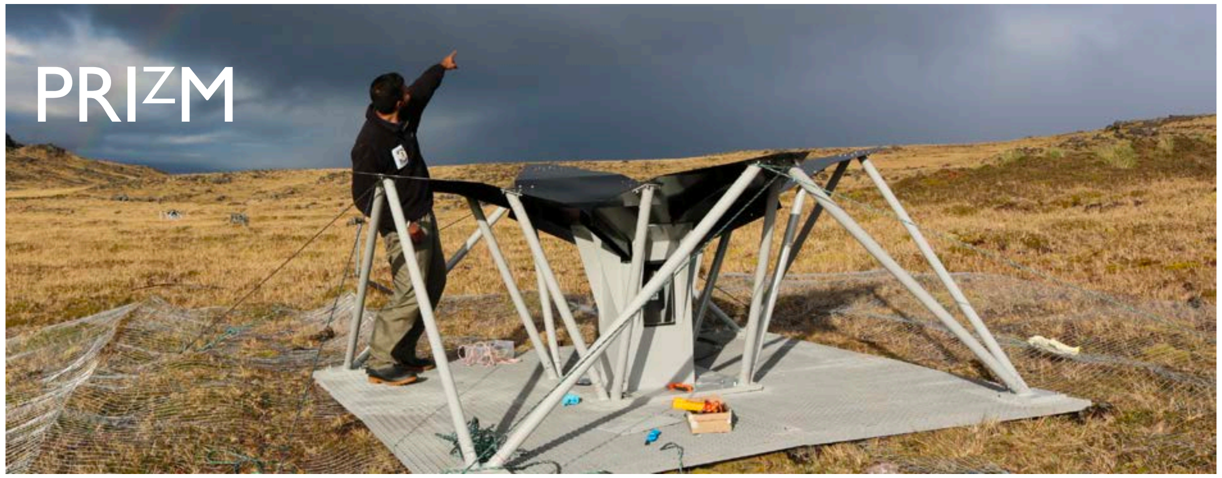
Current Global 21-cm Signal Experiments

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

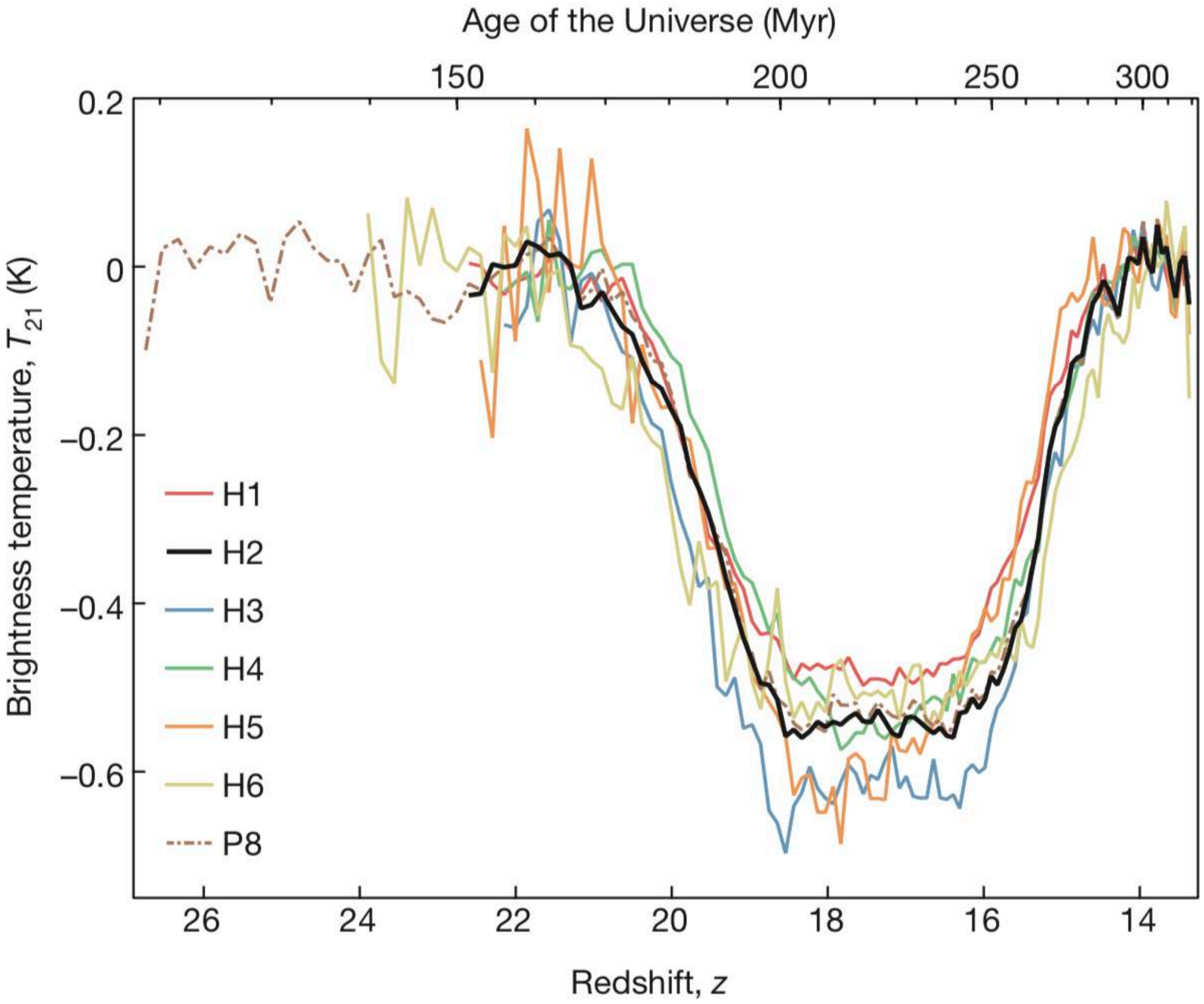
Peterson, Sievers, Chiang ++

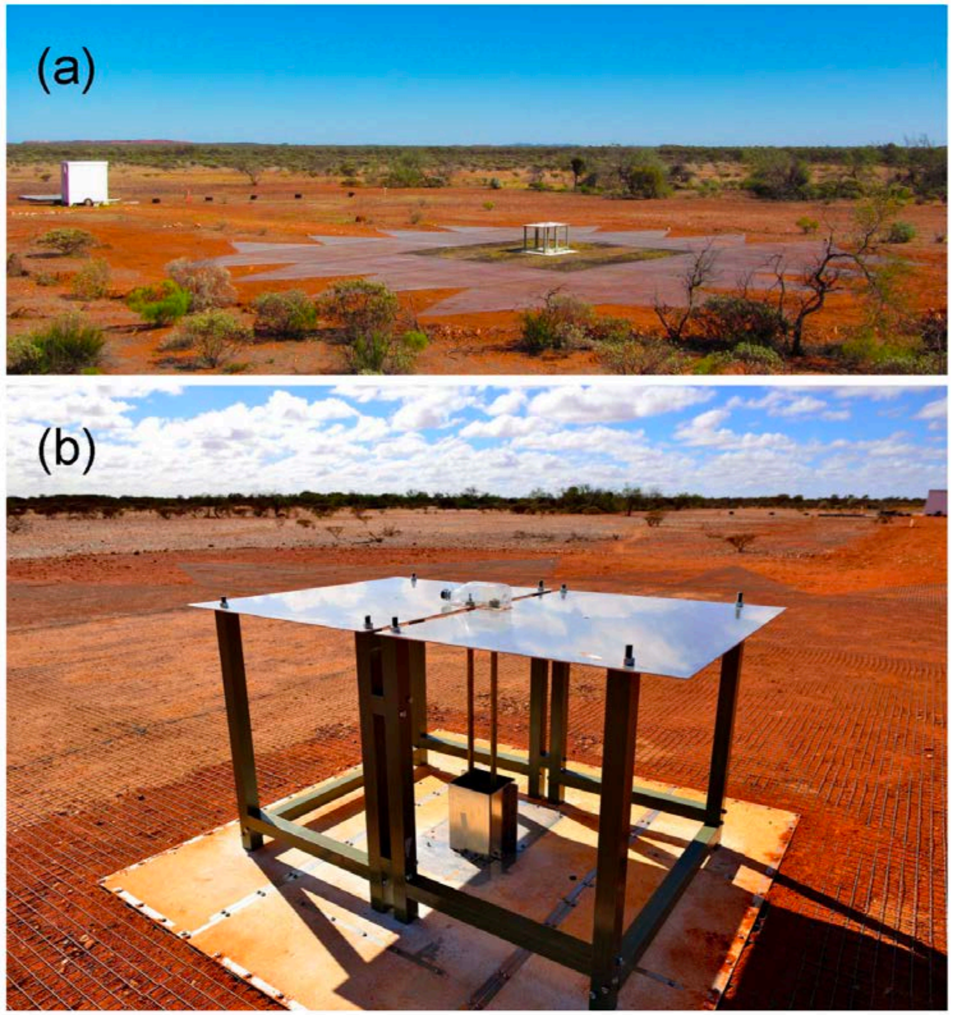
Specs:
- 40-120 MHz
- Lunar orbit, 125km above lunar surface

Burns et al. 2017

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!



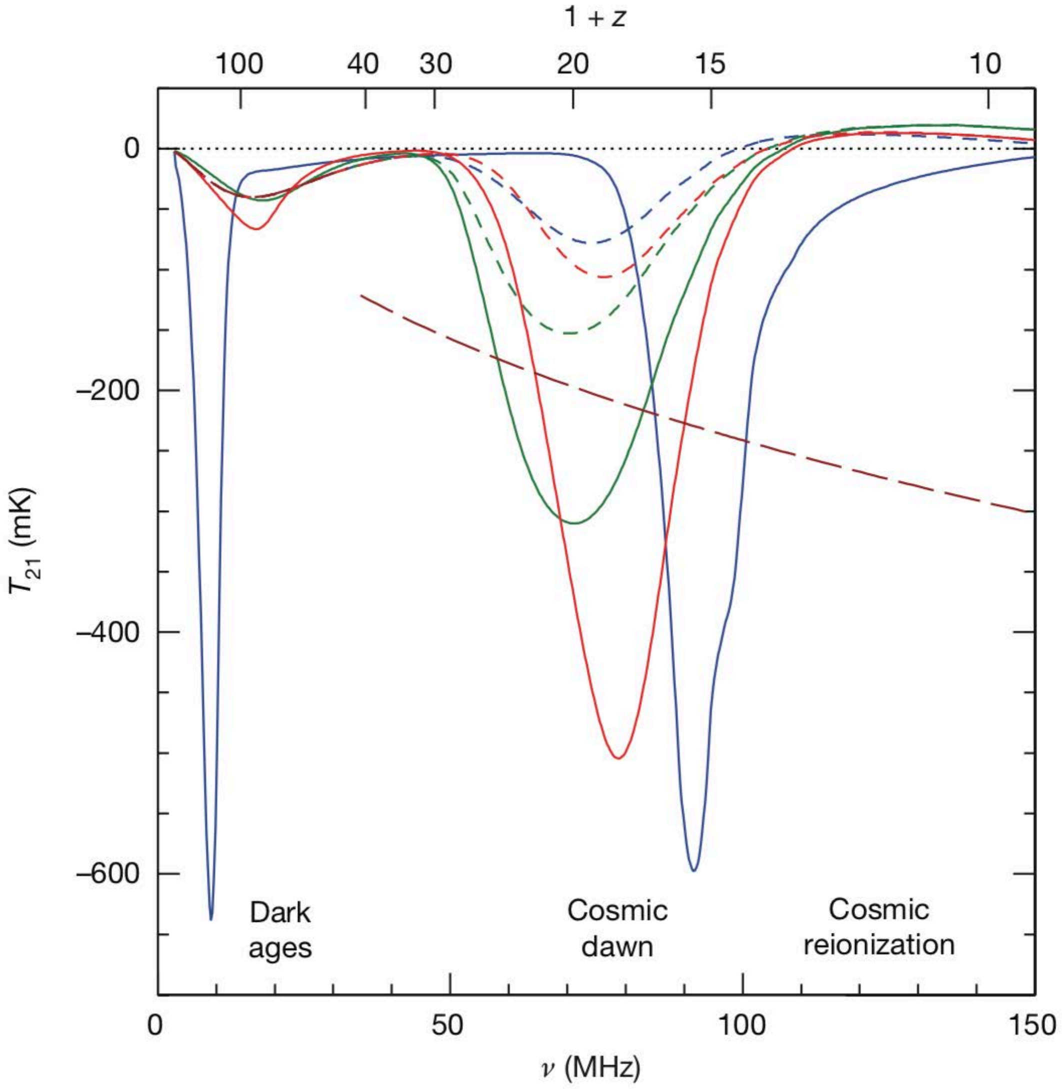


Bowman et al. 2018

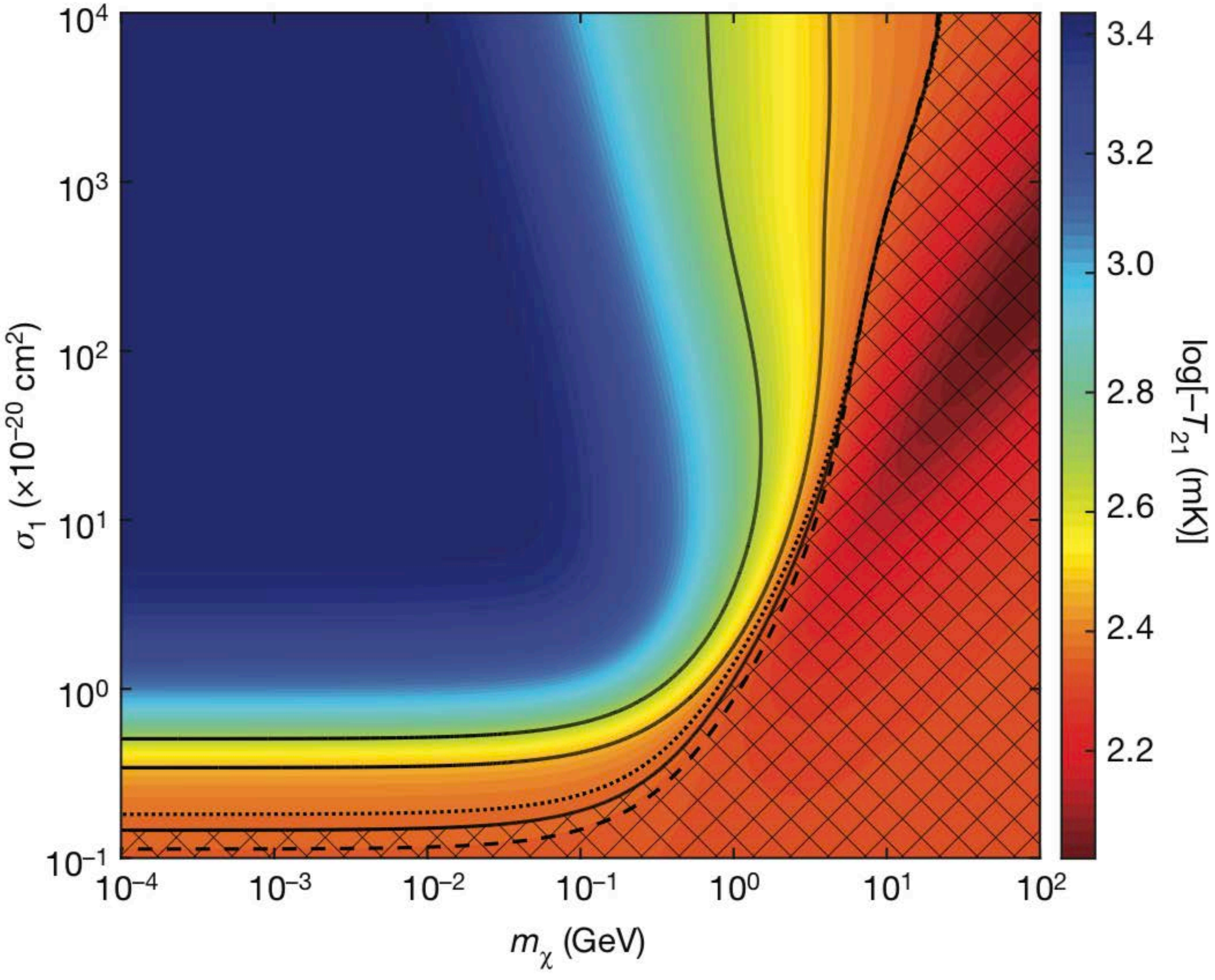
EDGES2

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



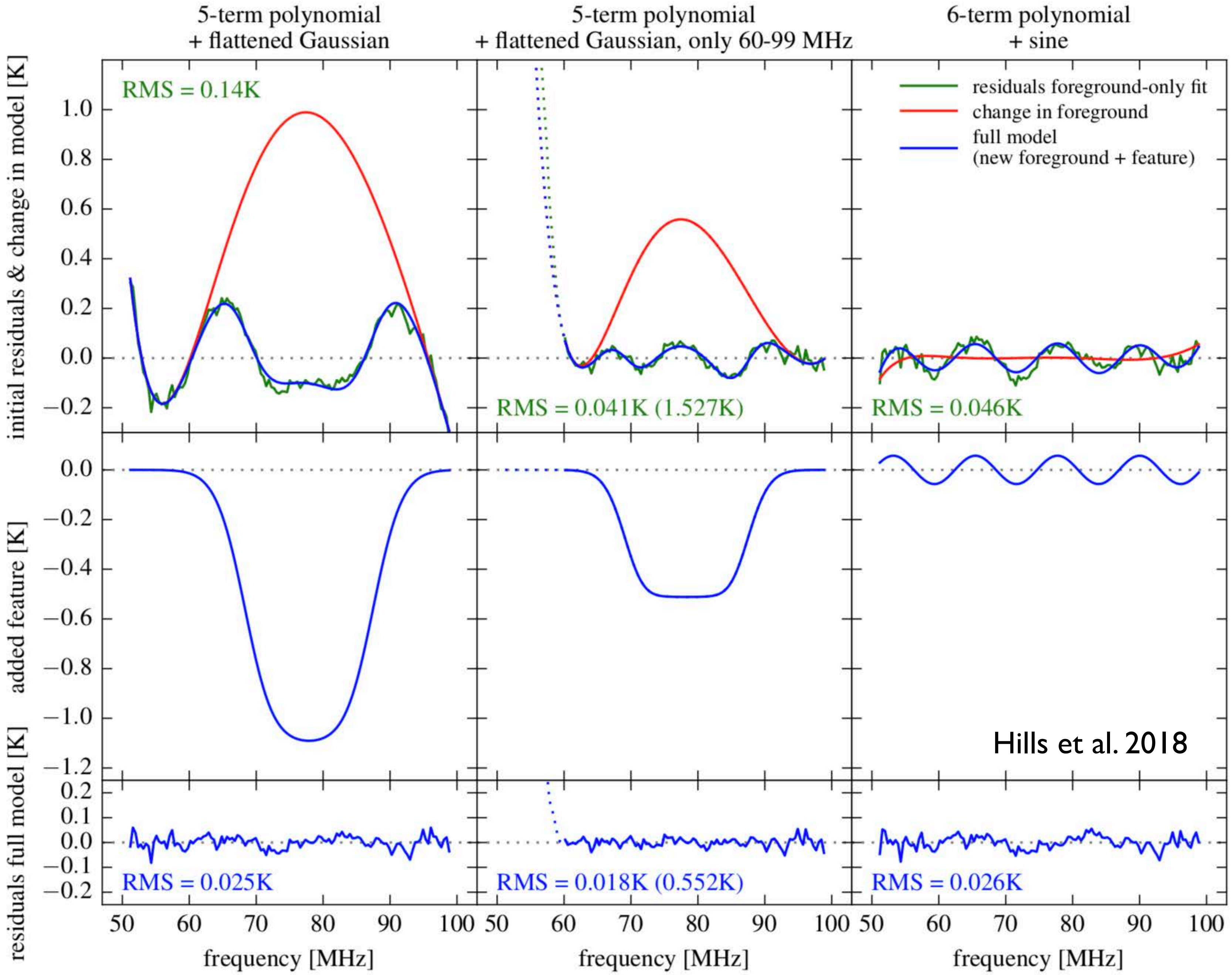
Constraint on DM particle mass and cross-section



Barkana 2018

EDGES2

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



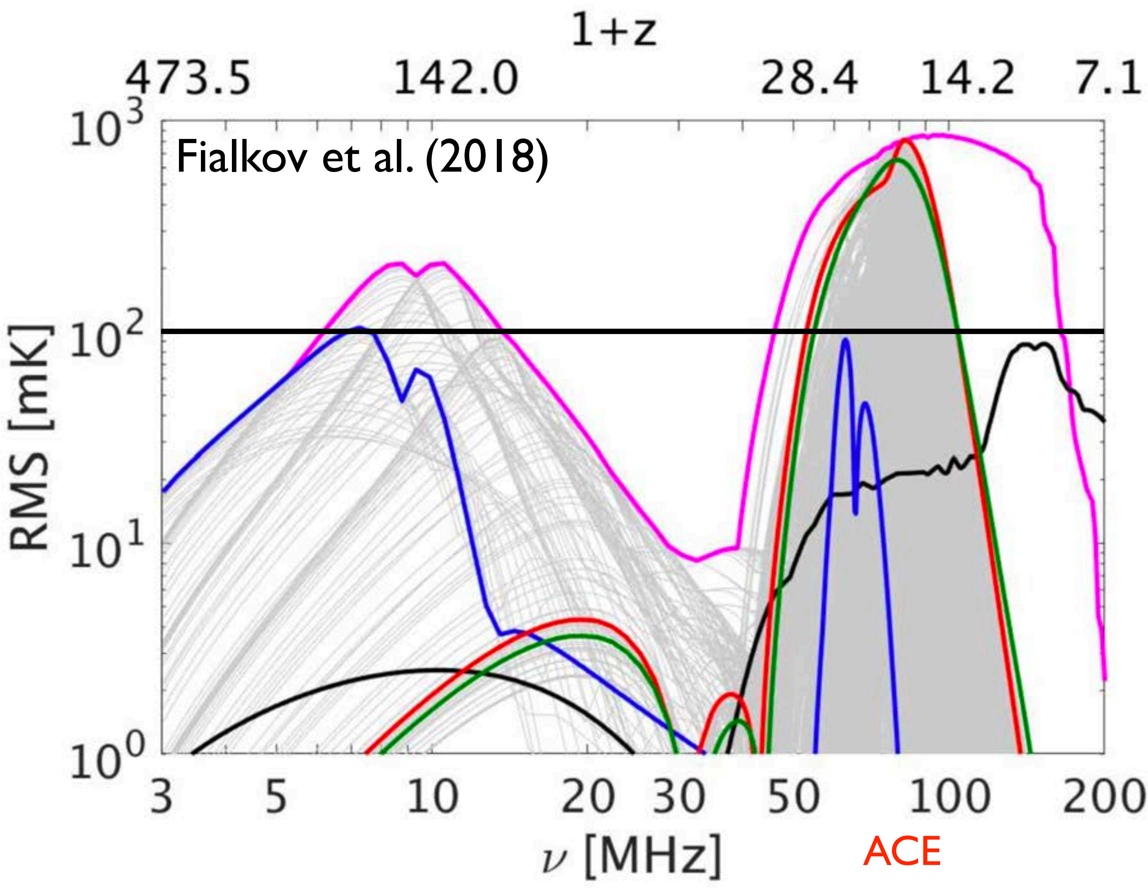
Hills et al. 2018

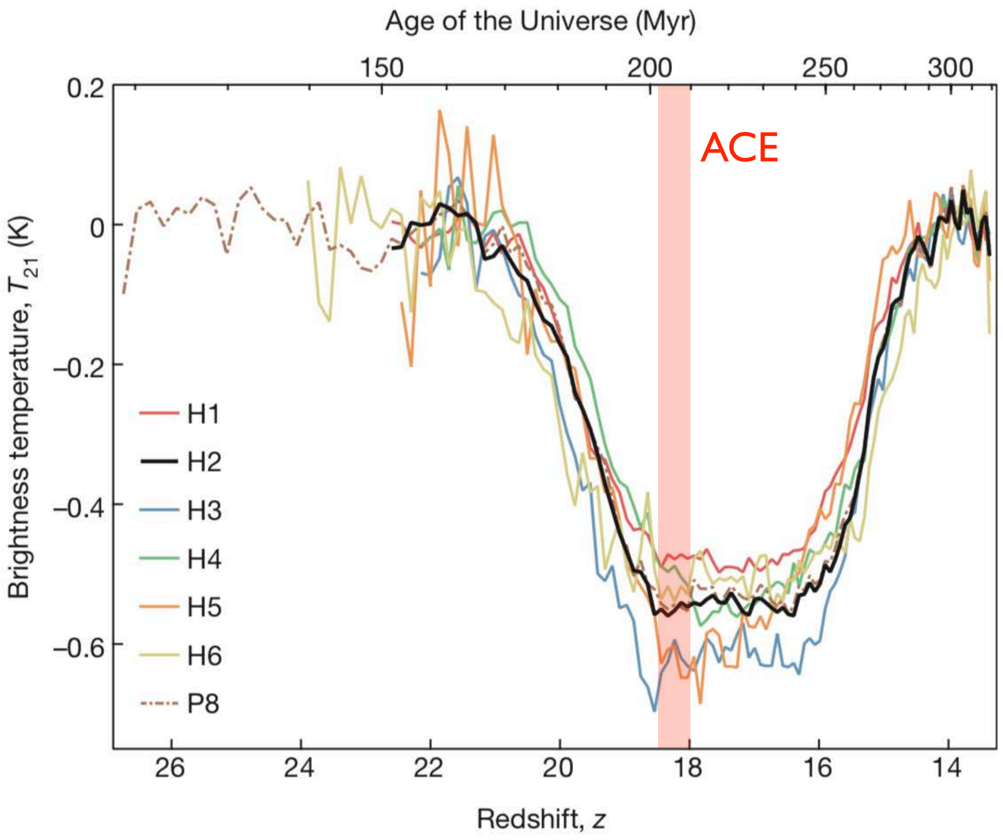
EDGES2 results needs confirmation by an independent instrument (e.g. SARAS3)

AARTFAAC Cosmic Explorer (ACE) Program

EDGES2 results motivated the 1000-hr ACE program (PIs: Koopmans & Gehlot) with LOFAR-LBA using AARTFAAC correlator (PI: R. Wijers, UvA, NL) .

AARTFAAC correlates all 576 receivers (dipoles or tiles) of LOFAR LBA/HBA at once over a ~3MHz BW





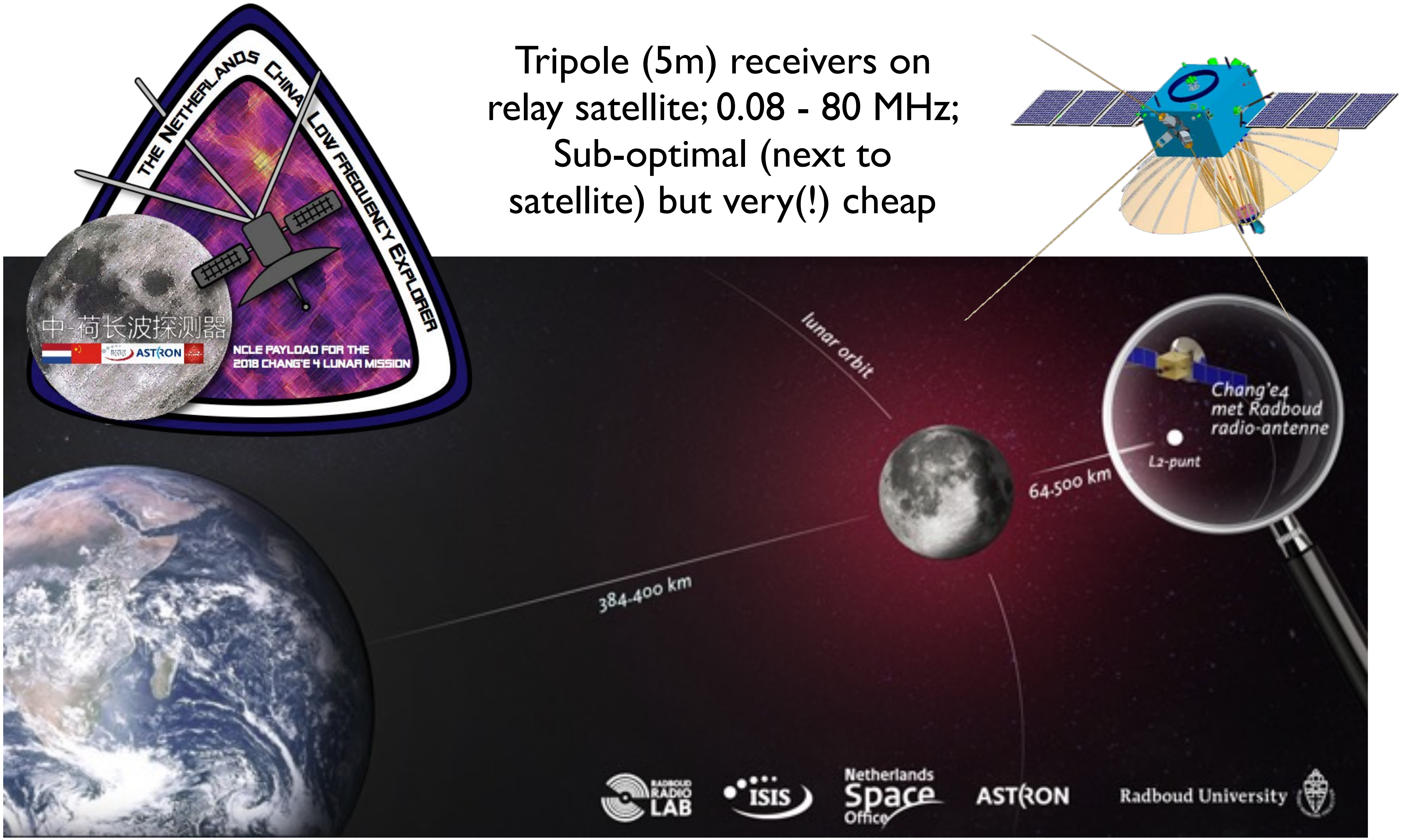
Netherlands China
Low-Frequency Explorer (NCLE)

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

Strasbourg, France, June 18, 2018

Netherlands China Low-frequency Explorer

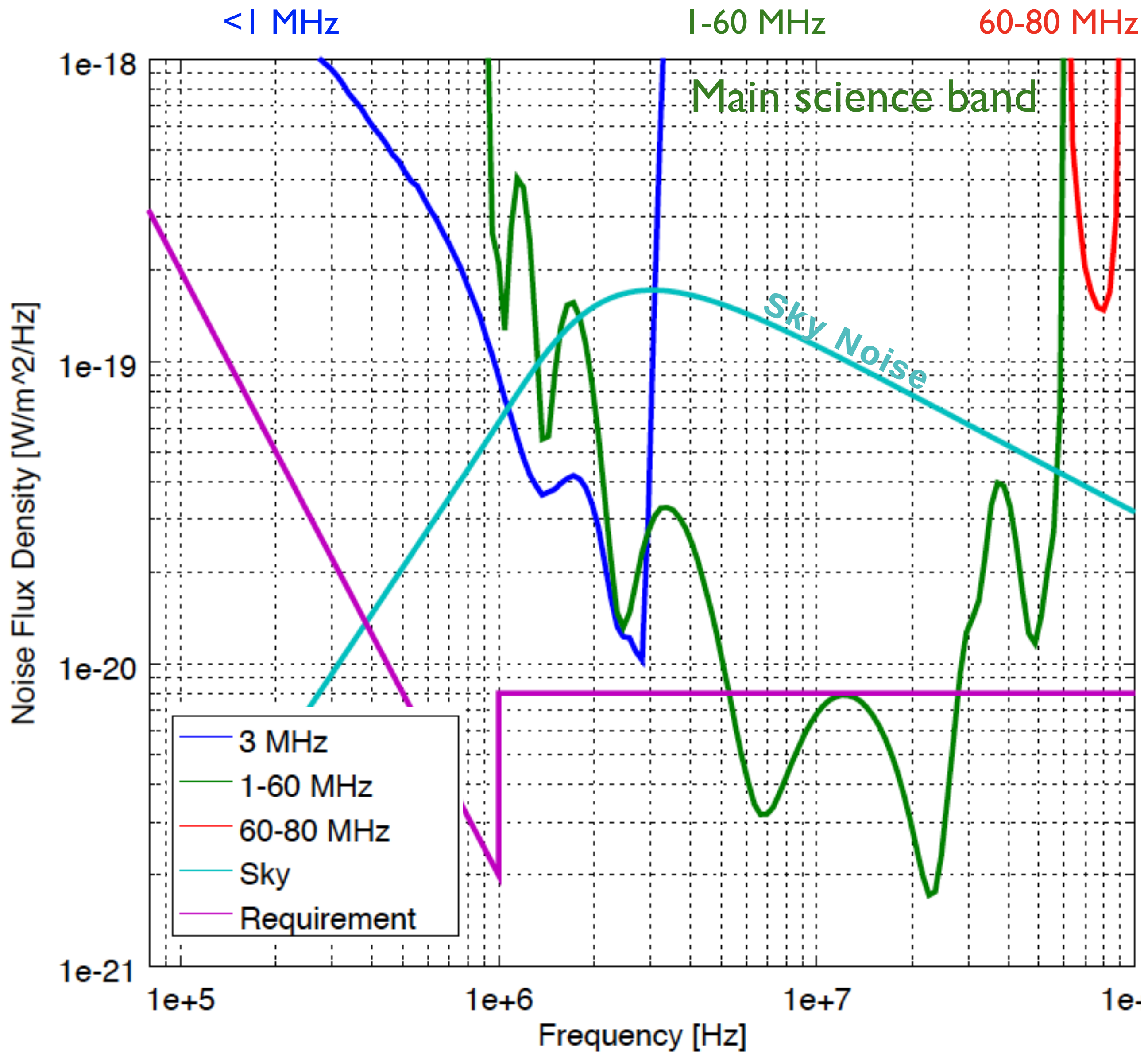
Tripole (5m) receivers on
relay satellite; 0.08 - 80 MHz;
Sub-optimal (next to
satellite) but very(!) cheap



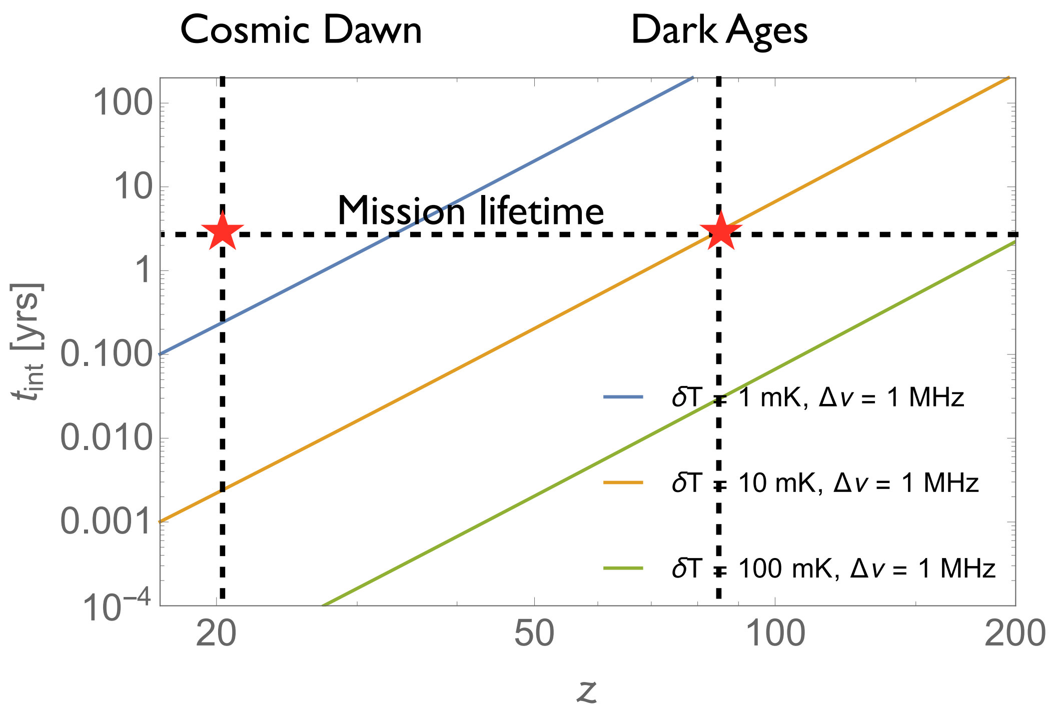
Onboard Chang'e4 Queqiao relay satellite at Earth-Moon L2
(first part of Chinese lunar far-side lander/rover mission)

Netherlands China Low-frequency Explorer

If EDGES2 result is correct *and* also Dark Ages 21-cm signal is -600mK, then NCLE could detect this 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 no systematics, etc.



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



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

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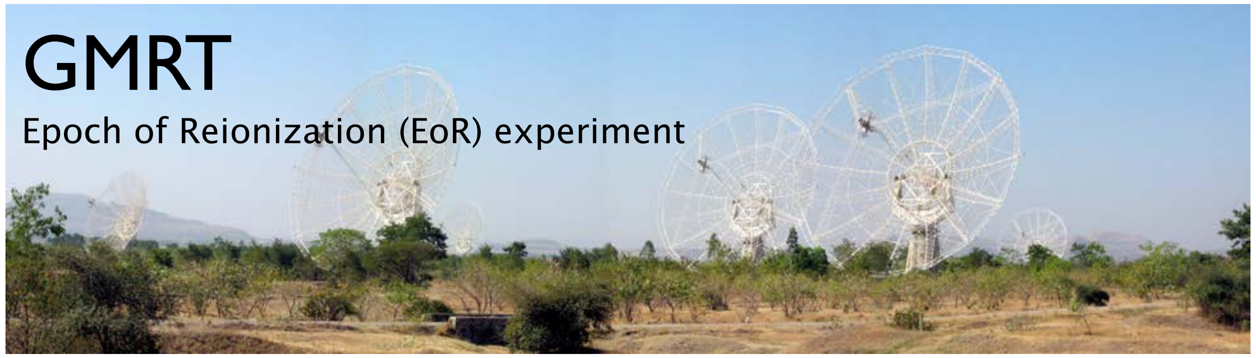
Interferometric 21-cm Signal Experiments

*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



GMRT

Epoch of Reionization (EoR) experiment

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
- $z = 8.1$-9.2

Paciga et al. 2013

MWA

Murchison Widefield Array

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

PAPER

Precision Array for Probing the Epoch of Reionization

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

LOFAR

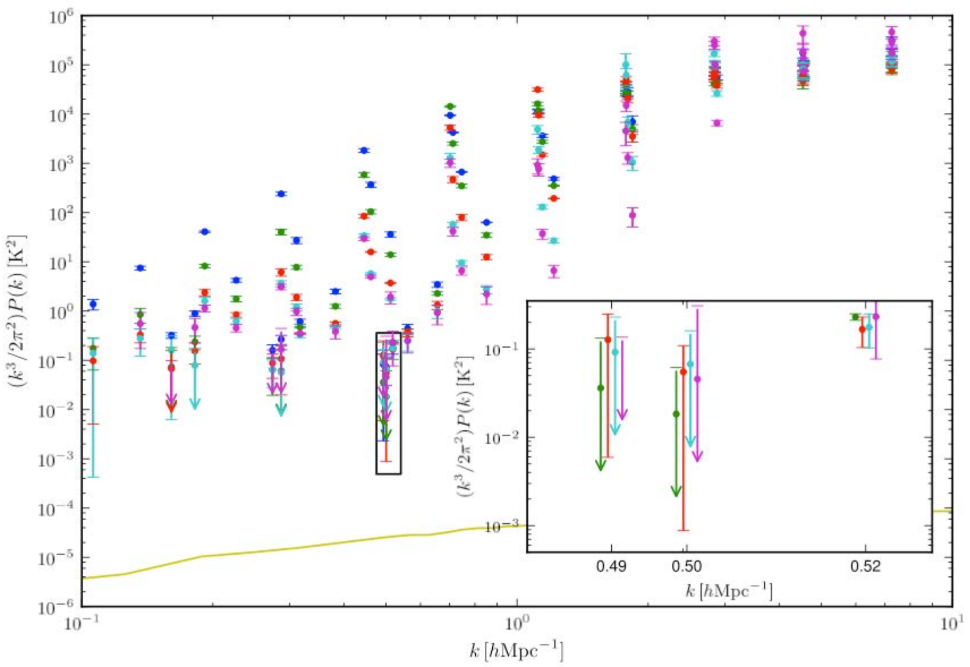
Low Frequency Array

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

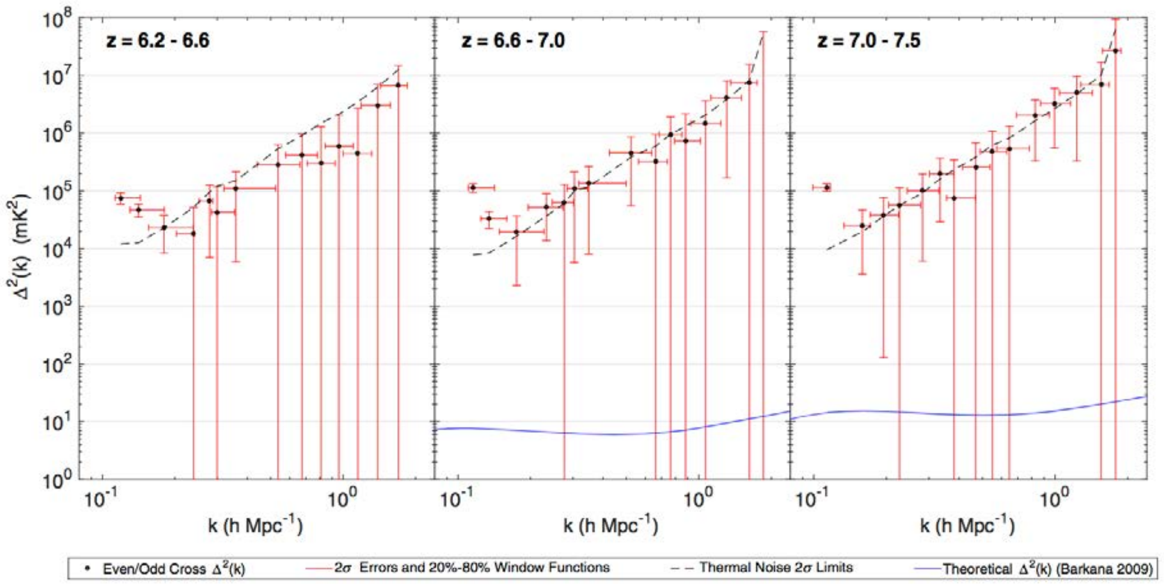
Patil et al. 2017

Current 21-cm Power-Spectrum Detection Experiments



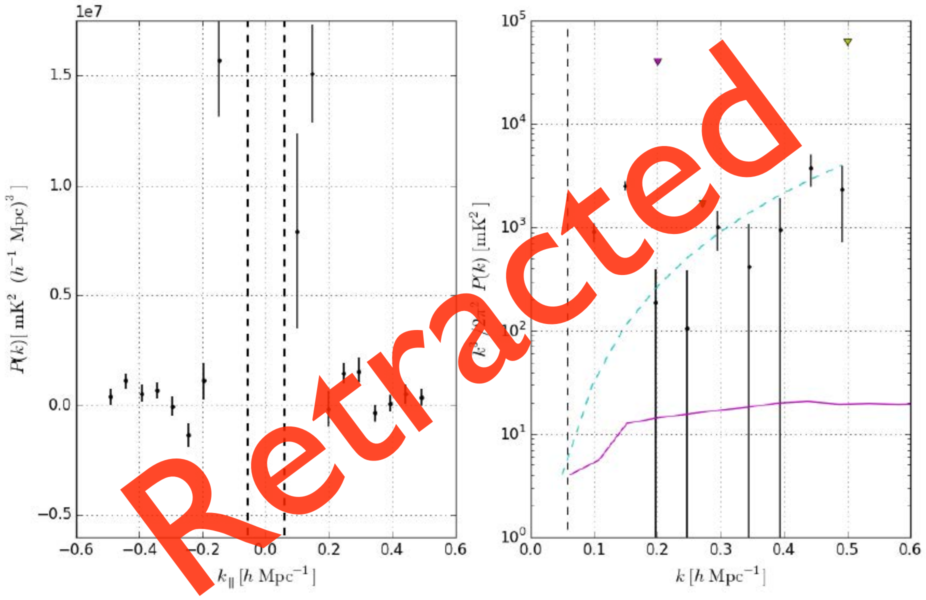
GMRT: Measurement of a 2σ upper limit of Δ(k) < 248 mK for k = 0.50 h Mpc^{-1} at z = 8.6.

Paciga et al. 2013



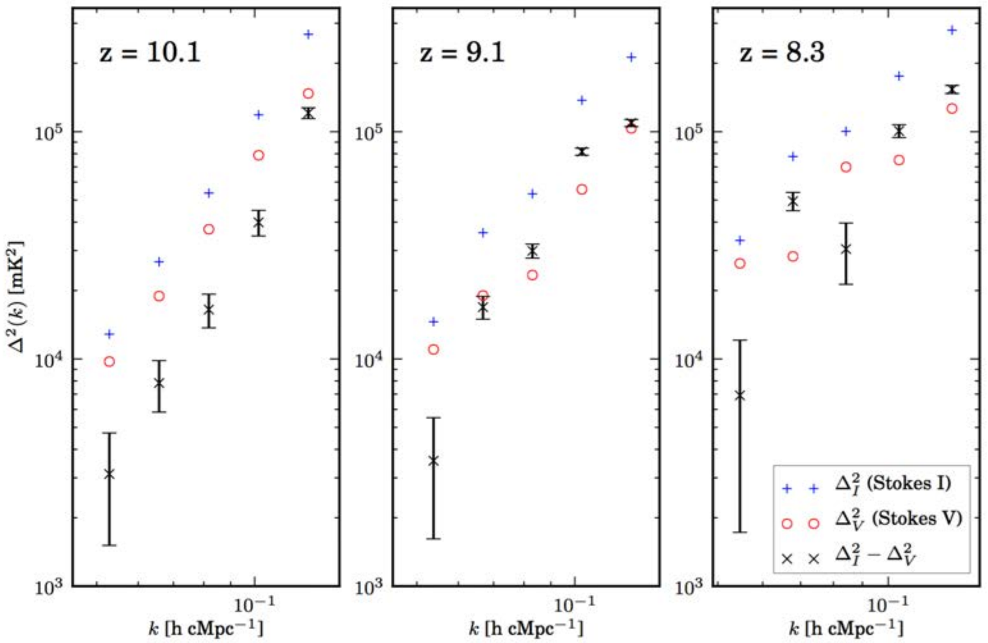
MWA-128T: Upper limits on the power spectrum from z = 6.2 to z = 7.5. The lowest limit is Δ(k) < 192 mK at 95% confidence at a co-moving scale k = 0.18 Mpc^{-1} at z = 6.8.

Dillon et al. 2015



PAPER 64-antenna: A best 2σ upper limit of Δ(k) < 22 mK for k = 0.15-0.5 h 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 Mpc^{-1} at z = 10.1.

Patil et al. 2017

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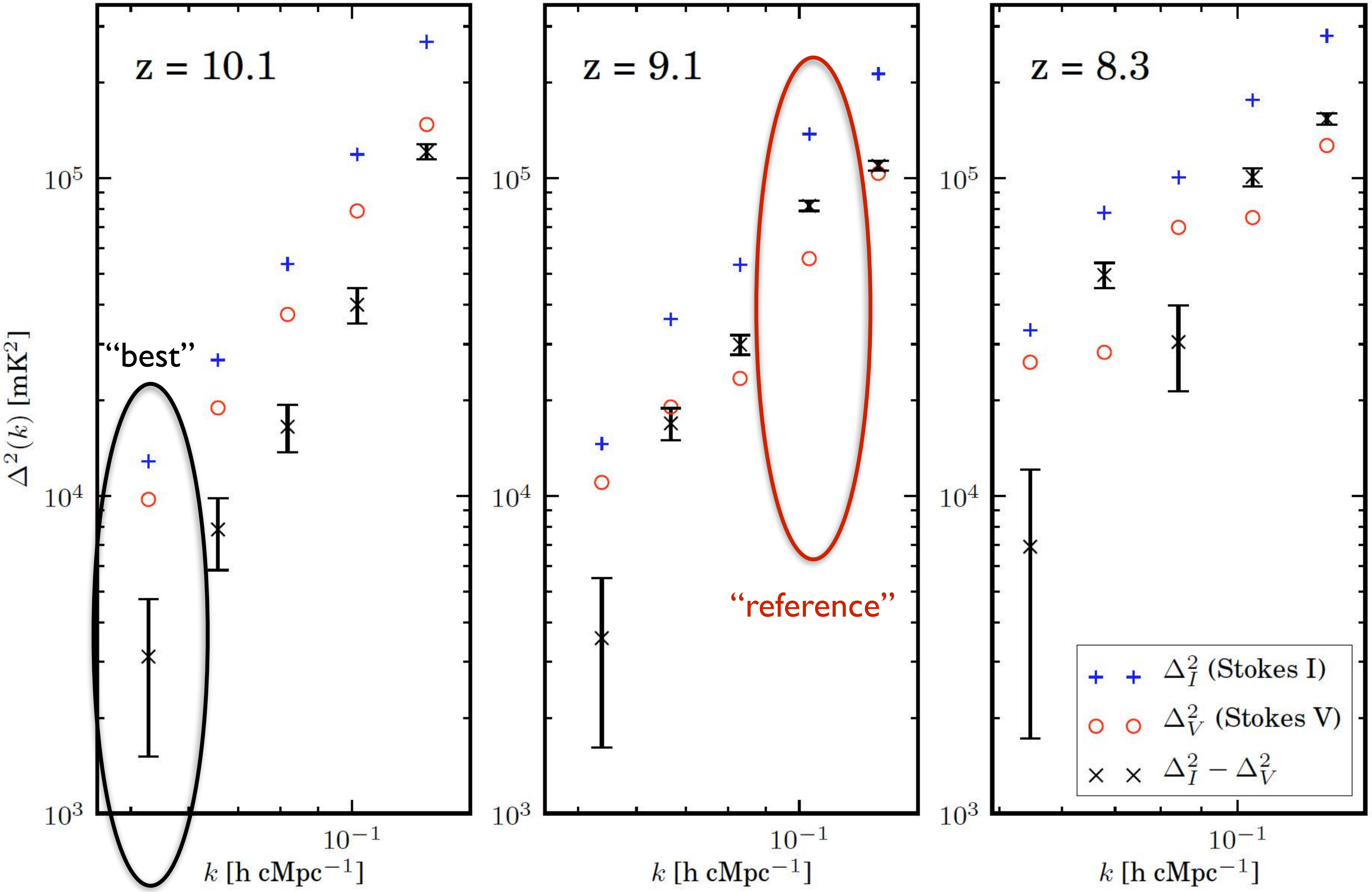
The Low Frequency Array (LOFAR) Reionization Key Science Project

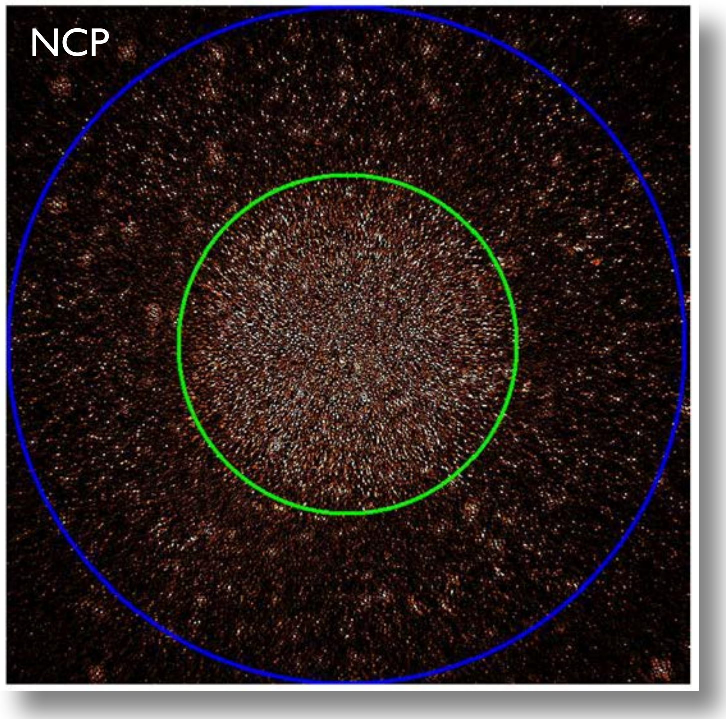
IAU, 2018

Power-Spectra 2017 - North Celestial Pole

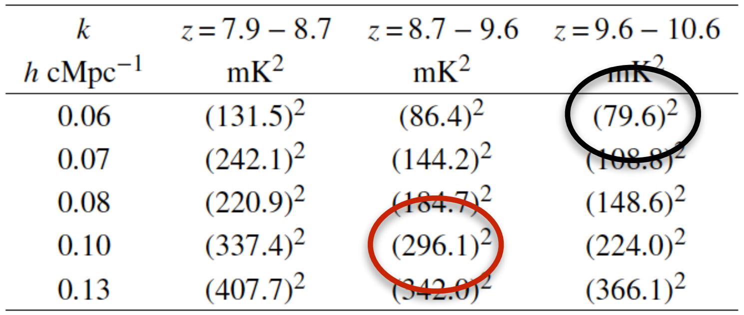
Averaging spherically provides the lowest errors (maximum # of samples per shell).



"best" upper limits



2-sigma upper limits



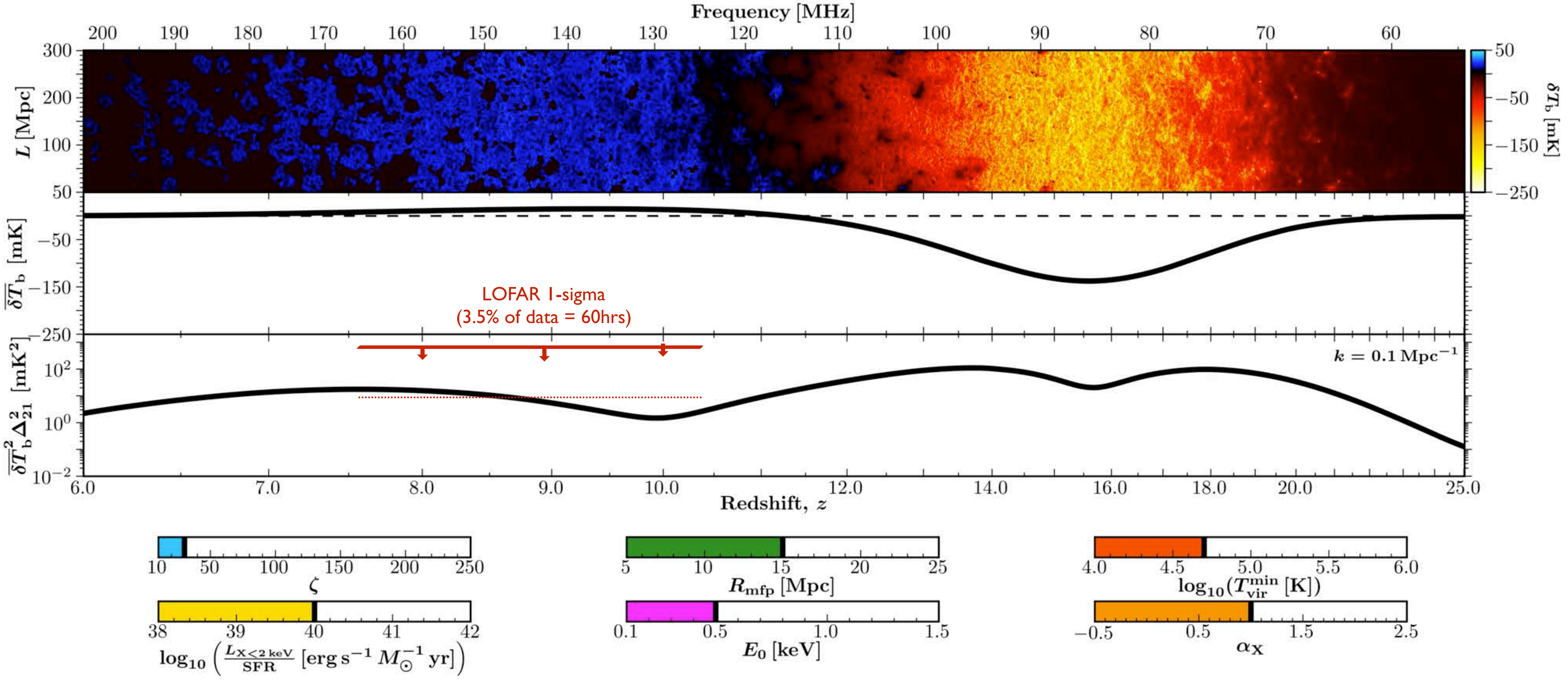
k h cMpc^{-1}	$z = 7.9 - 8.7$ mK^2	$z = 8.7 - 9.6$ mK^2	$z = 9.6 - 10.6$ mK^2
0.06	$(131.5)^2$	$(86.4)^2$	$(79.6)^2$
0.07	$(242.1)^2$	$(144.2)^2$	$(108.8)^2$
0.08	$(220.9)^2$	$(184.7)^2$	$(148.6)^2$
0.10	$(337.4)^2$	$(296.1)^2$	$(224.0)^2$
0.13	$(407.7)^2$	$(342.0)^2$	$(366.1)^2$

Patil et al. (2017, ApJ)

Physical Limits on the Cosmic Dawn

21CMFAST - varying the X-ray heating luminosity.

Credit: Mesinger & Greig



LOFAR 1-sigma
(3.5% of data = 60hrs)

Note: Excess noise (I over V) is incoherent (averages away): we assume it drops in the cross-variance and plot the 1-sigma upper limits (in 21CMMC, we double the errors)

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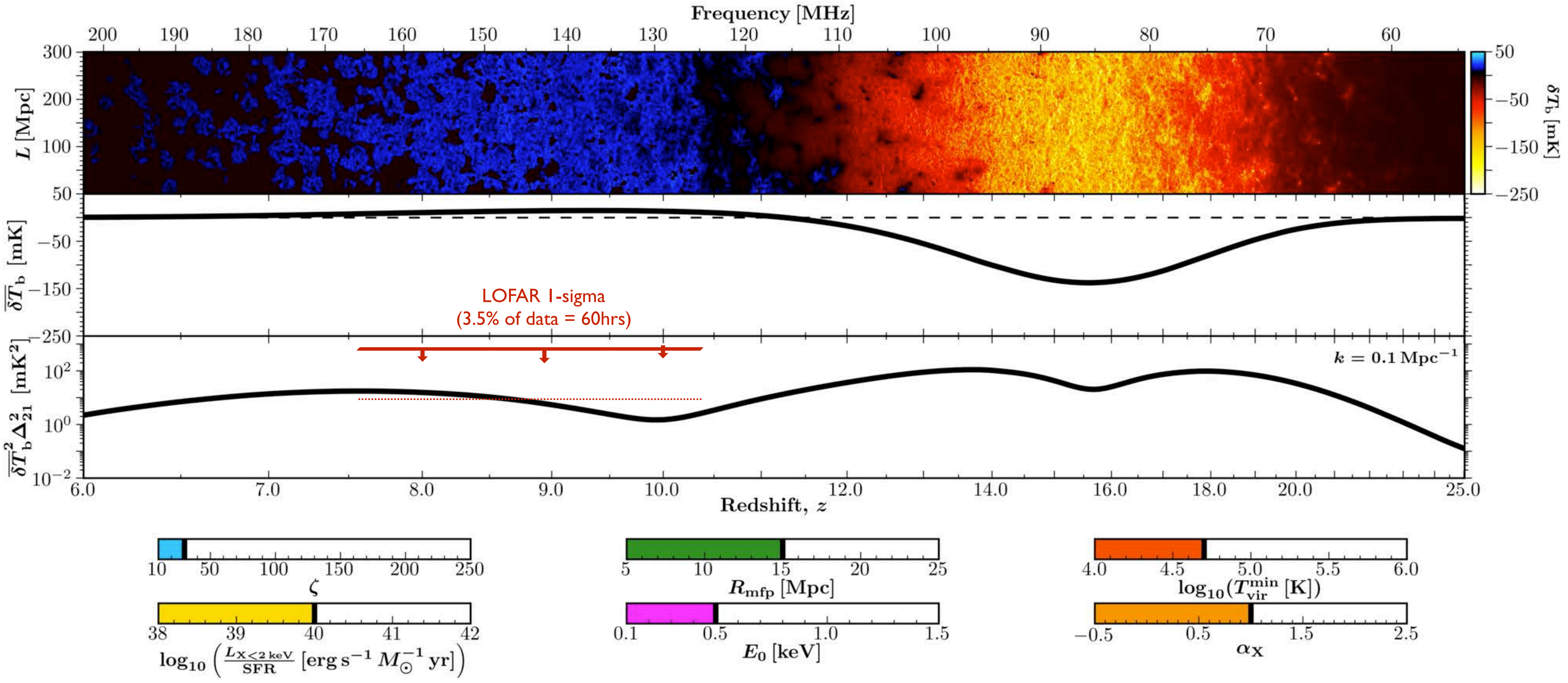

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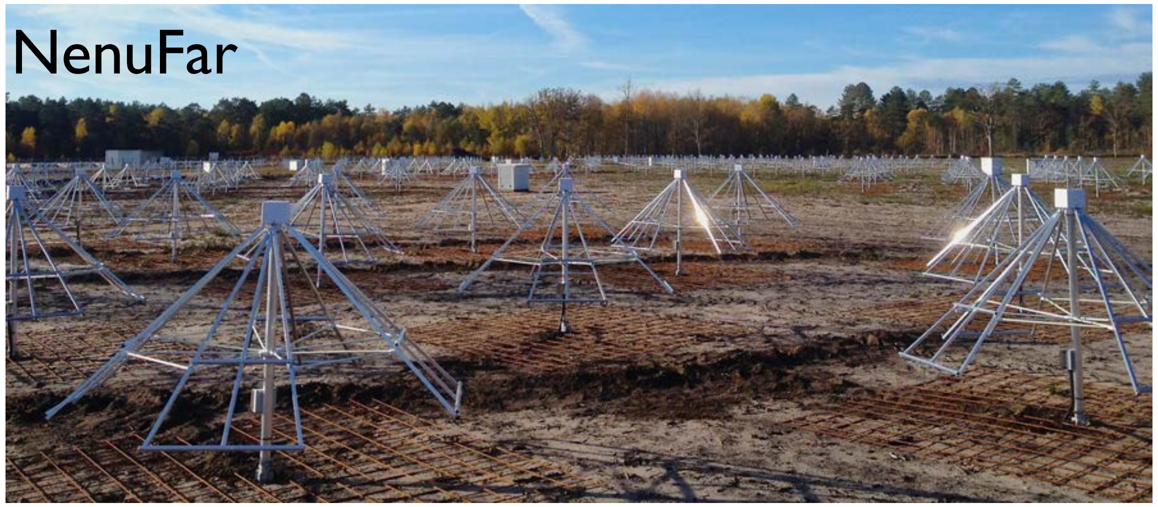
Ongoing Developments

Exciting new 21-cm Power-Spectrum/Tomography Instruments

2019


NenuFar

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

~2020


HERA

Hydrogen Epoch or Reionization Array

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

Paciga et al. 2013

~2025


SKA-low

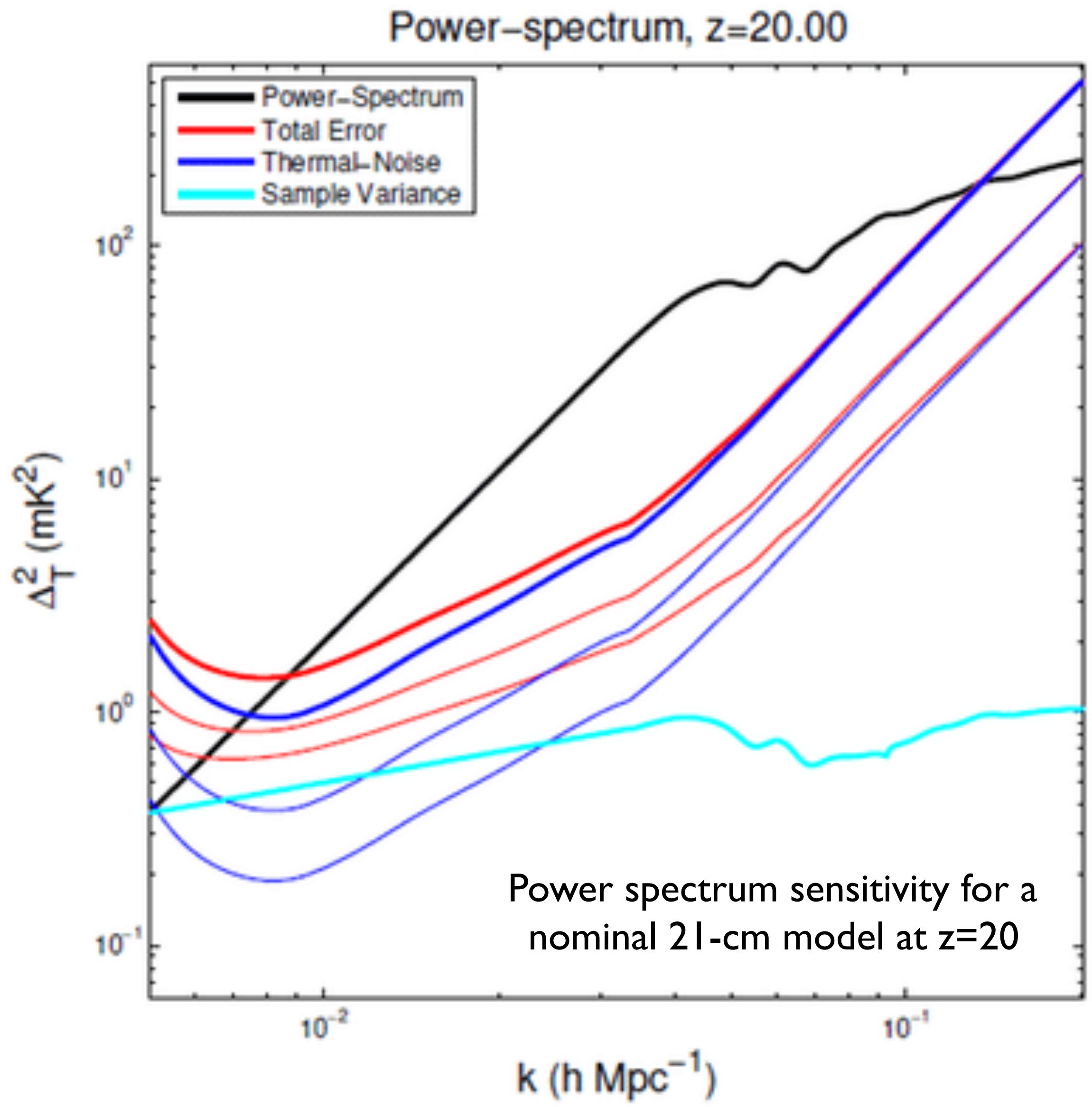
Square Kilometre Array

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

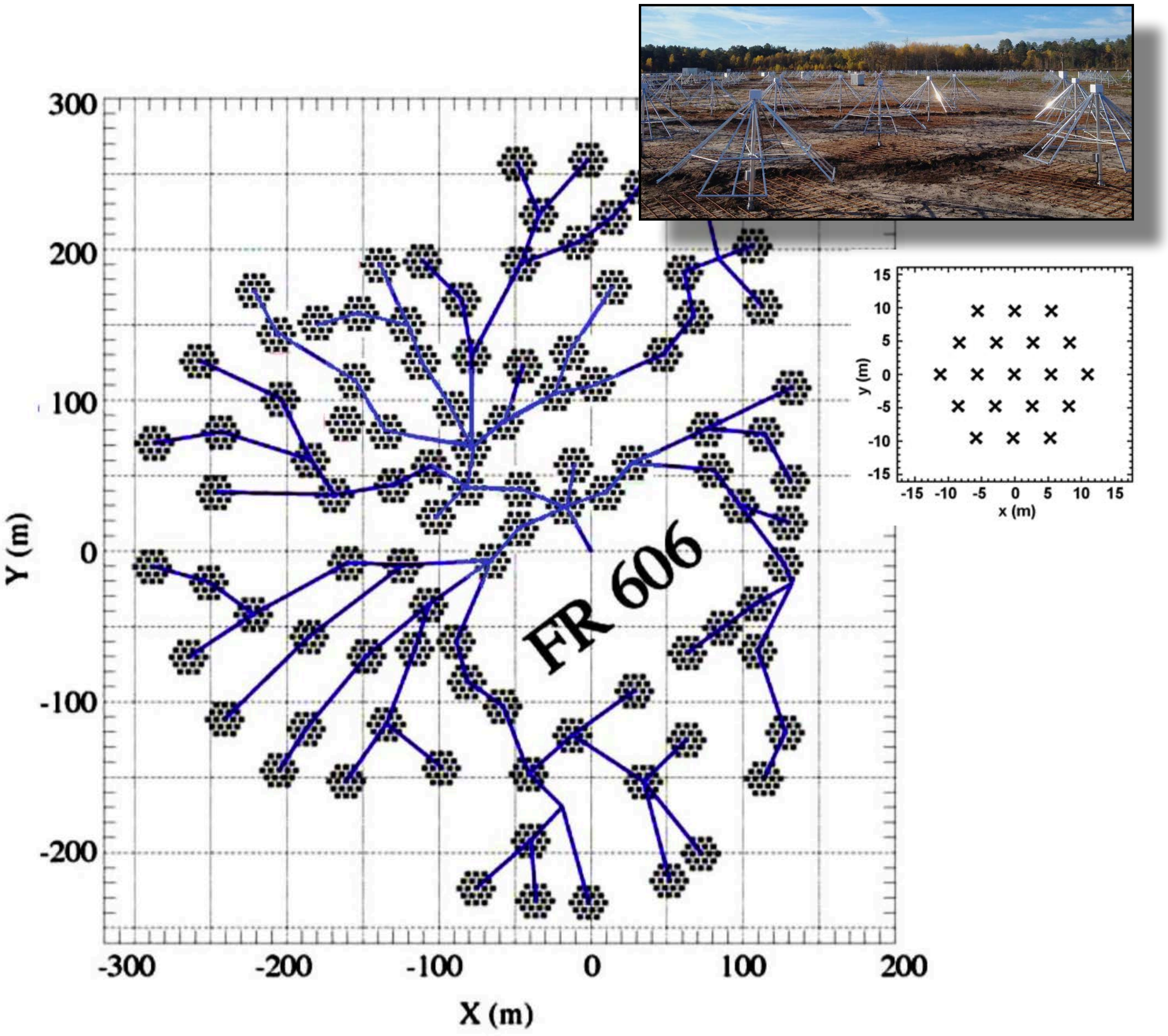
Dillon et al. 2015

New Extension in Nançay Upgrading LOFAR: NenuFar

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



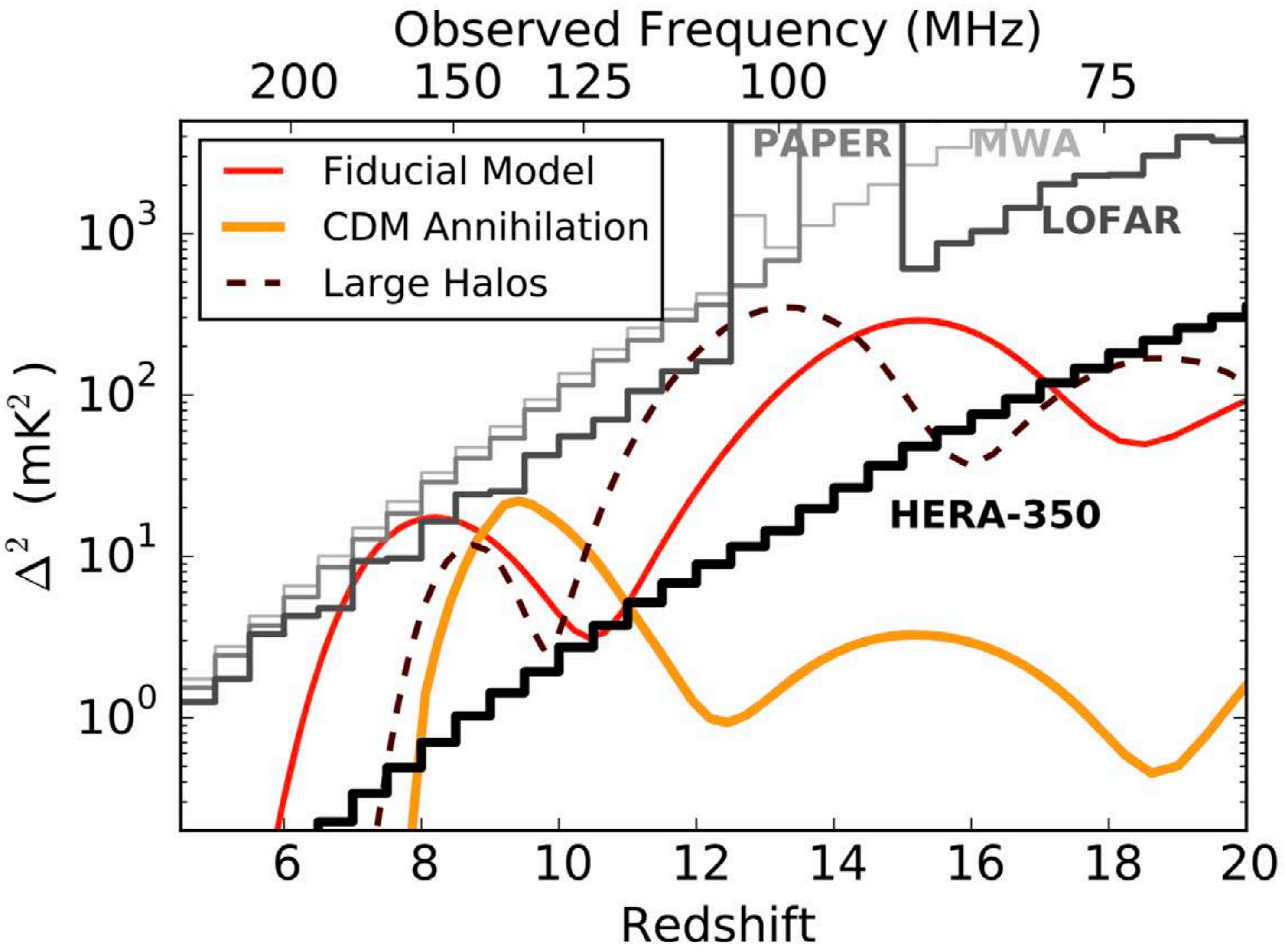
Power spectrum sensitivity for a nominal 21-cm model at z=20

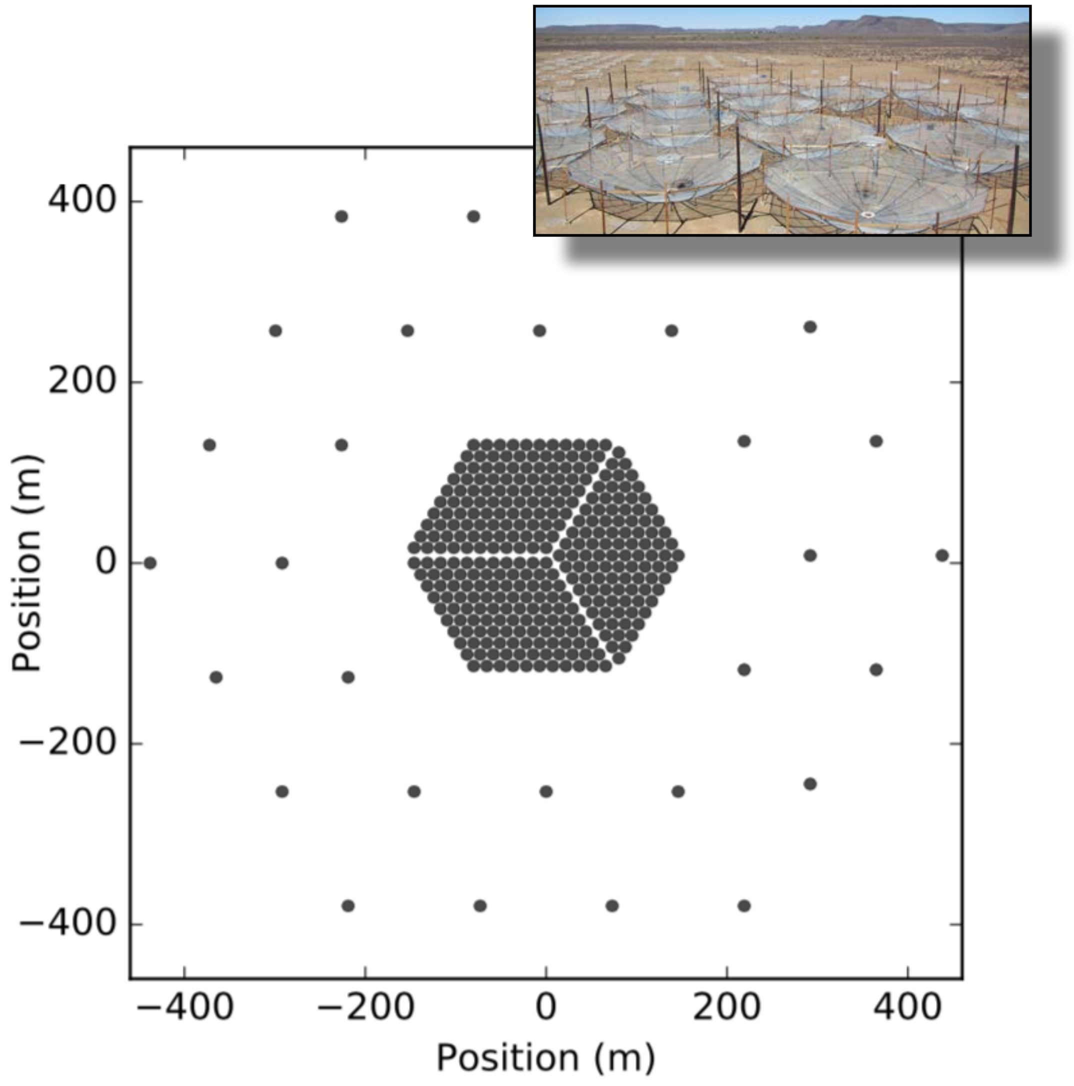


Zarka et al. 2015

Hydrogen Epoch of Reionization Array: HERA

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

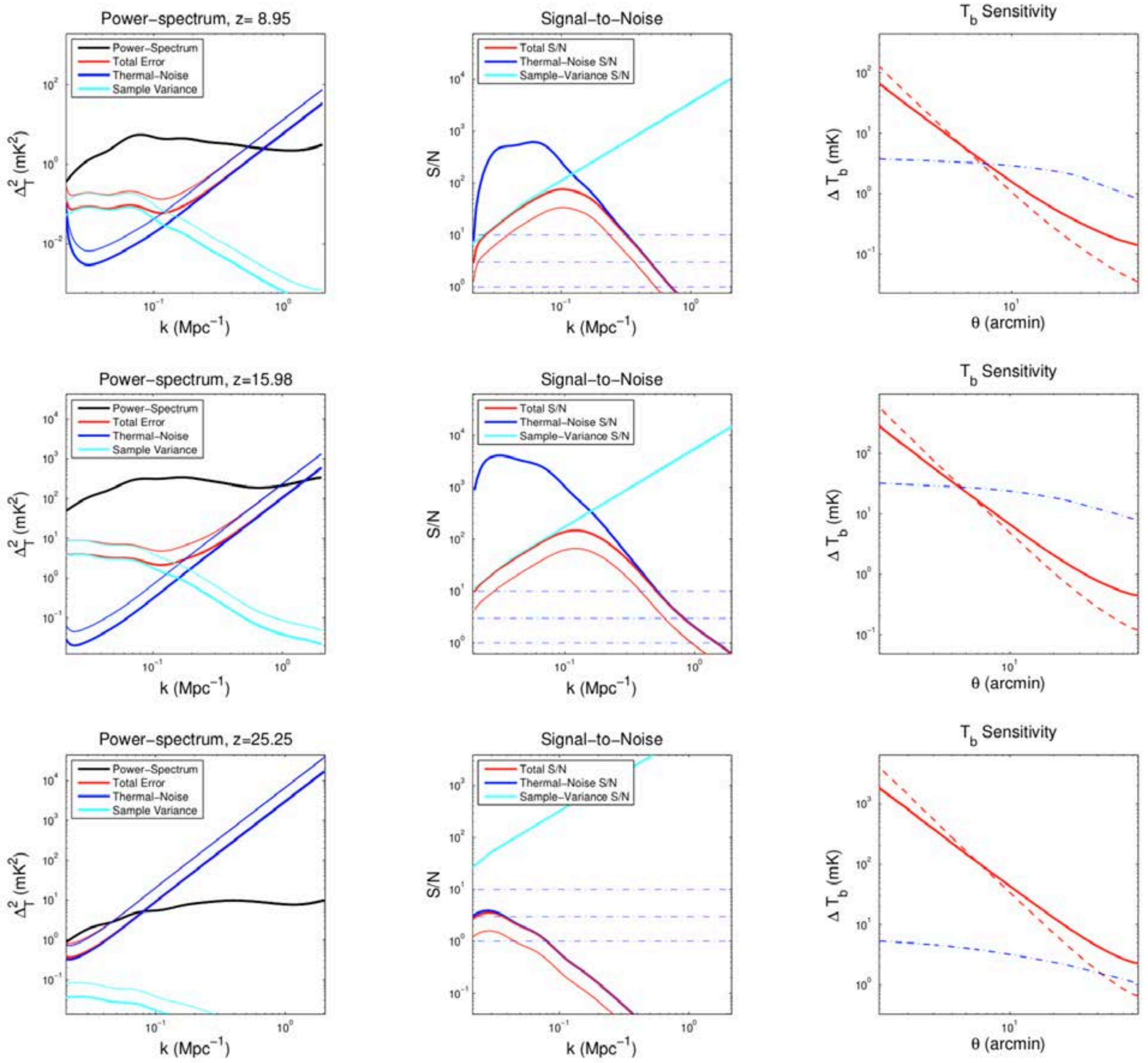


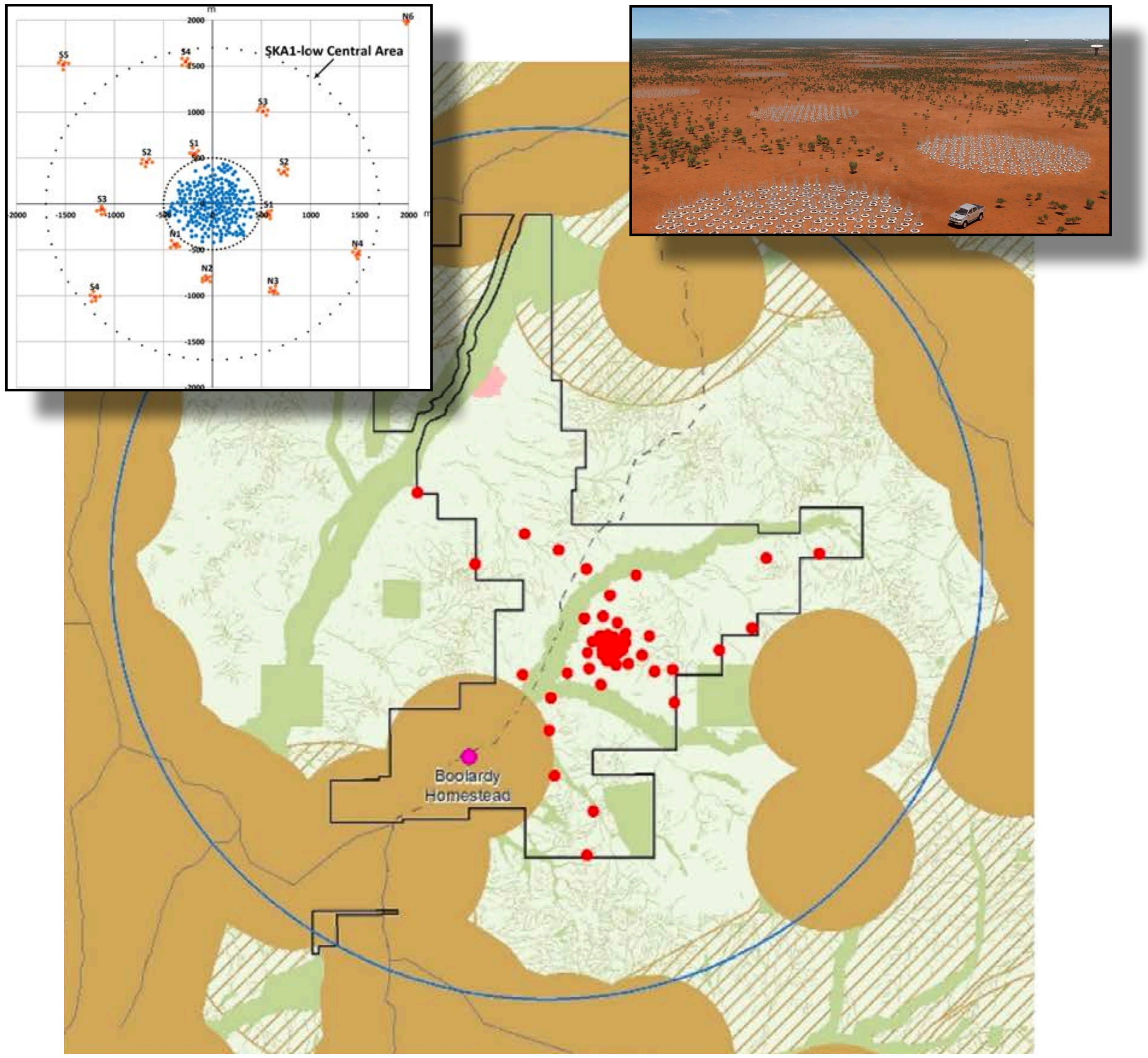


deBoer et al. 2016

The Square Kilometre Array: SKA(1)-Low

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

SKA CD/EoR Survey Designs

Wider versus Deeper

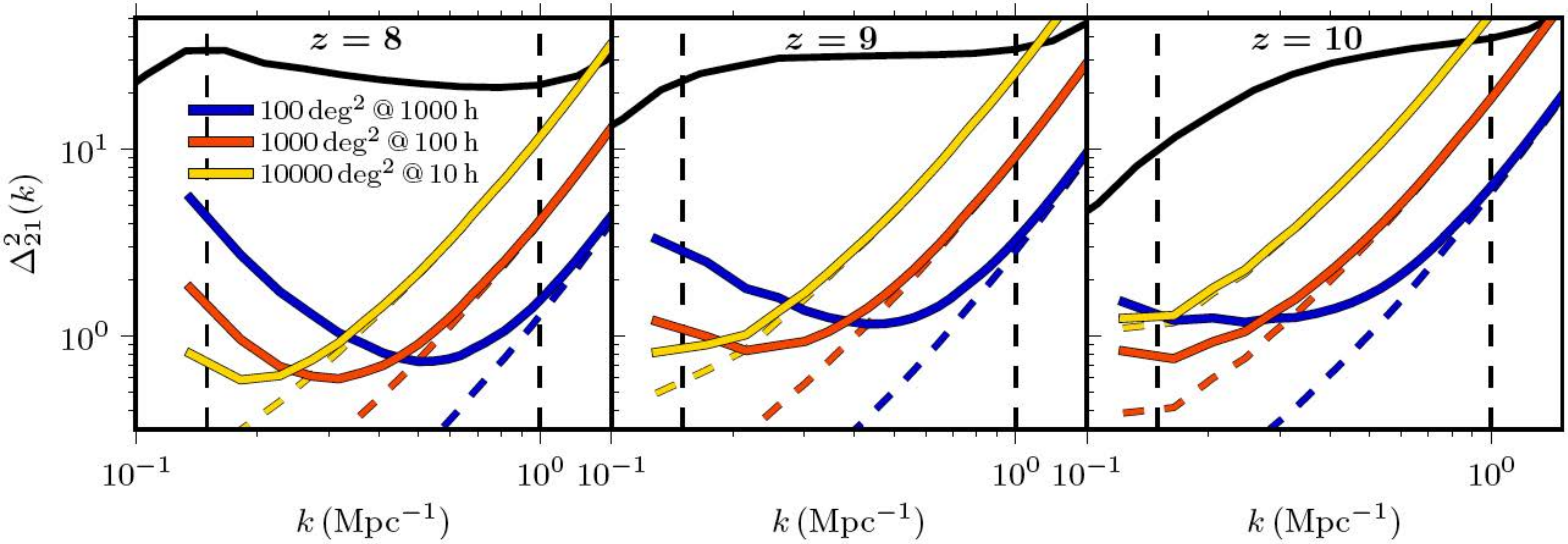
A three tiered-survey (3x5,000hrs):

- 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)

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: deepest (2-sigma) prelim. upper limits on PS (@ k=0.1, z=9)

- 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.