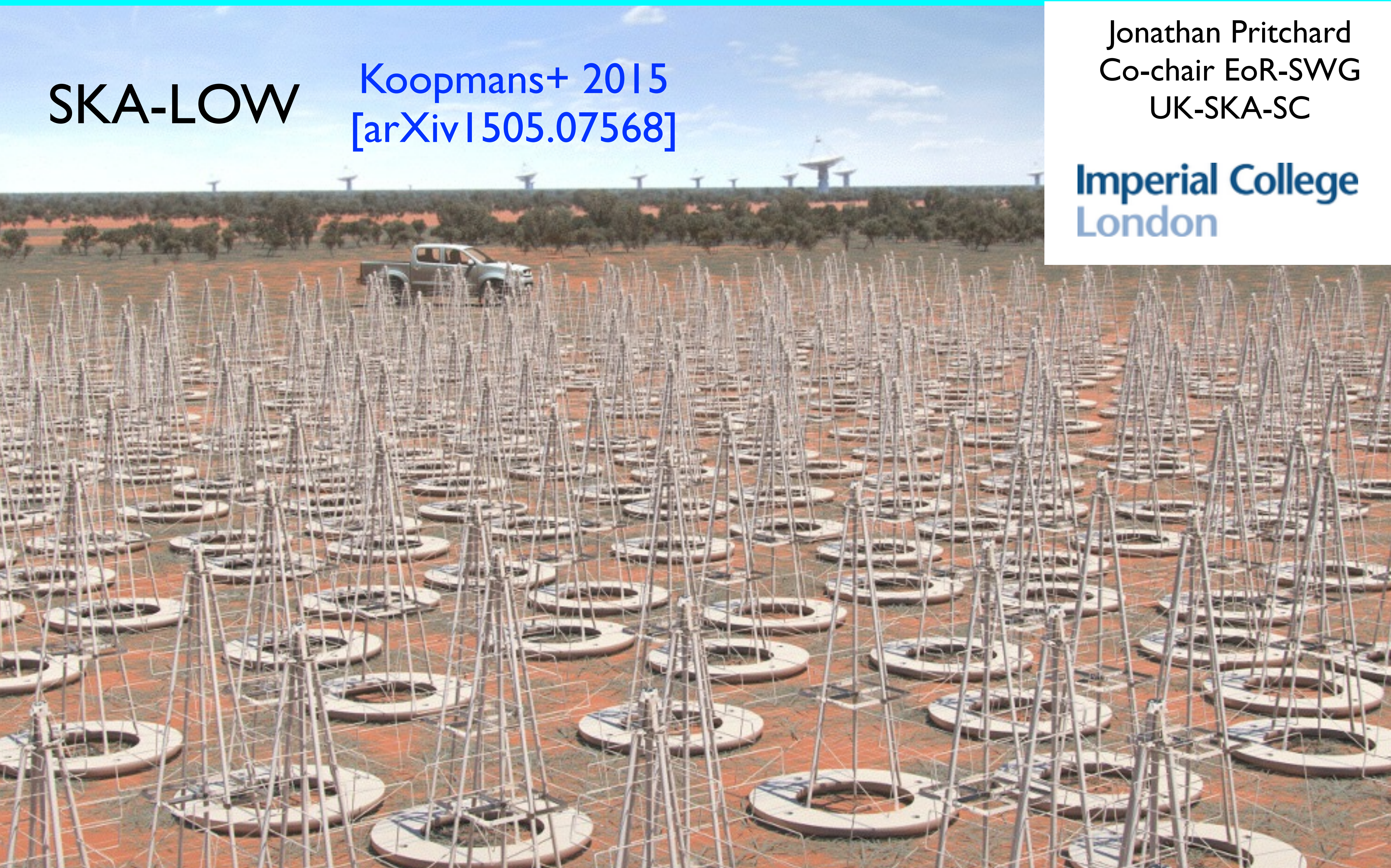
Epoch of Reionization and Cosmic Dawn



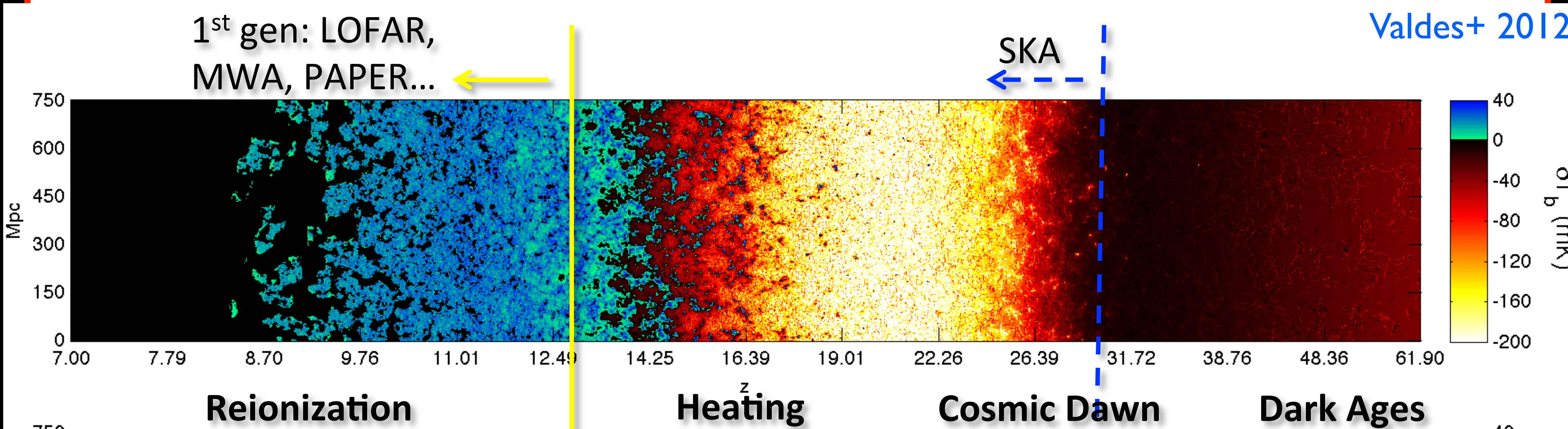
SKA-LOW

Koopmans+ 2015
[arXiv1505.07568]

Jonathan Pritchard
Co-chair EoR-SWG
UK-SKA-SC

Imperial College London

Reionization and cosmic dawn



Possible hints of neutral hydrogen at z~7, e.g. z=7 QSO, LAE/LBG ratio

By 2020: possible advances...

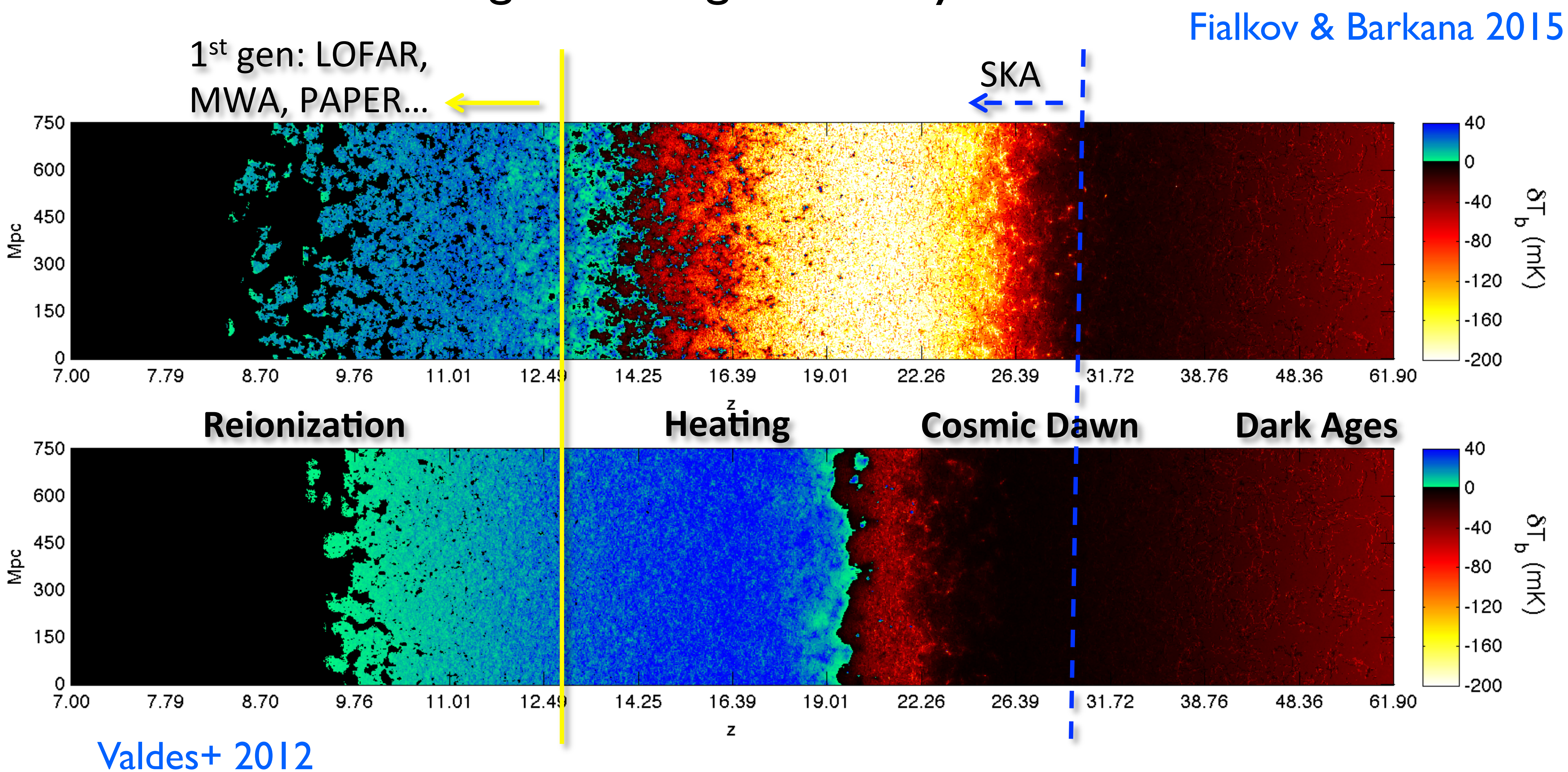
1) Planck polarisation could constrain redshift and duration of reionization
2) HST+JWST will have observed bright end of luminosity function to higher redshifts (faint end will still be incomplete; connection to ionizing photons may still be unclear)
3) Little advance in QSO (more at z~7) - wait for Euclid in 2020 to push to z~8
4) LAE surveys into EoR will be more advanced (HSC) - maybe clustering => patchy reionization?

21 cm is a unique probe of reionization and cosmic dawn

Alternative histories

Broad parameter space for heating prescriptions
- X-ray binaries, mini-quasars, DM annihilation, …
- uncertain star formation history

Effect of feedback on galaxies e.g. metals, Lyman-Werner, bulk flows



21 cm science

Key Science Questions

- Formation and evolution of galaxies over cosmic time
- Nature of first stars and black holes
- Thermal history of the IGM over cosmic time
- Topology and processes of reionization
- Distribution of matter at z >6

Key Science Goals*

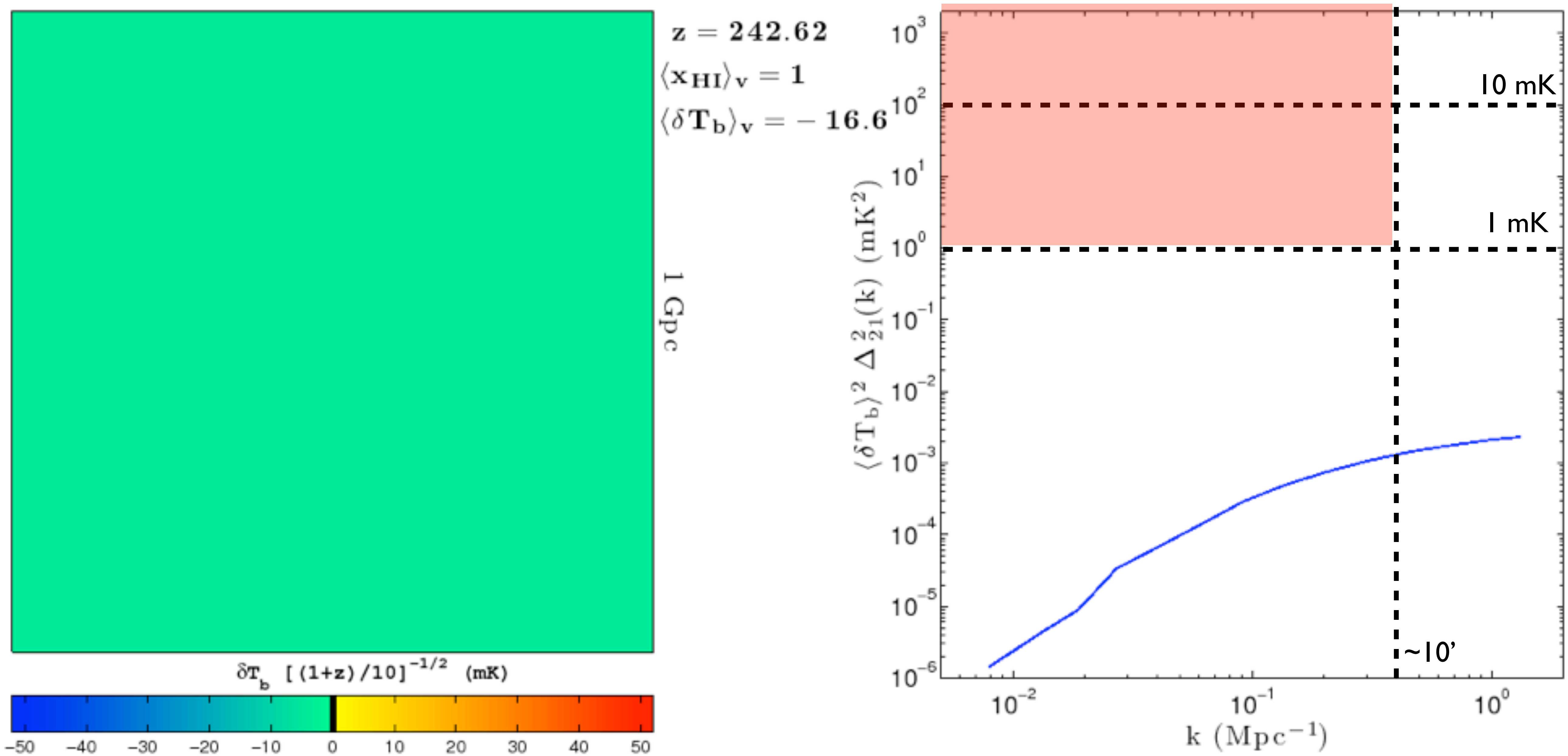
- Power spectrum measurements from z=28 - 6
- Imaging of 21cm signal during reionization >5 arcmin, 1 mK
- Spectral 21cm forest observations to z>6 bright radio sources

* requires detailed characterisation of ionosphere,
diffuse foregrounds and bright radio point sources

Science questions

1. When did heating/ionization/radiativecoupling of the IGM commence and complete?
2. What is the spatial brightness temperature distribution of the IGM as function of redshift?
3. How did the first first stars, galaxies, BHs, stellar remnants form and evolve?
4. How did the IGM/ISM ionize and how did it enrich with metals?
5. What is the spatial structure of ionization structures (i.e. bubbles) as function of redshift?
6. What are the dominant physical mechanisms and sources responsible for heating, ionizing, enrichment and feedback to the IGM/ISM?
7. What effect did feedback and early structure formation have on galaxy formation (e.g. substructure).
8. How and when did the first black holes form and evolve to highz AGN?
9. Did structures in the early Universe evolve in accordance with LCDM?
10. Does DM annihilation contribute to early structure formation?
11. Were there any popIII stars, what were their properties and how did the transition to popII stars take place?
12. What is the effect of baryonic bulk flows on early structure and star formation?
13. How does the IGM (in particular 21cm emission) (anti)correlate with other observables such as e.g. CO, CII, Ly-alpha emitters, GRBs
14. How does the end of reionization transition to the high-z observable universe (e.g. HI in galaxies).

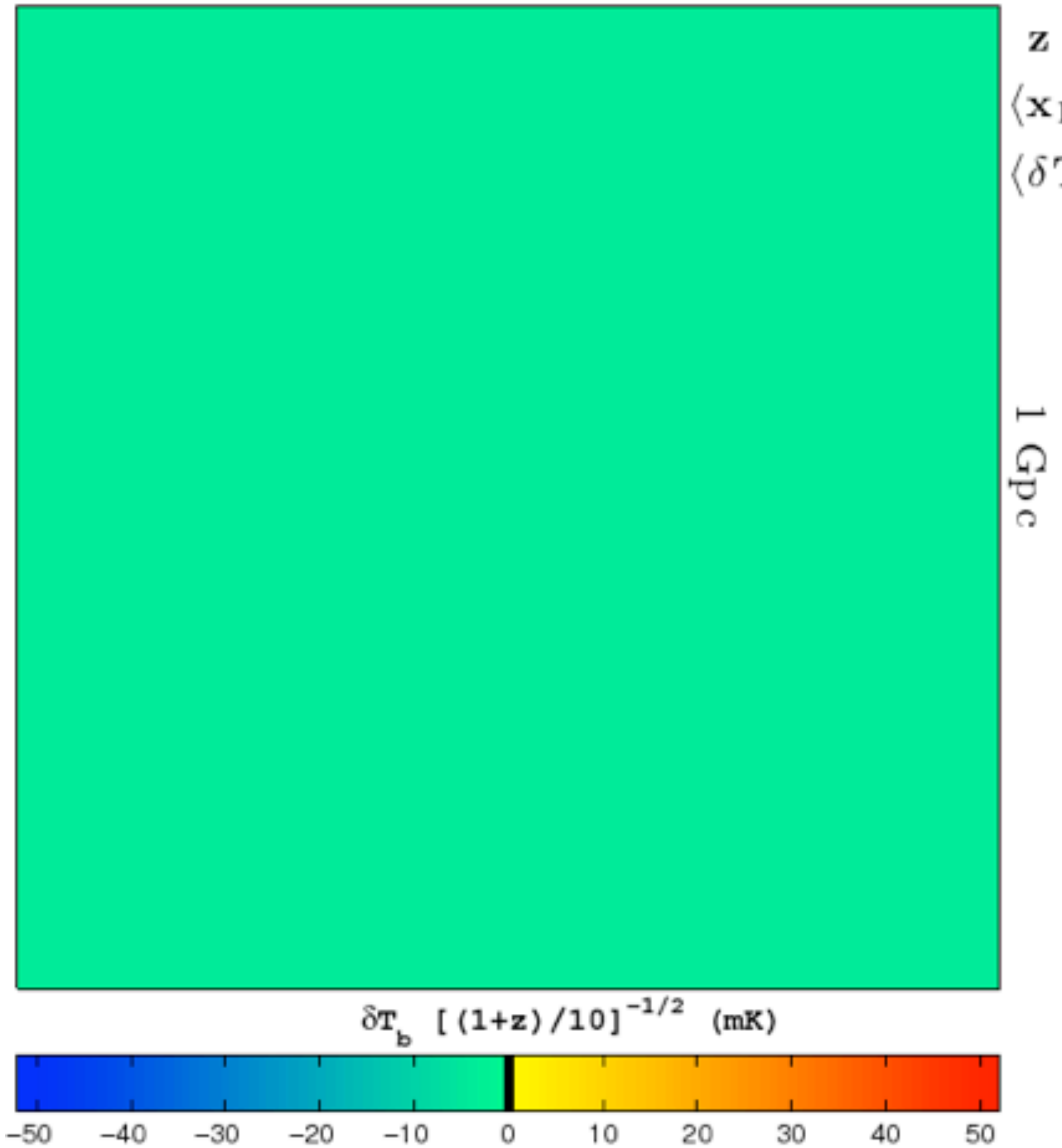
(1) Evolution of the power spectrum

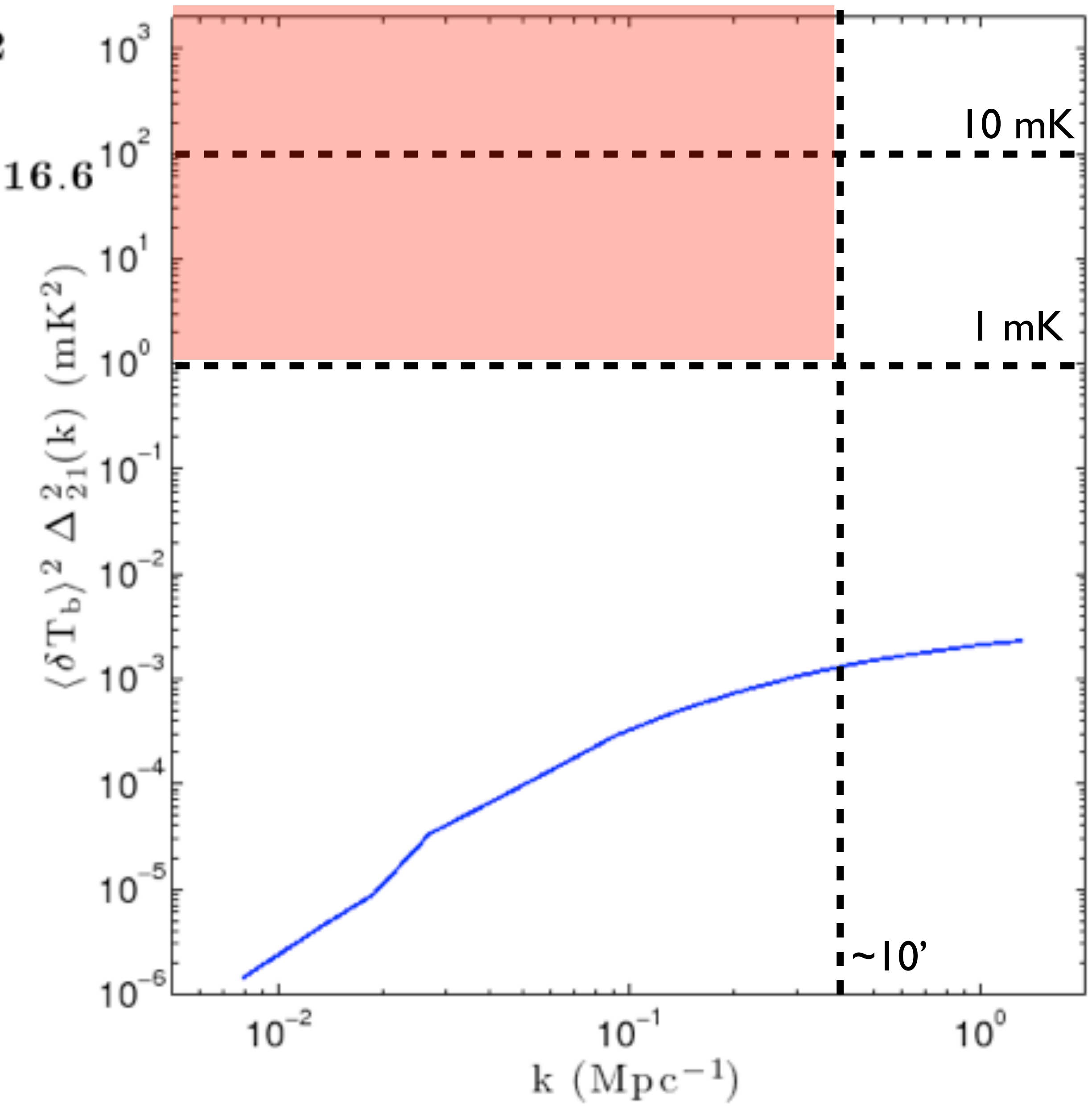


Mesinger+ 2010

Rich science contained in spatial and redshift evolution of 21cm power spectrum

(1) Evolution of the power spectrum





Mesinger+ 2010

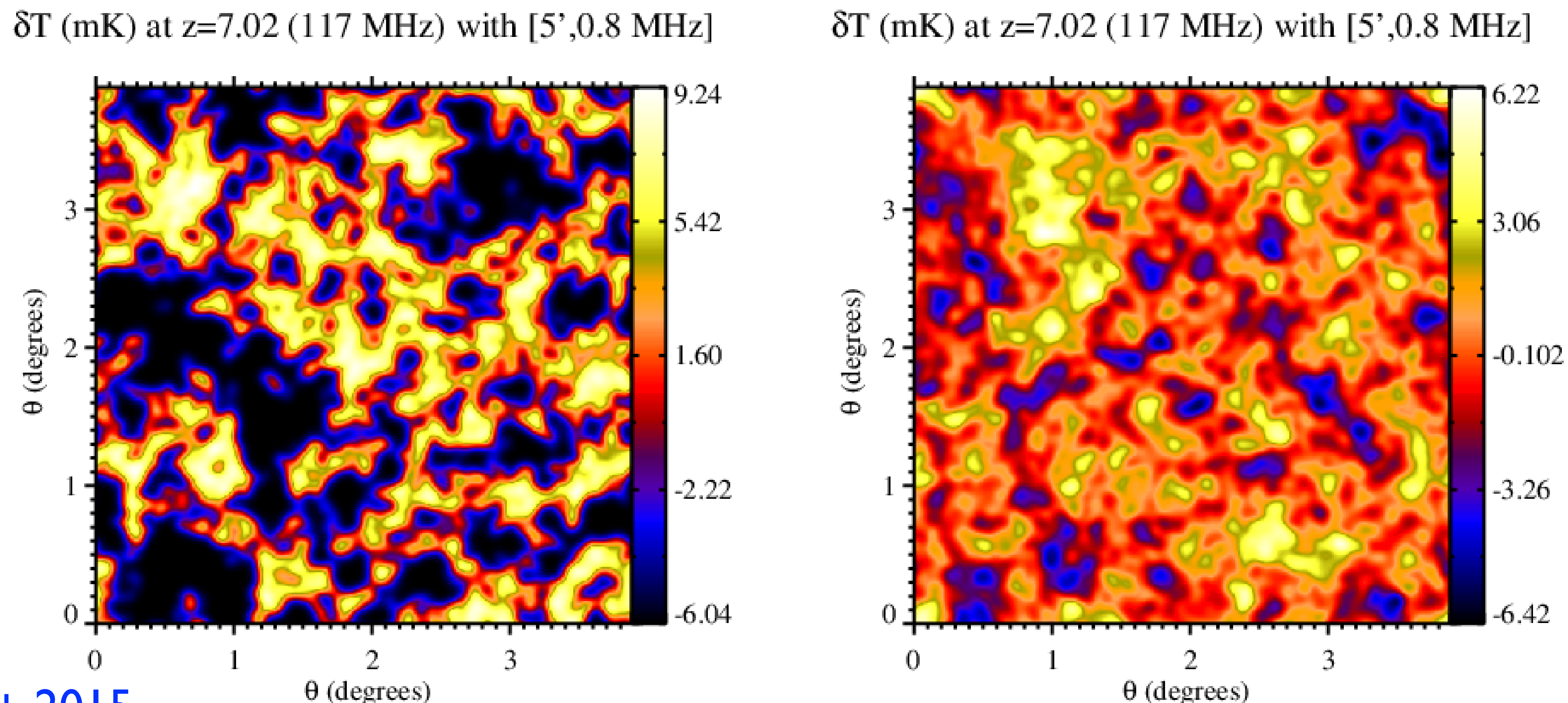
Rich science contained in spatial and redshift evolution of 21cm power spectrum

(2) 21cm tomography

3D maps of topology of reionization - few arcmin res, >10 deg^2 size

Directly image large HII regions around AGN/bright sources

Environmental information for other probes of reionization



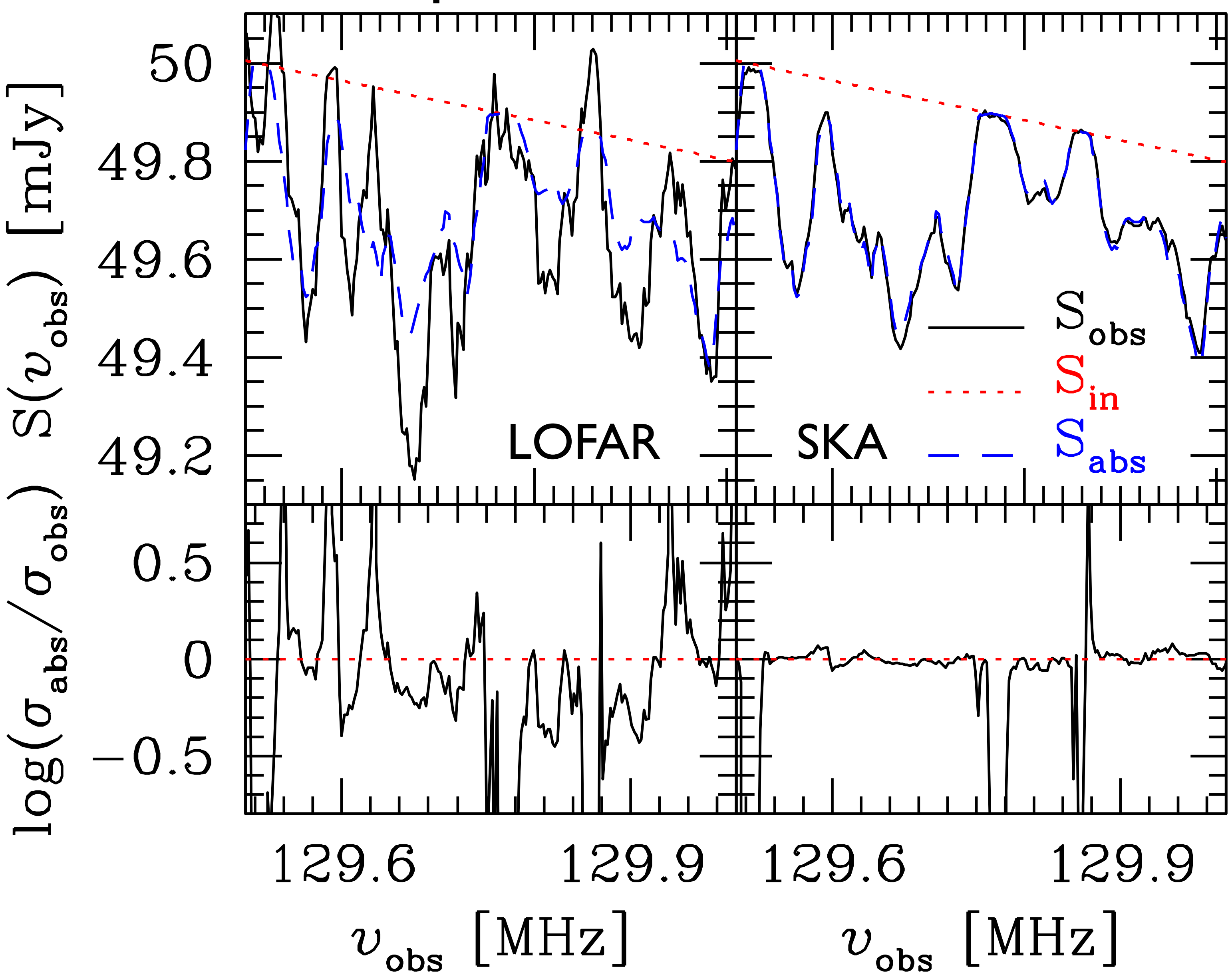
Mellema+ 2015

(3) 21cm Forest

~kHz resolved spectra of 21cm forest in bright radio sources at z>6

Alternative view of reionization/thermal history

Resolve dense ~kpc scale structures in IGM



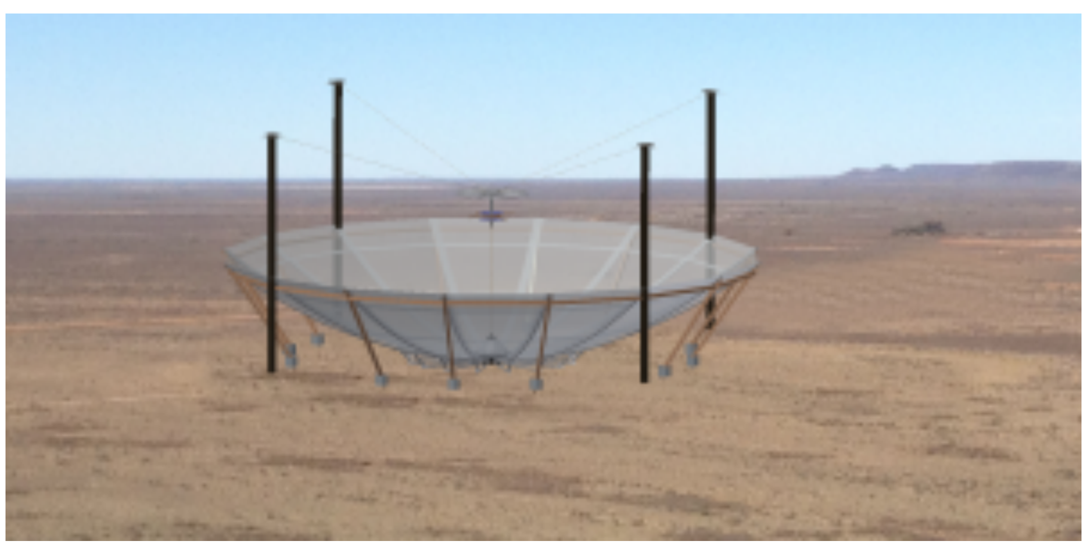
50mJy source @z=10

Ciardi+ 2015

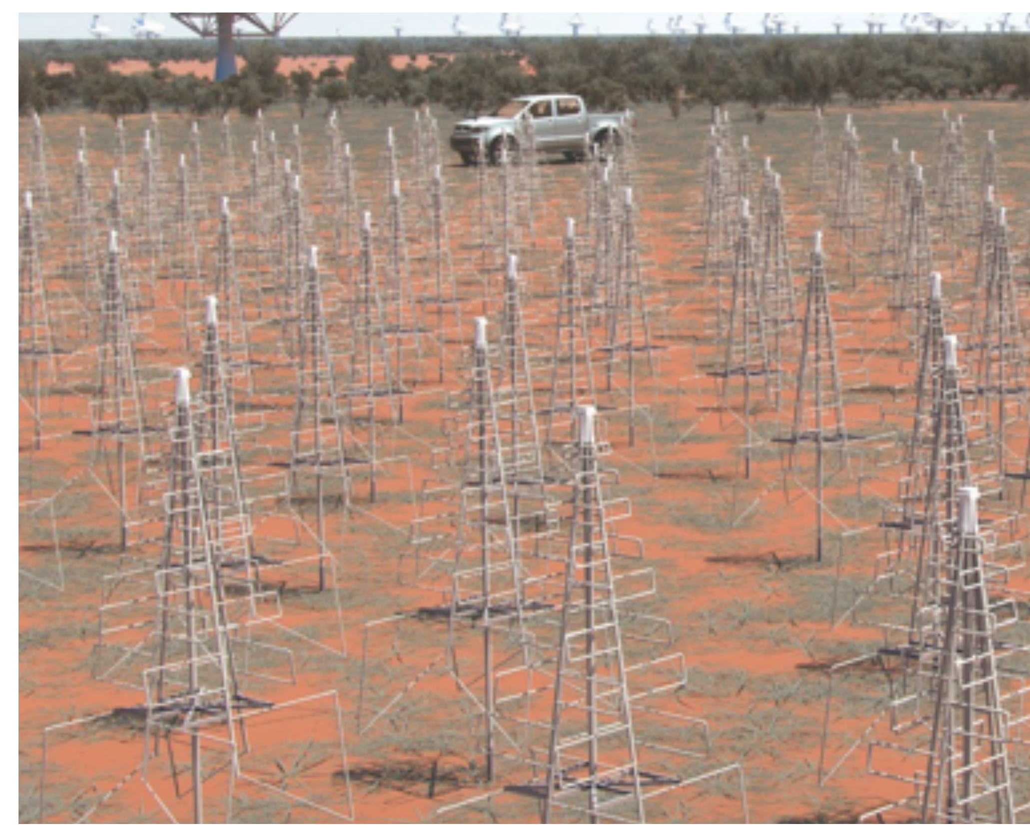
MWA

LOFAR

PAPER
+21CMA



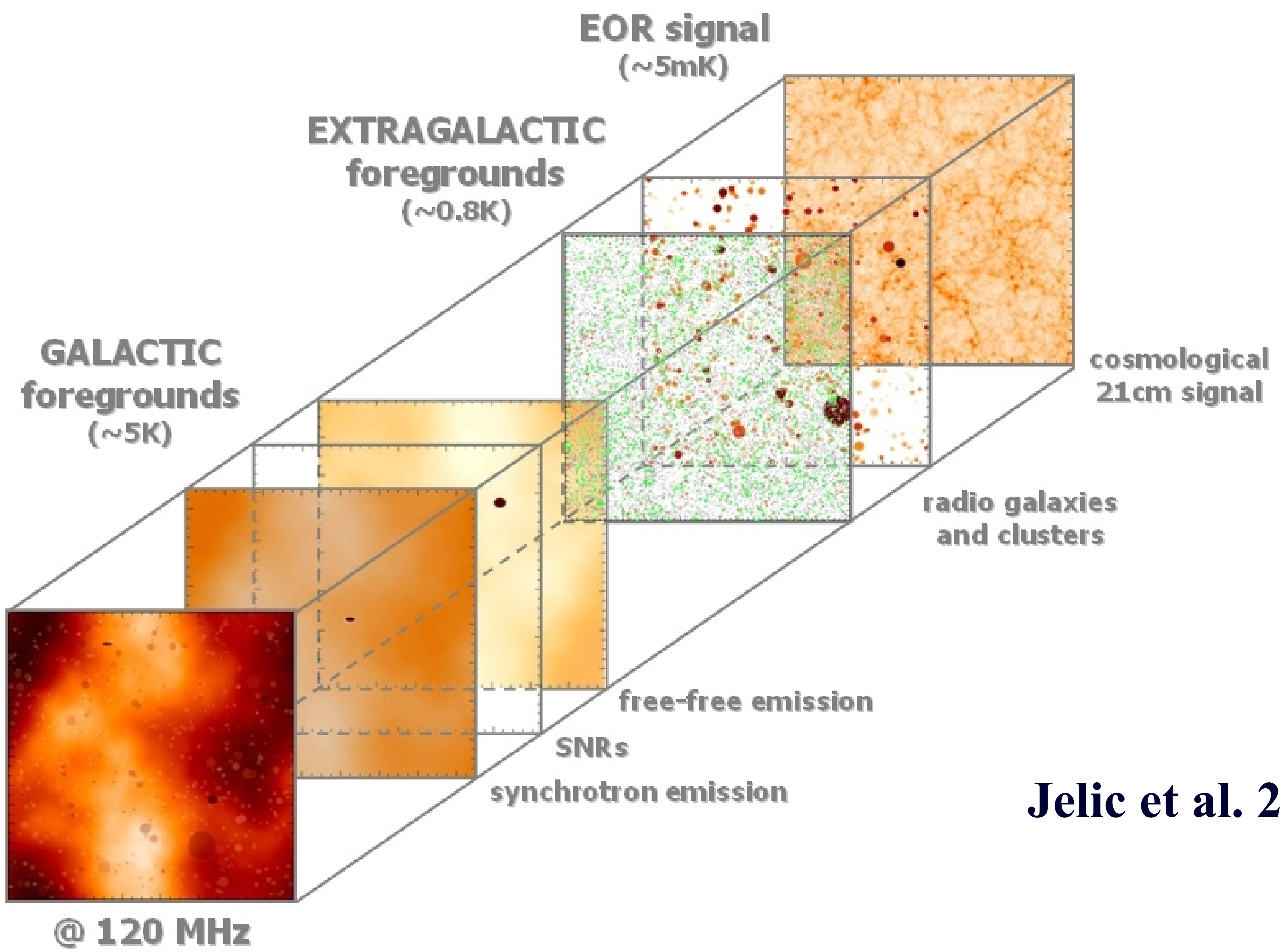
HERA
+NenuFAR



SKA

21 cm sky

Challenge: (1) separate 21cm sky from foregrounds
(2) extract scientific content of 21cm signal



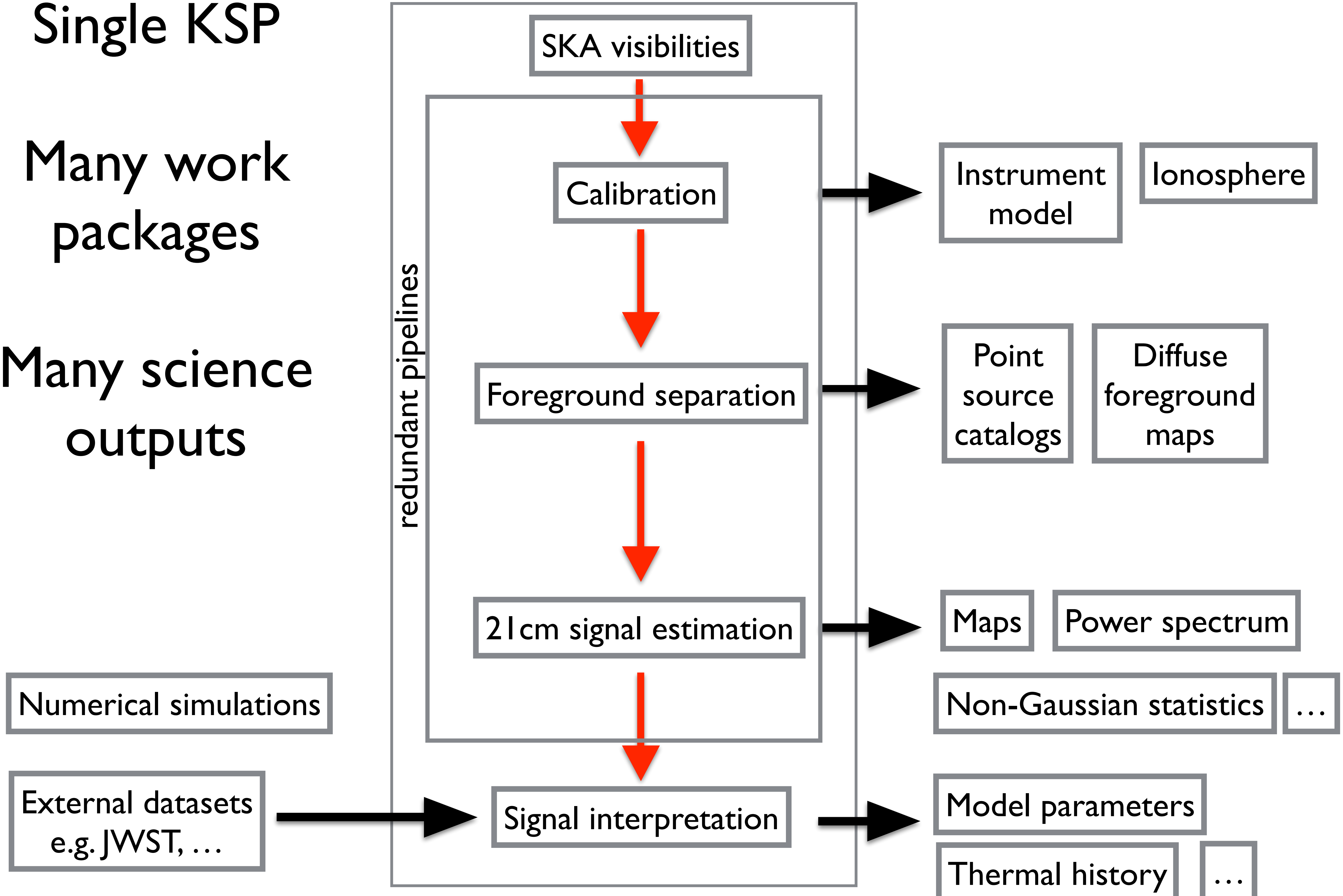
Jelic et al. 2008

Analysis

Single KSP

Many work packages

Many science outputs



21 cm foregrounds

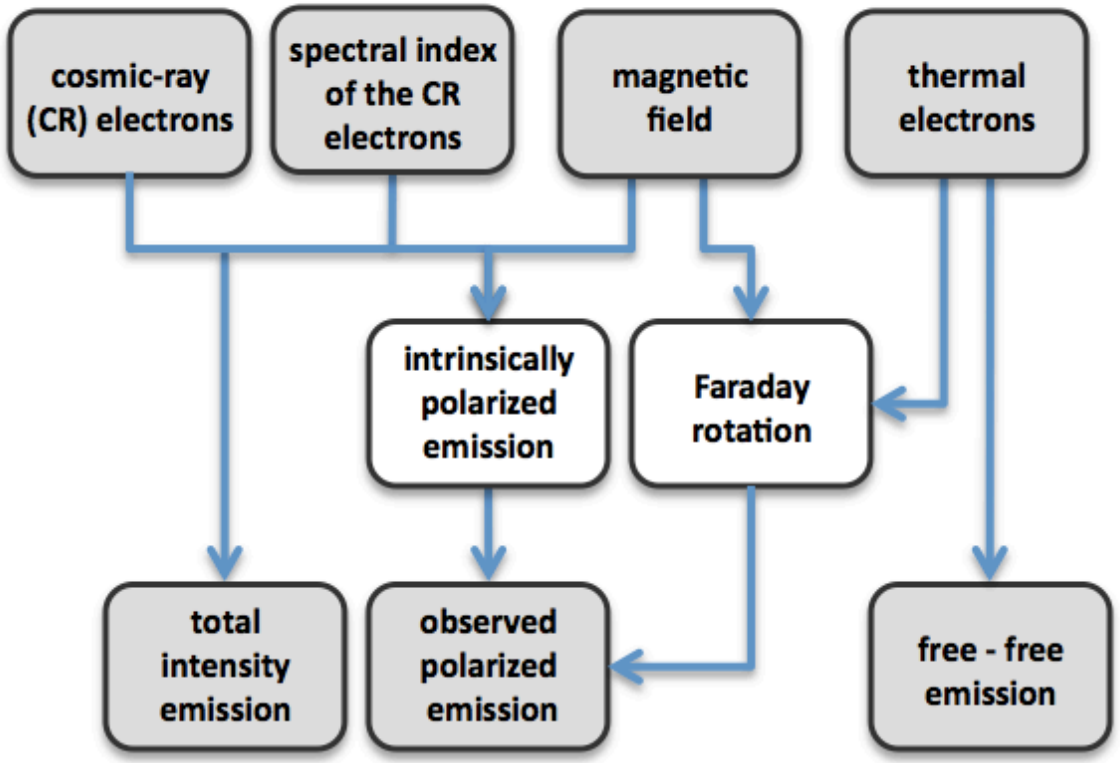
Imperial College London

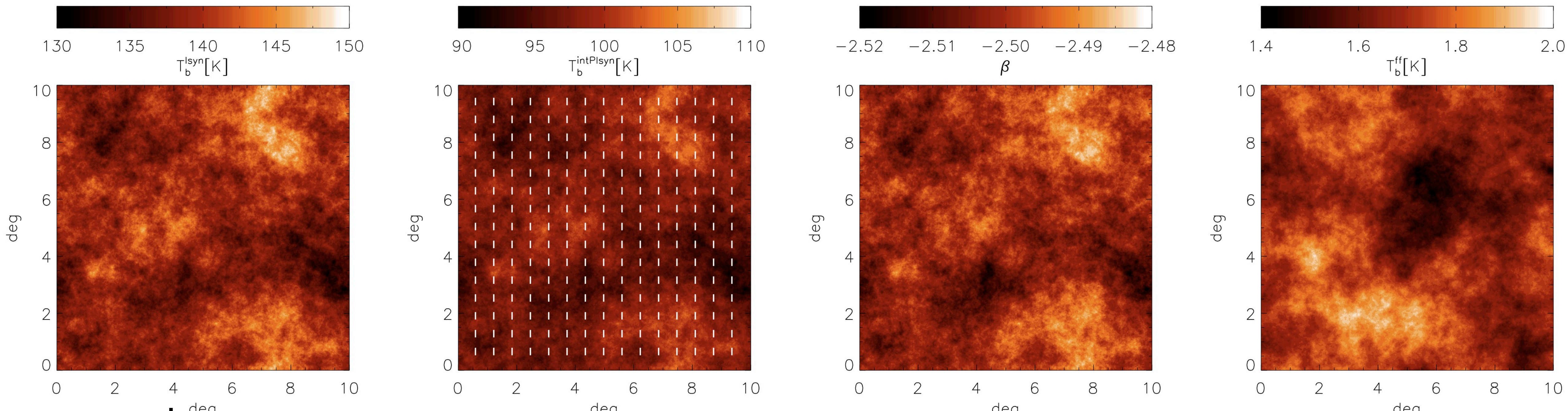
Ionosphere

Radio point sources:
FRI/II, star-forming gal

Diffuse foregrounds

Polarisation particularly important
- Faraday rotation





synchrotron total intensity | synch. polarisation | synch. spectral index | free-free intensity

Jelic+ 2008, 2010

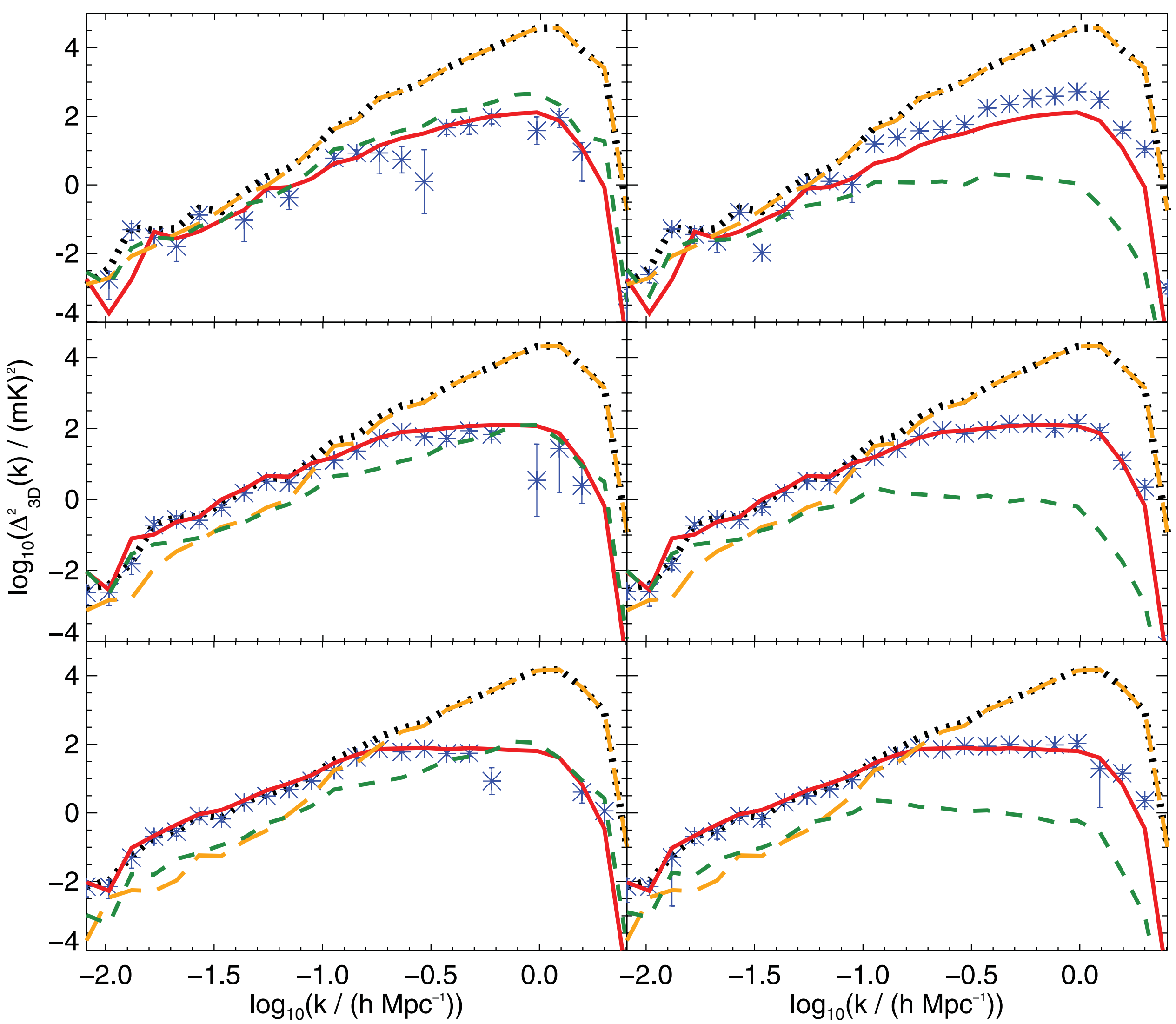
10 deg x 10 deg at 1 arcmin resolution

Foreground removal & signal estimation

Several techniques under development
"removal is not separation"

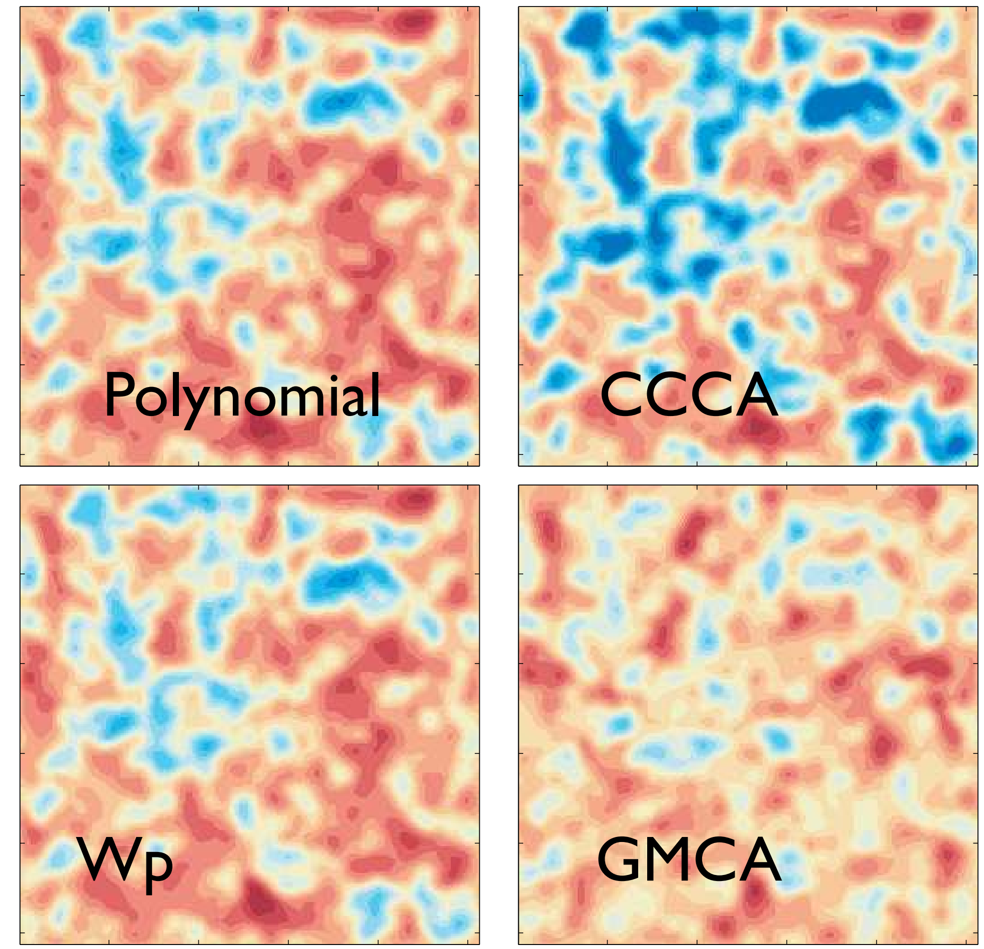
e.g. Generalised Morphological Component Analysis (GMCA) Chapman+ 2013

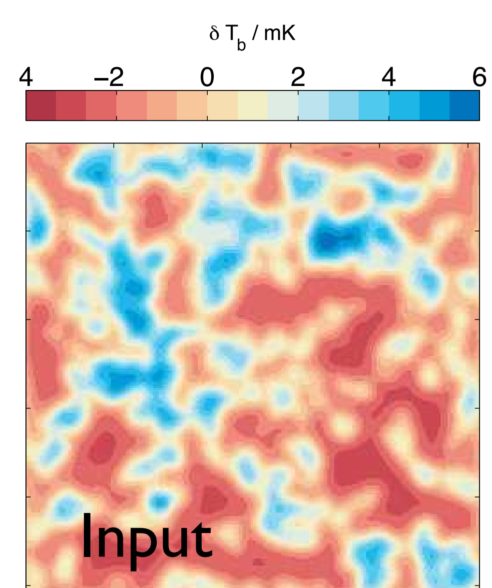
Correlated Component Analysis Bonaldi+ 2015

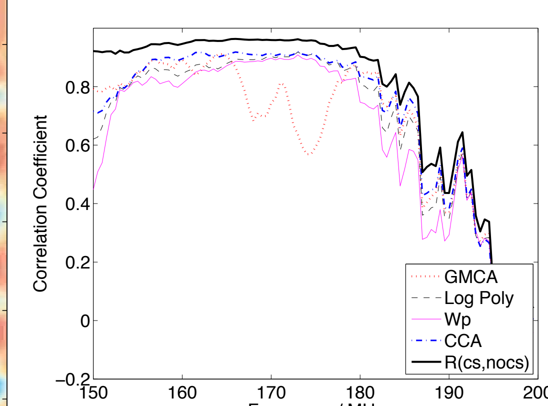


Chapman+ 2013

Imaging of the EoR will be new with SKA



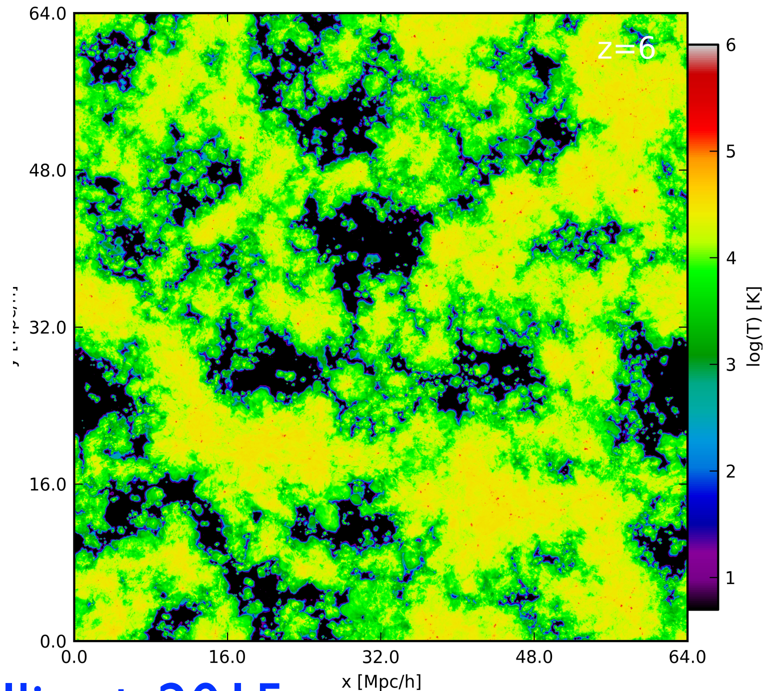




Chapman+ 2015

Numerical simulation

21cm signal depends upon complex underlying physics
=> numerical simulations required to understand/forecast expectations

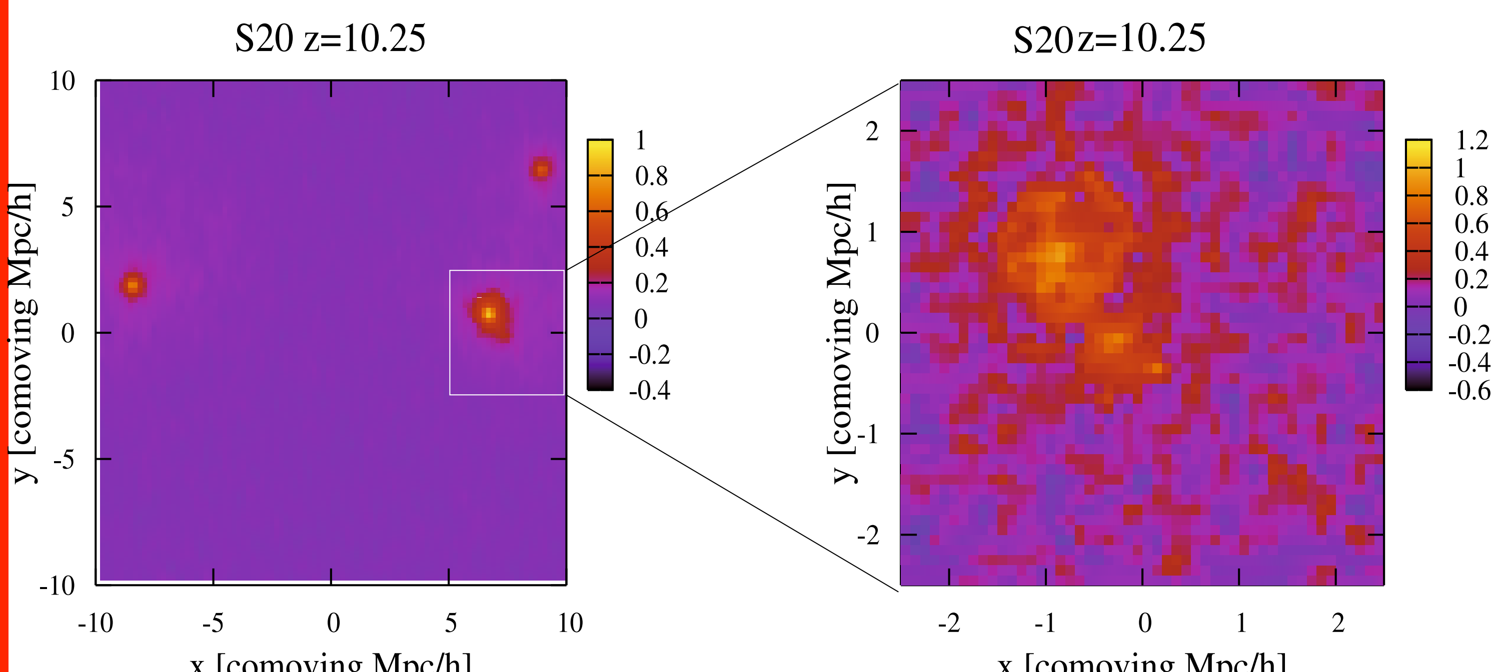


Iliev+ 2015

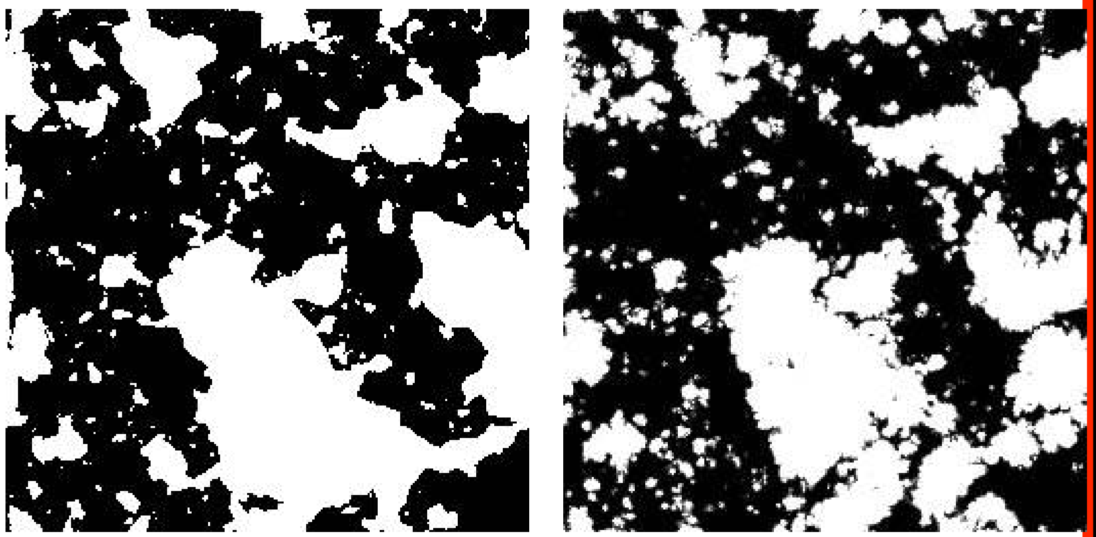
~4096^3 particles

PRACE4LOFAR

Challenge to obtain
- dynamic range of small & large scales
- RT of UV, X-ray, Lyman alpha
- explore wide parameter space



GADGET + LICORICE Baek+ 2009, 2010



filter linear density RT N-body halos

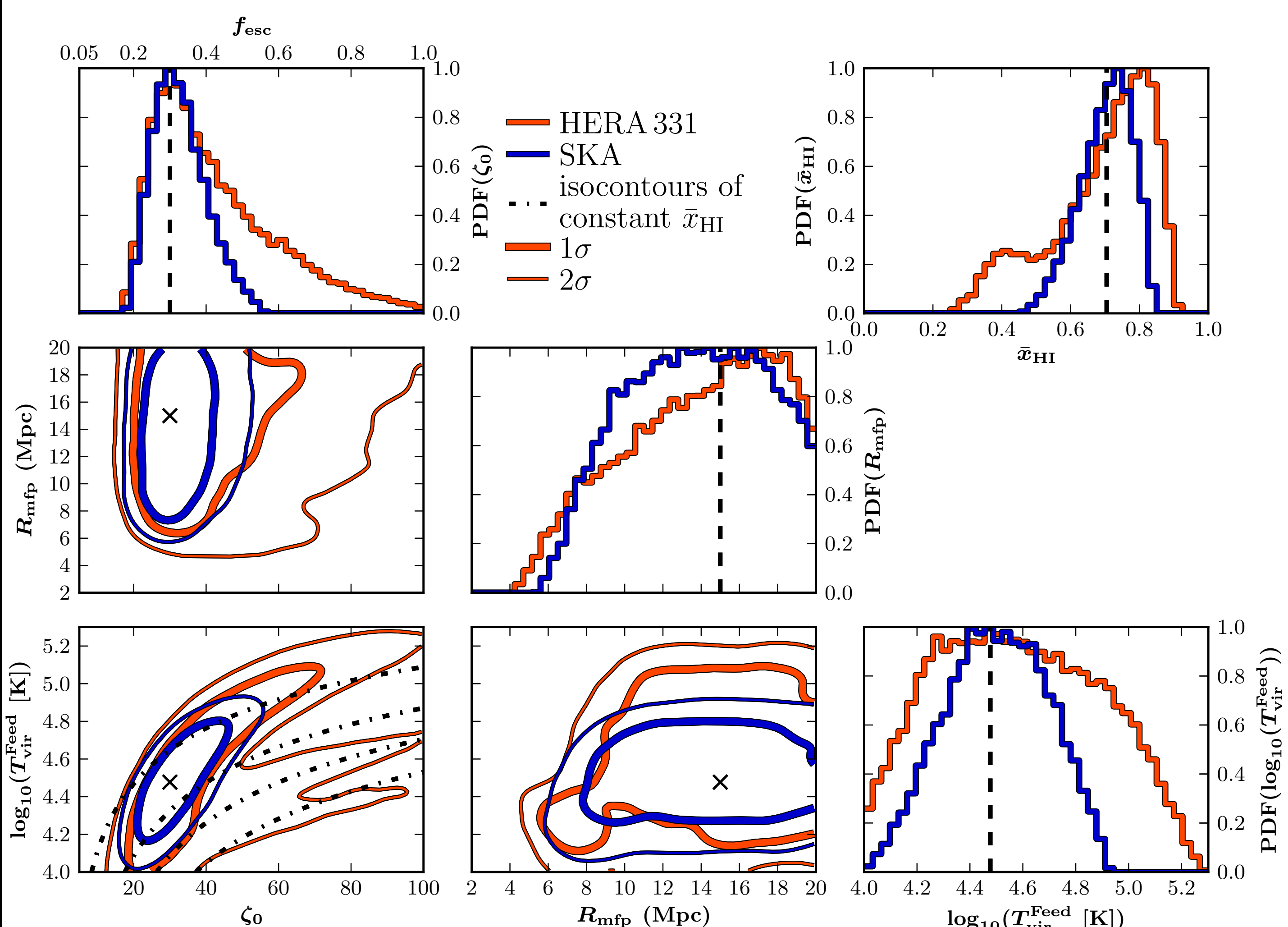
21cmFast Mesinger & Furlanetto 2007

Signal interpretation

21cm signal depends upon complex underlying physics
=> analyse observables in variety of ways for different science outputs

Model independent observables? e.g. thermal history, reionization history

Bayesian parameter estimation
in context of source model



Greig & Mesinger 2015

Imaging + non-Gaussian statistics to distinguish scenarios

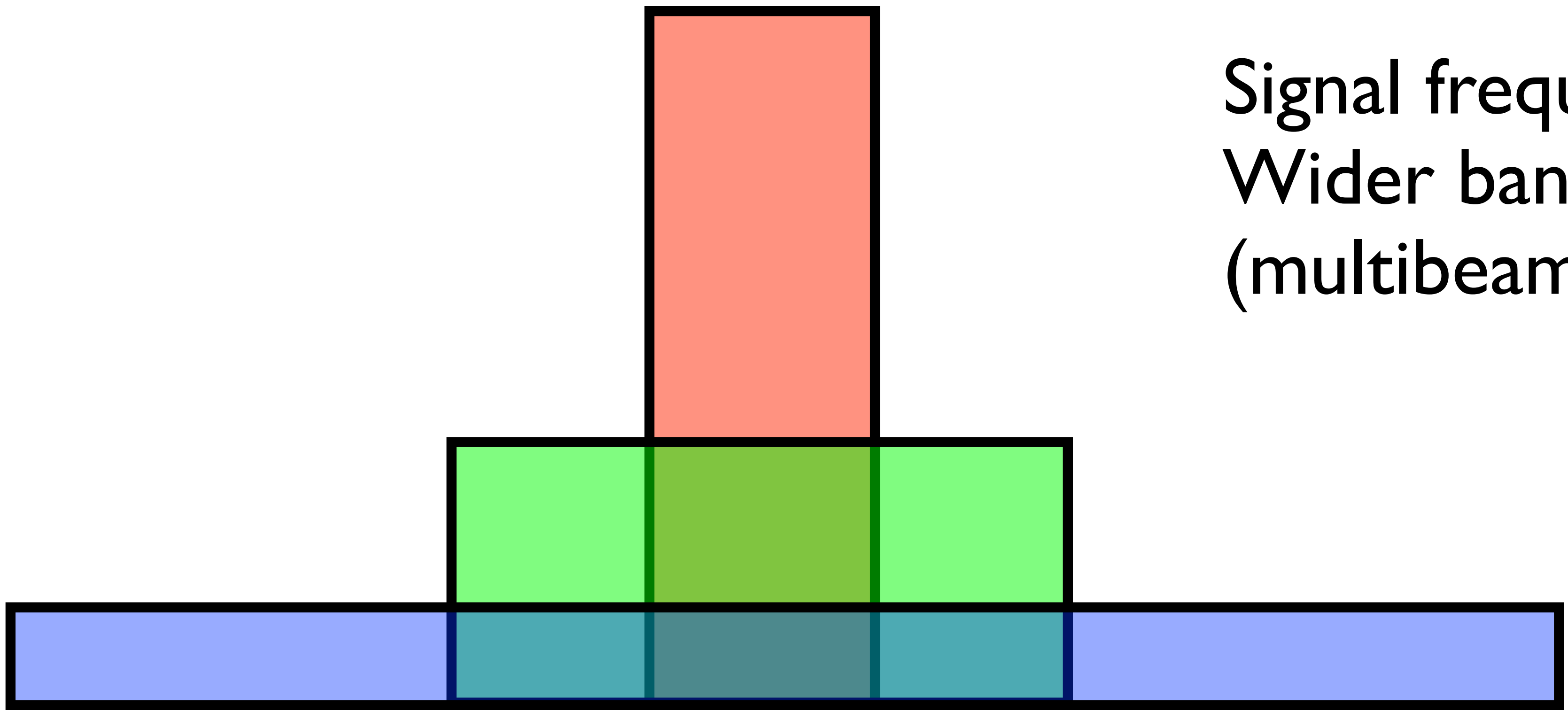
Cosmology and exotic physics

Combination of 21cm data with other data sets
e.g. JWST, HSC, CO, [CII]…

SKA observing strategy

Koopmans+ 2015 [arXiv1505.07568]

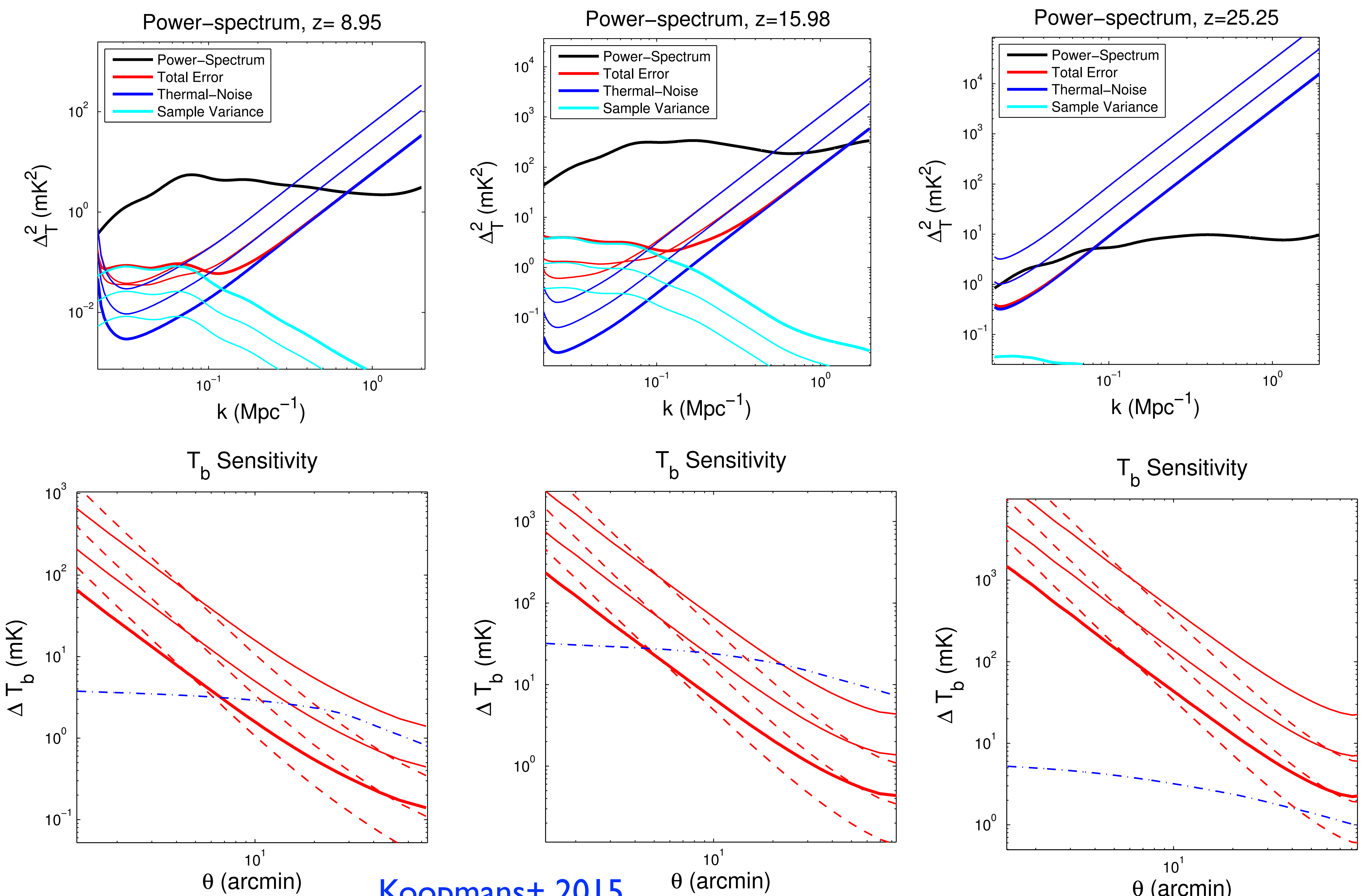
Deep: 5 x 1000hr integration => 100 deg^2 field
Middle: 50 x 100hr integration => 1,000 deg^2 field
Shallow: 500 x 10hr integration => 10,000 deg^2 field



Signal frequencies: 200-50MHz
Wider band for foregrounds
(multibeaming to reduce tint)

Shallow: LOFAR-like power spectrum sensitivity over 10000 deg^2.
Middle: Shallow imaging + power spectrum over 1000 deg^2
Deep: Power spectrum to z<28 & deep imaging over 100 deg^2

Sensitivity



Koopmans+ 2015

Data Products

High Level Data Products:

A. Redshift evolution of 21cm moments (variance, skewness, etc).

B. Redshift evolution of 21cm power spectrum as well as e.g. bi/tri spectra.

C. Tomographic image cubes with S/N > 1.

High Level Data ByProducts:

D. Full Stokes spectral datacubes of Galactic and extra Galactic foregrounds with varying spectral resolution (plus their RM cubes).

E. Temporal and frequency behaviour of foreground sources from seconds to years.

F. Temporal and frequency structure of the ionosphere from seconds to years.

G. Temporal and frequency behaviour of SKA-low from seconds to years.

Low Level Data Products:

1. Flagged/Calibrated full Stokes visibility data from 50-200MHz (z=27.4-6.1) on all baseline
2. Directionally dependent complex gain solutions (instrument and ionosphere) as function of time and frequency.
3. Absorption 21cm line spectra in selected directions with kHz spectral resolution.

Commensality/Synergy

- Continuum
  (e.g. galaxies/AGNs, galaxy clusters)
    - Radio galaxies in EoR observations
    - Radio galaxies z>6
    - Input global sky model for CD/EoR foregrounds
- Cosmology
    - Intensity mapping 3 <z < 6
    - Techniques (intensity mapping)
- Extragalactic molecular spectroscopy
    - CO from EoR
- HI galaxy science
  (e.g. extragalactic emission & absorption)
    - Post-reionization observations of 21cm
- Magnetism
    - Galactic (polarized) foregrounds
- Our Galaxy
  (e.g. star formation, evolved stars, HI & continuum)
    - Galactic foregrounds
- Solar/Heliospheric physics
    - Ionospheric measurements and monitoring (CD/EoR FG)
- Transients
    - Transients in EoR observations
    - Transients during CD/EoR
    - Coherent/Incoherent Surveys

Other facilities
e.g. JWST, Planck, ALMA, intensity mapping, GRB, …

Conclusions

21 cm offers a unique probe of reionization and cosmic dawn

Learn ionization, thermal, and star formation histories.
Infer properties of first galaxies and their evolution.
Map distribution of matter in wide volume & constrain cosmology.

SKA will allow (1) Power spectrum from z = 6 - 28
(2) Imaging during reionization
(3) 21cm Forest observations (if sources found)

EoR requires integrated approach starting with visibilities
to jointly model 21cm signal + foregrounds + instrument.

Layer-cake survey to maximise 21cm information.
- Shallow: 10k sq.deg., Middle: 1k sq.deg., Deep 0.1k sq.deg.

EoR foregrounds are data sets for other science.

KSP discussion here and at Oct meeting in Groningen

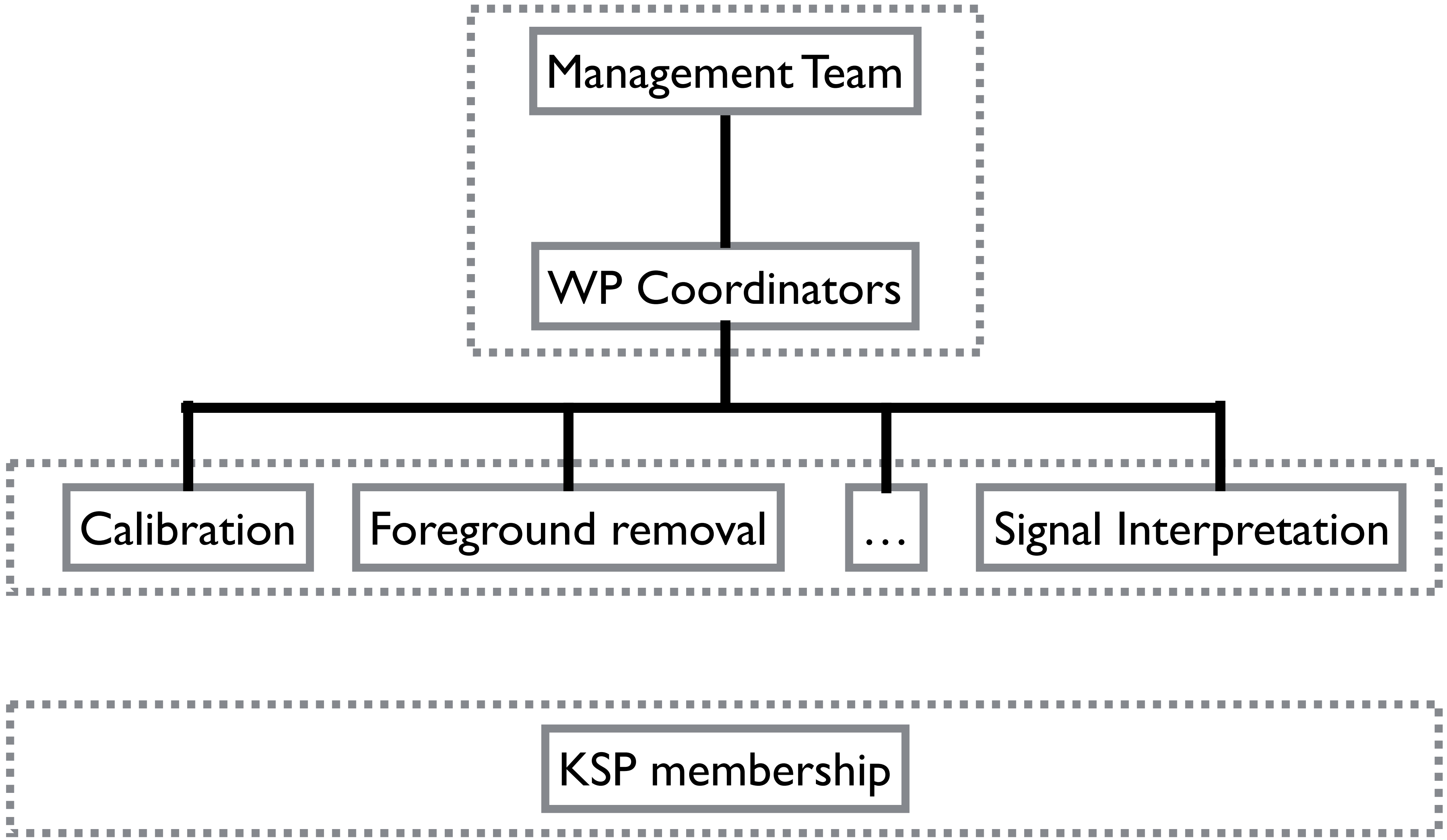
Fin

EoR Science Team (proto-KSP)

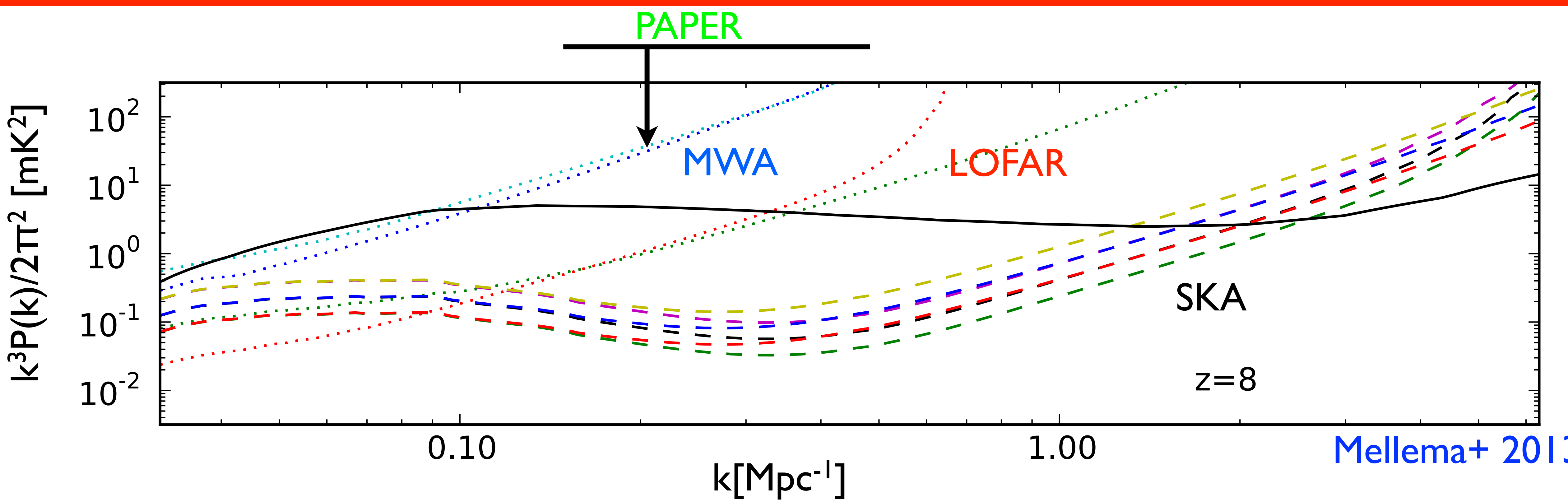
EoR proto-KSP being discussed: 12-15 October meeting in Groningen

Executive

Work packages



Overview of experiments

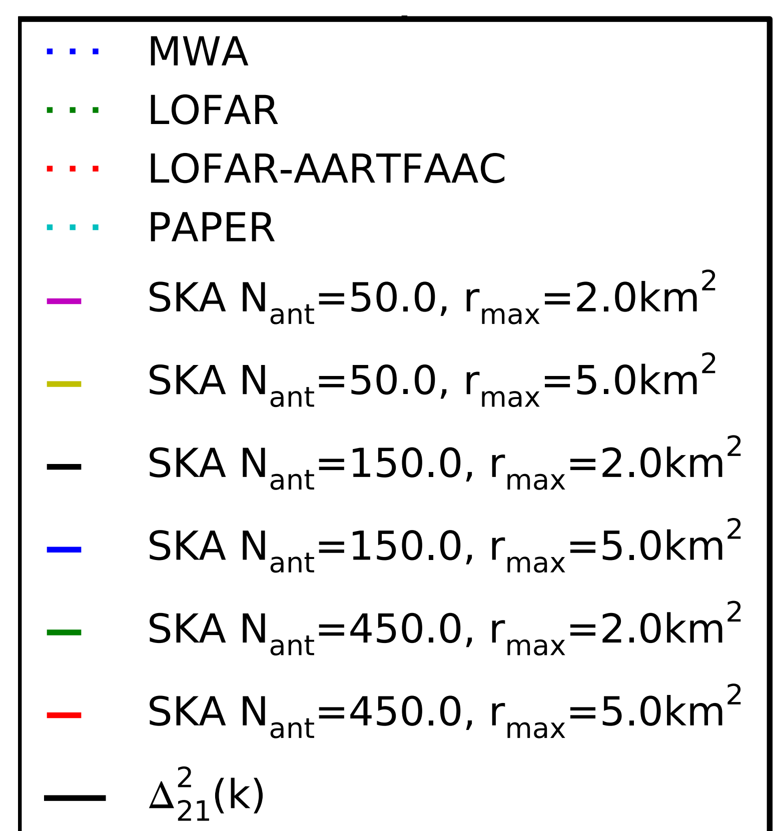


MWA-32T: <(300mK)^2 at k=0.07 hMpc^{-1} at z=9.5 Dillon+ 2013

GMRT: <(248mK)^2 at k=0.50 hMpc^{-1} at z=8.6 Paciga+ 2013
(previous claim was <(70mK)^2)

PAPER-64: <(22mK)^2 at k~0.2hMpc^{-1} at z=8.4 Ali+ 2015

LOFAR: comparable to PAPER, but still being processed c.f. Yatawatta+ 2013



21 cm line in cosmology

T_γ T_S T_b

$z = 13$ $z = 0$

$\nu = 1.4\,\mathrm{GHz}$ $\nu = 100\,\mathrm{MHz}$

CMB acts as back light

Neutral gas imprints signal

Redshifted signal detected

neutral fraction

baryon density

spin temperature

peculiar velocities

brightness temperature

$$T_b = 27 x_{\rm HI}(1+\delta_b)\left(\frac{T_S - T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\right)^{1/2}\left[\frac{\partial_r v_r}{(1+z)H(z)}\right]^{-1}\,\mathrm{mK}$$

spin temperature set by different mechanisms:

Radiative transitions (CMB) $T_{\rm Spin} \Rightarrow T_{\rm CMB}$

Collisions $T_{\rm Spin} \Rightarrow T_{\rm gas}$

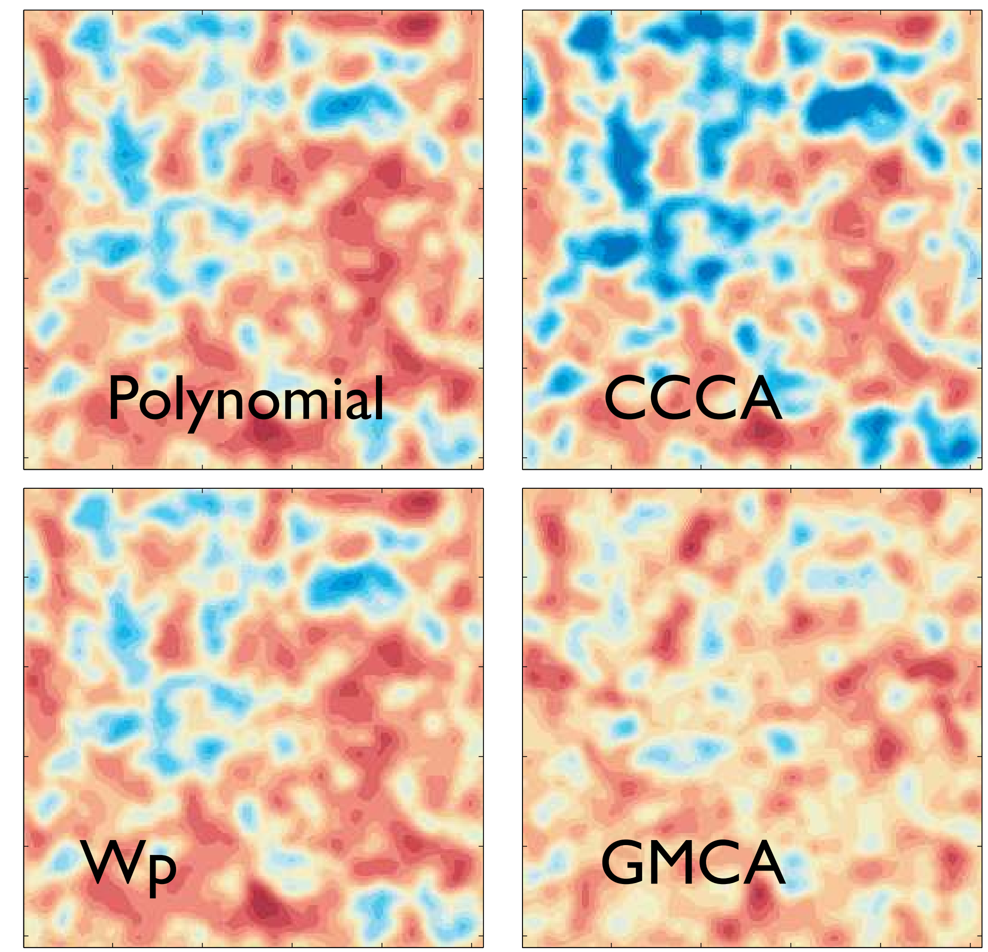
Wouthysen-Field effect (resonant scattering of Lyα) $T_{\rm Spin} \Rightarrow T_{\rm gas}$

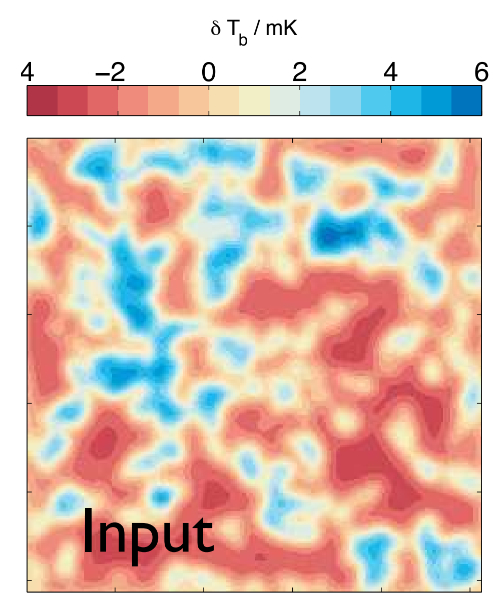
Imaging

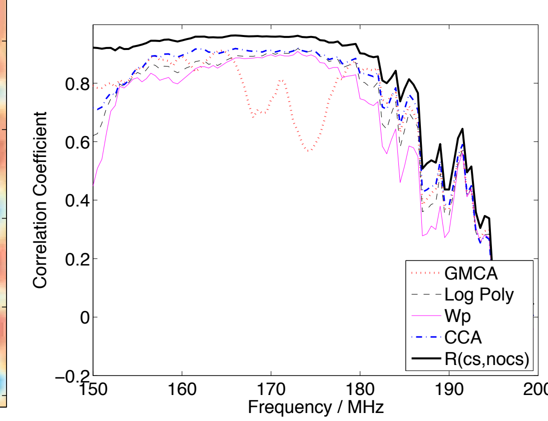
Imaging of the EoR will be new with SKA (LOFAR/HERA restricted to large scales)

Imaging affected by systematics in a different way. Early work on foreground removal is promising.

SKA beam will be sufficient to resolve structures during mid to end of reionization

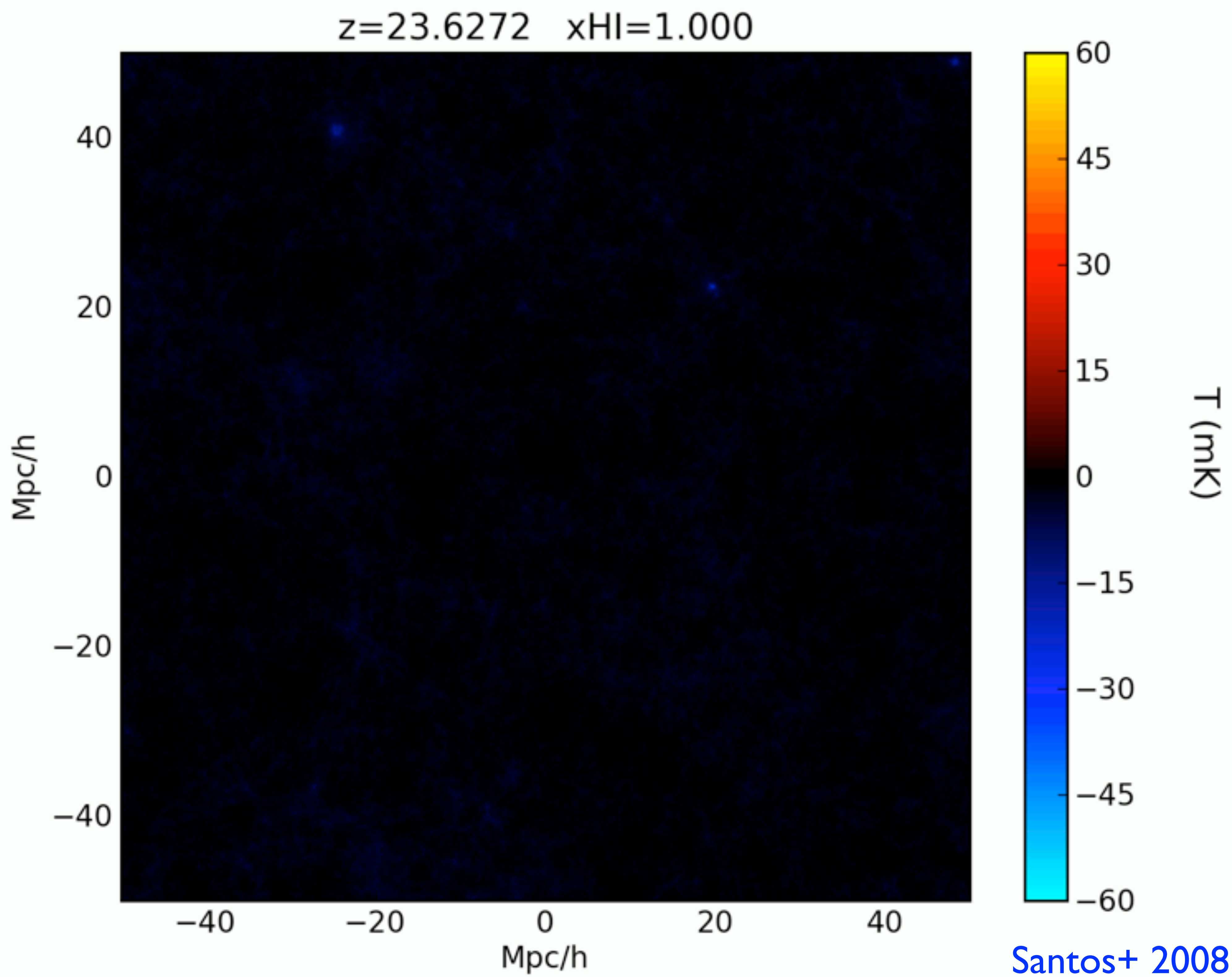






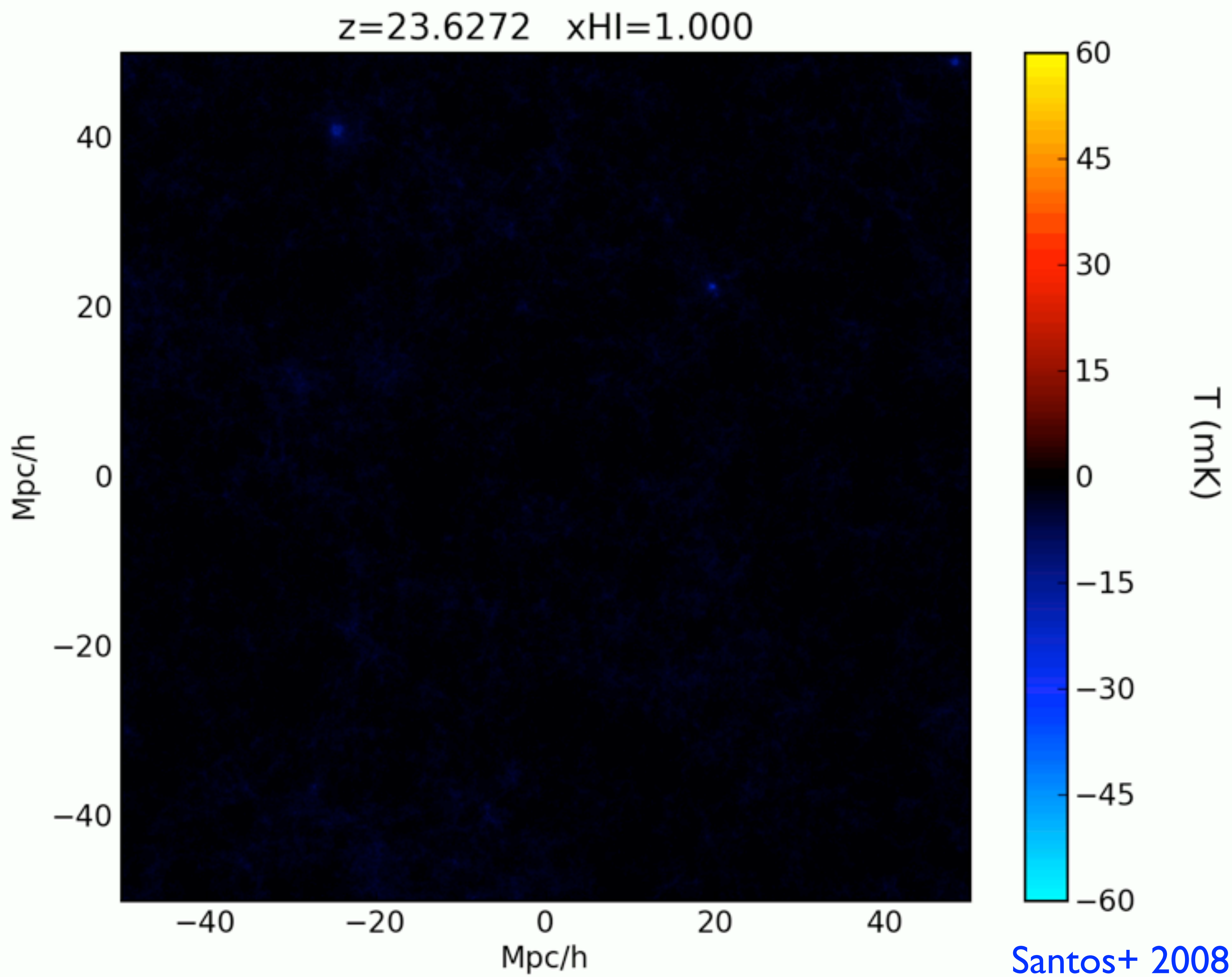
Chapman+ 2015

Images



Santos+ 2008

Images



Santos+ 2008

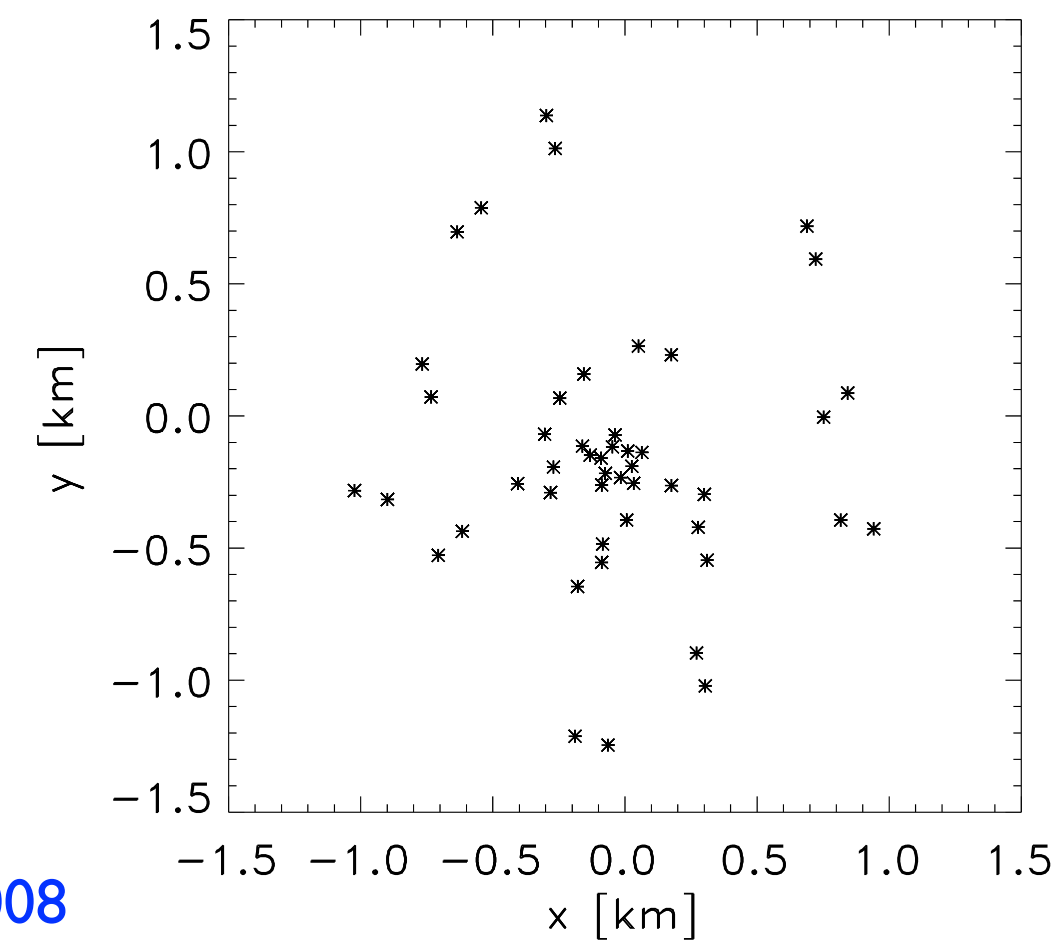
Instrument simulation

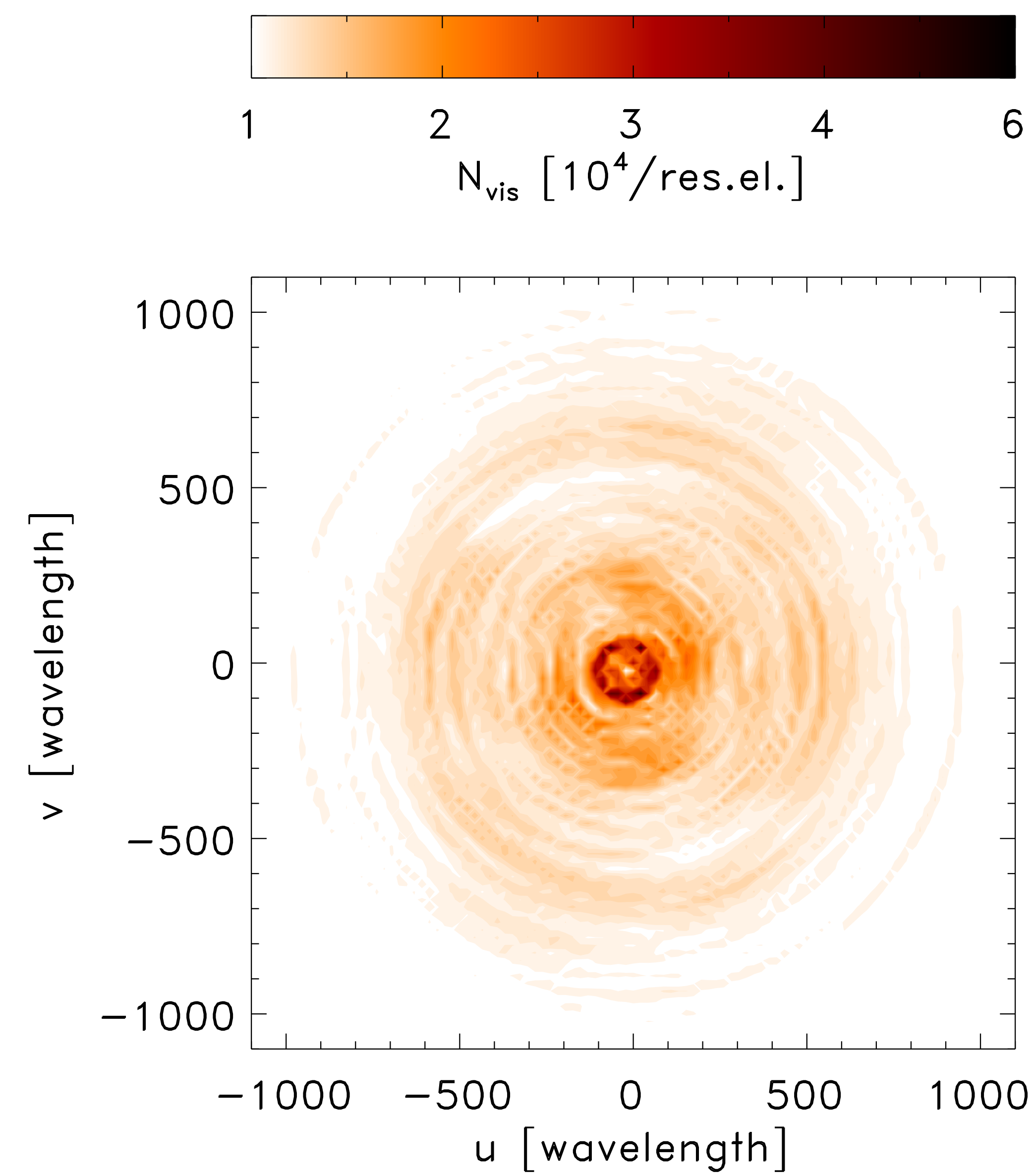
Radio interferometers essentially measure Fourier transform of sky

$$V_f(u,v) = \int A(l,m) I_f(l,m) \mathrm{e}^{i(ul+vm)} \mathrm{d}l\mathrm{d}m \qquad \sigma_{noise} = \frac{1}{\eta_s} \times \frac{SEFD}{\sqrt{N \times (N-1) \times \Delta\nu \times t_{\mathrm{int}}}}$$

Direction dependent effects important if imaging large fields of view

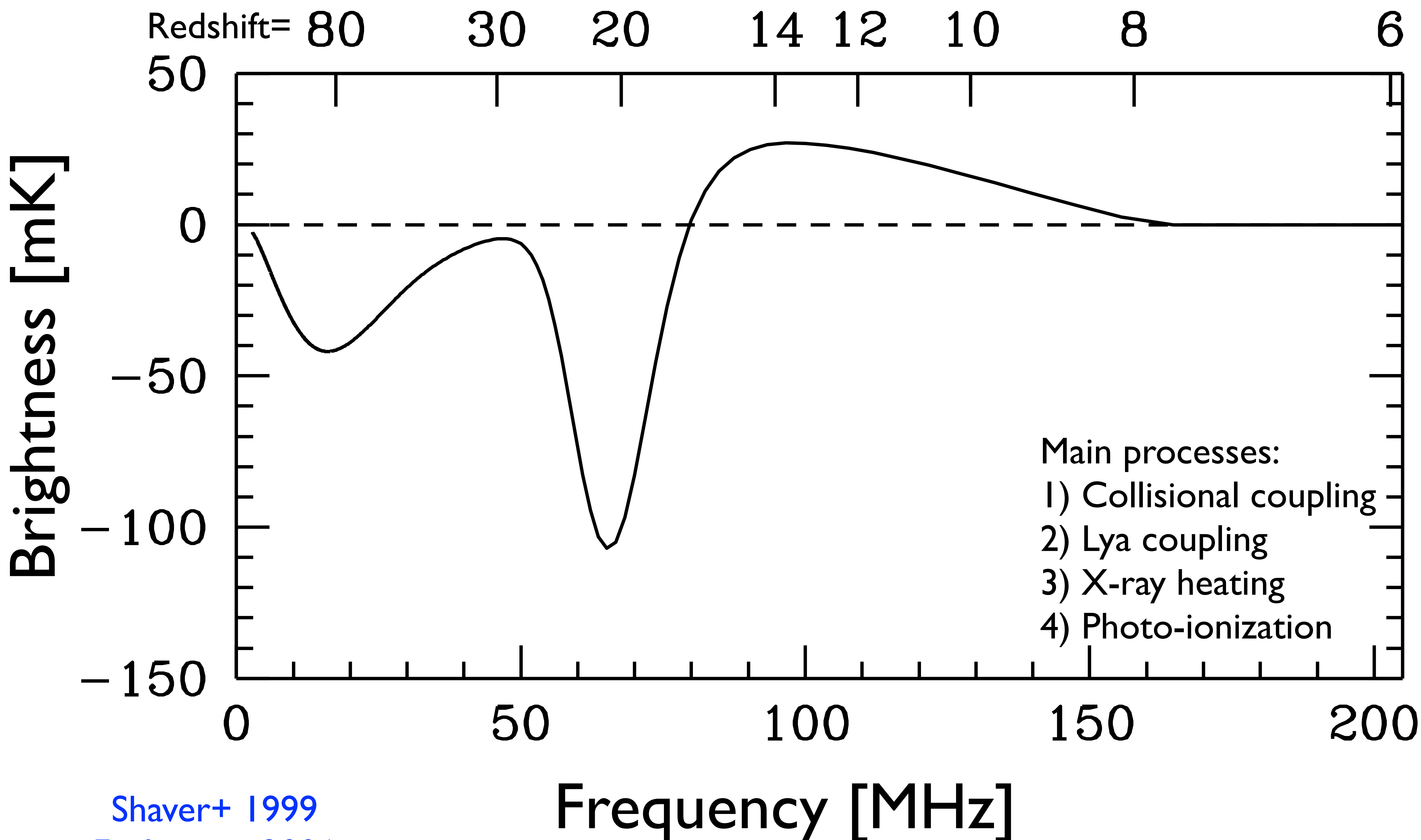
LOFAR





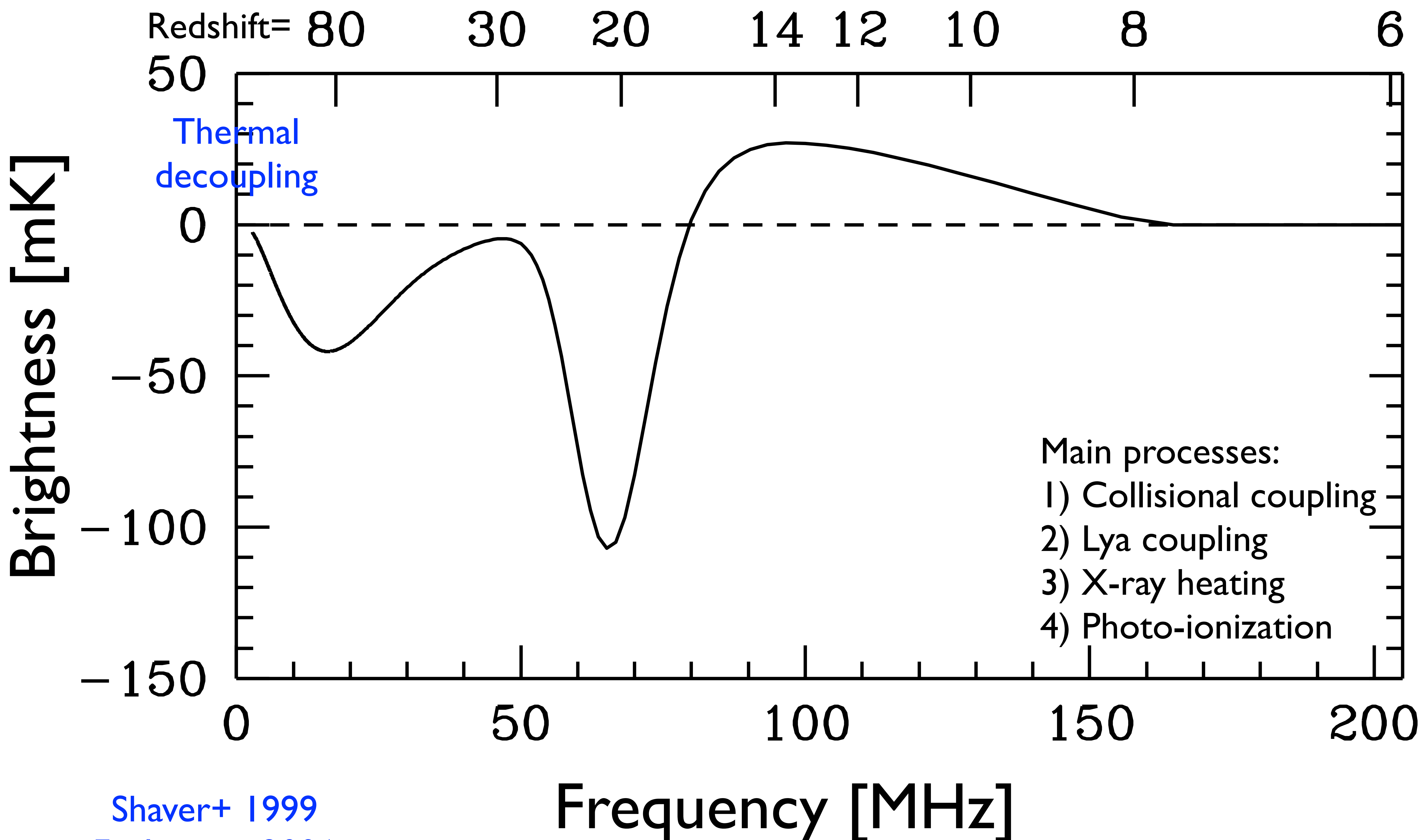
Jelic+ 2008

21 cm global signal



Shaver+ 1999
Furlanetto 2006
Pritchard & Loeb 2010

21 cm global signal



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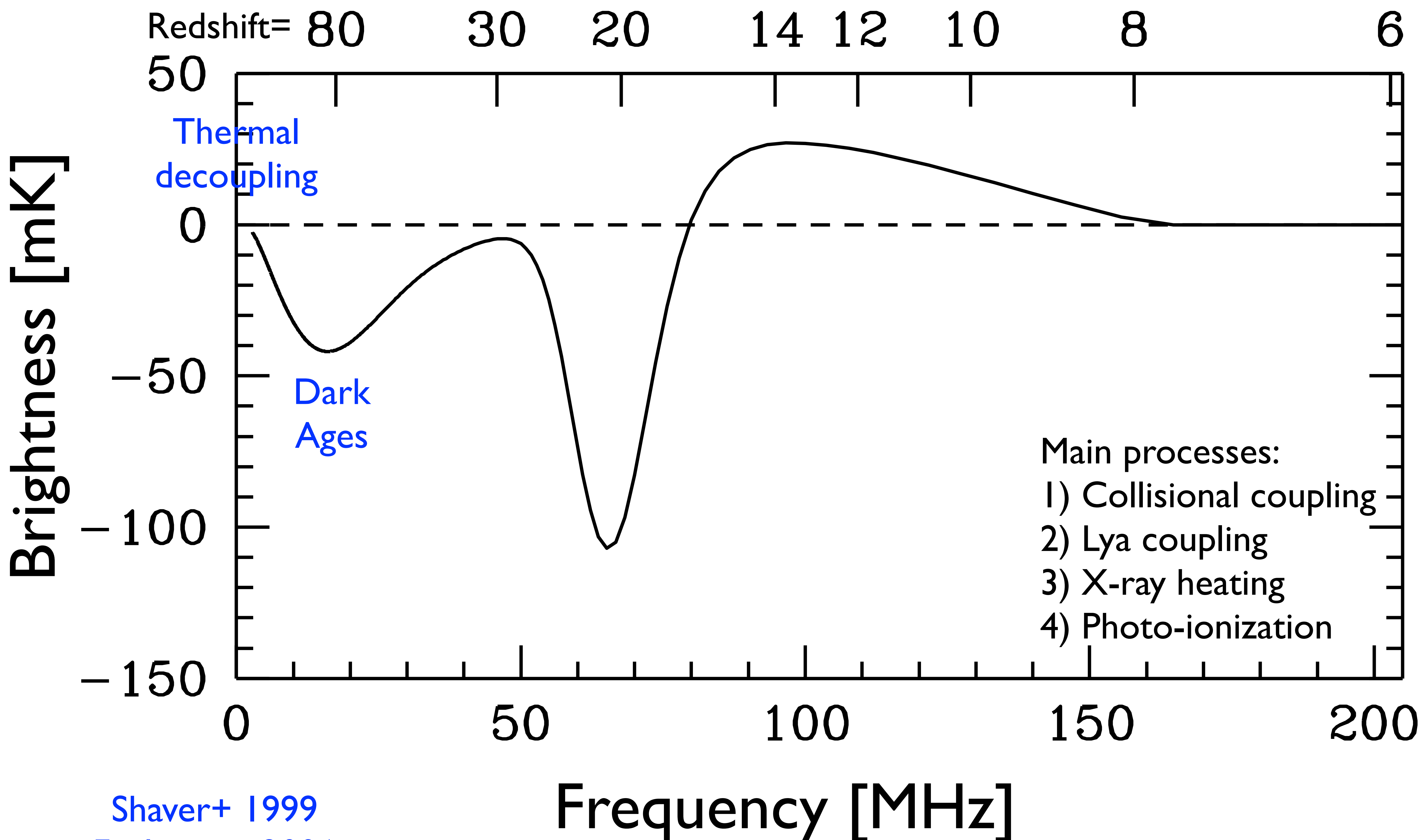

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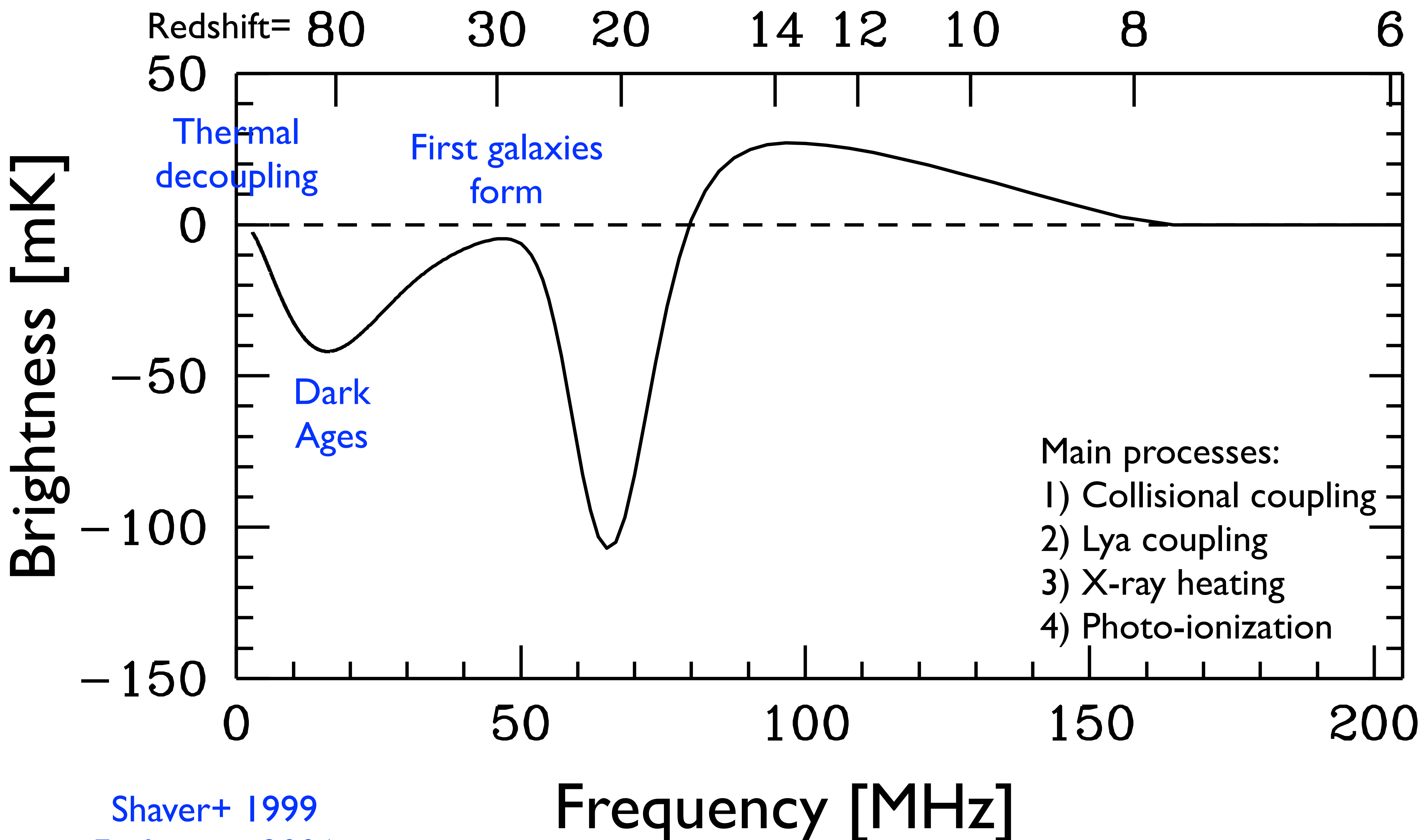

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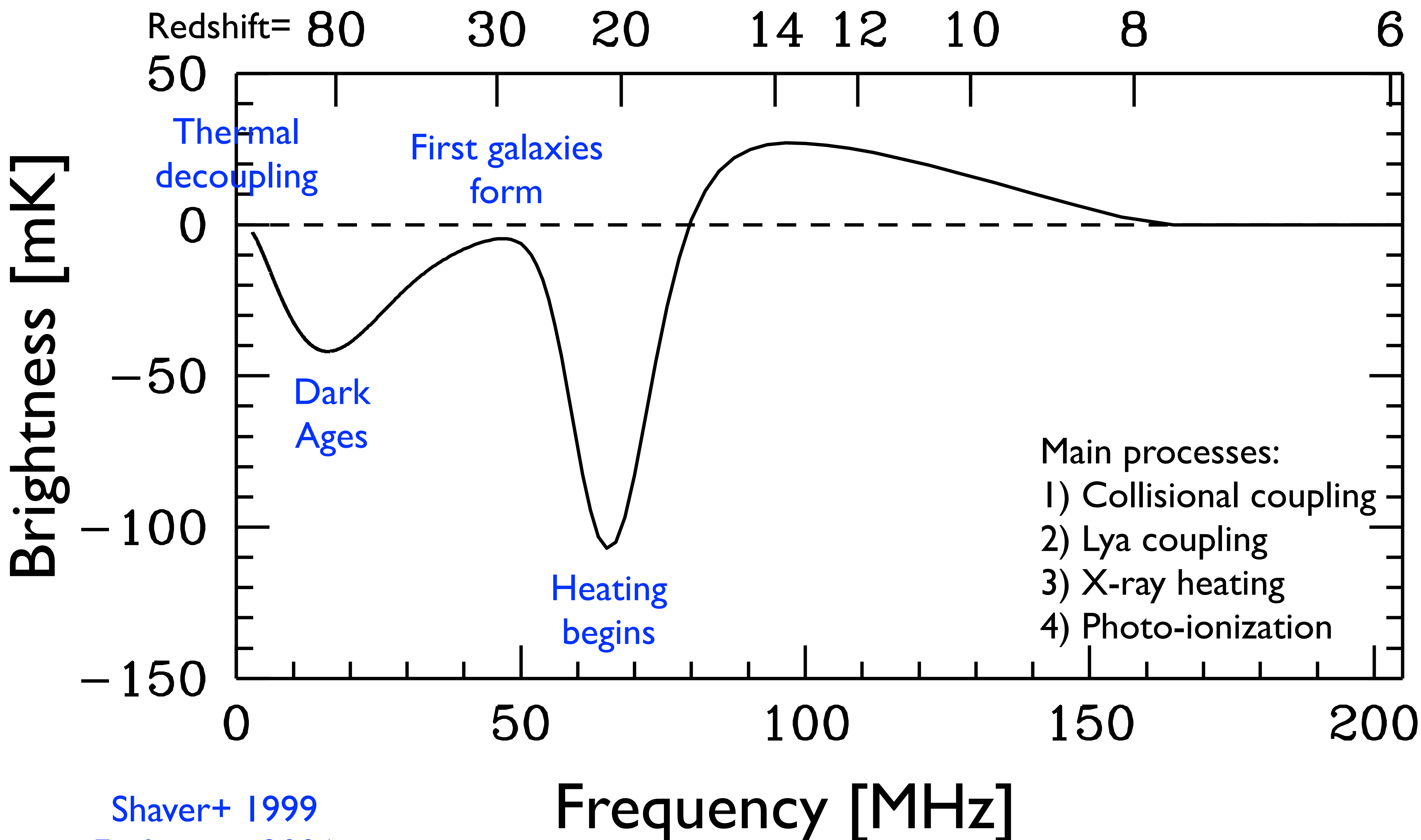

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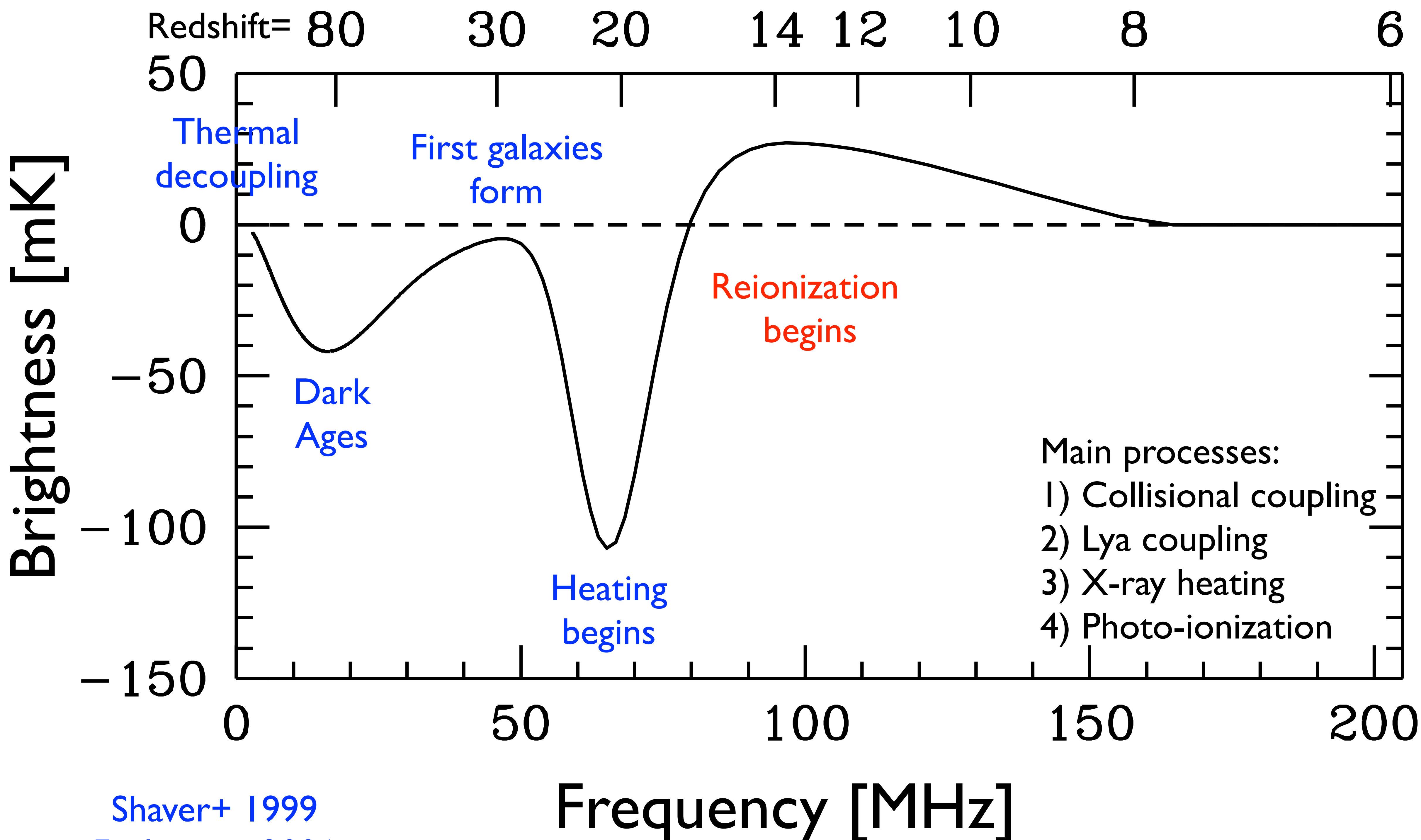

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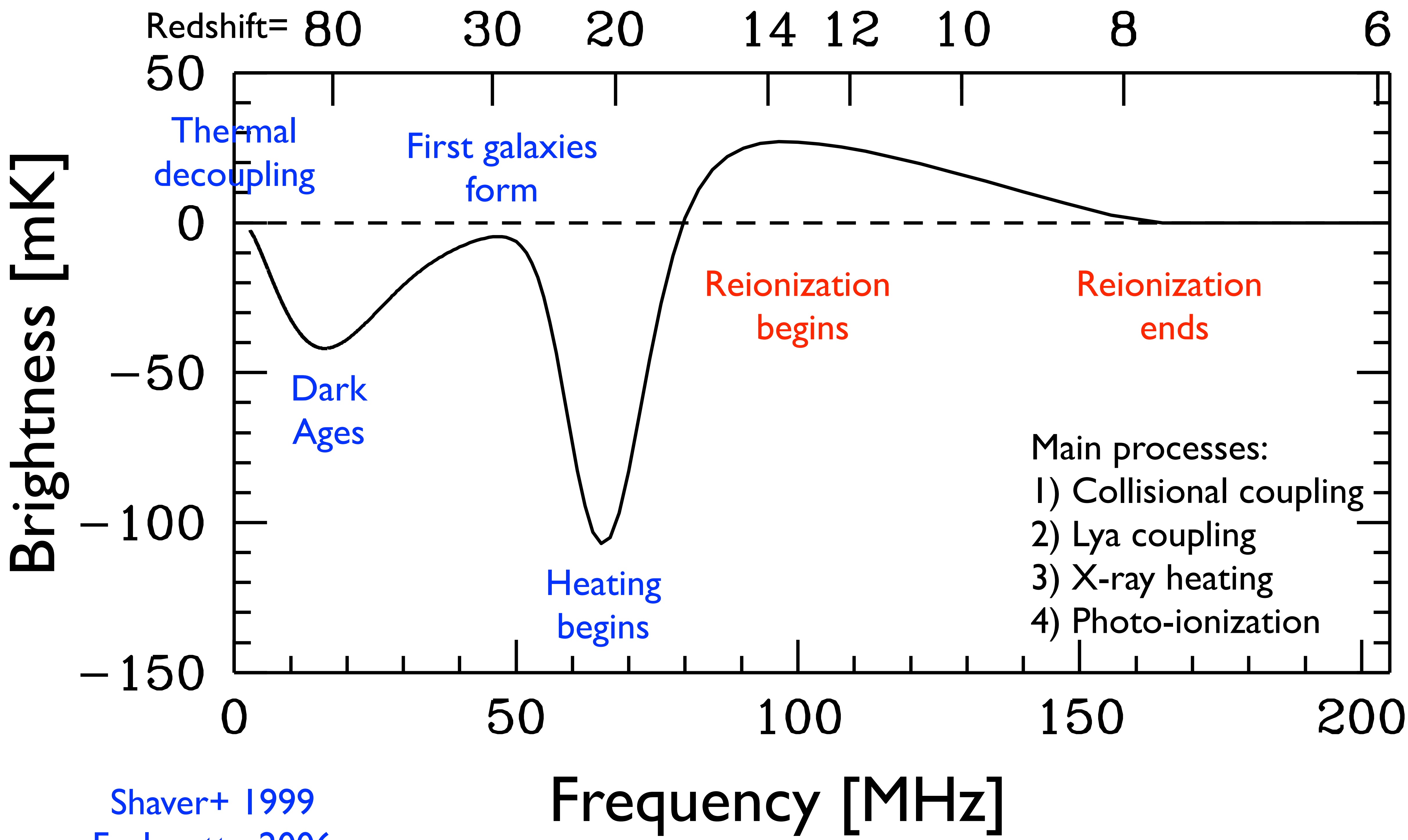

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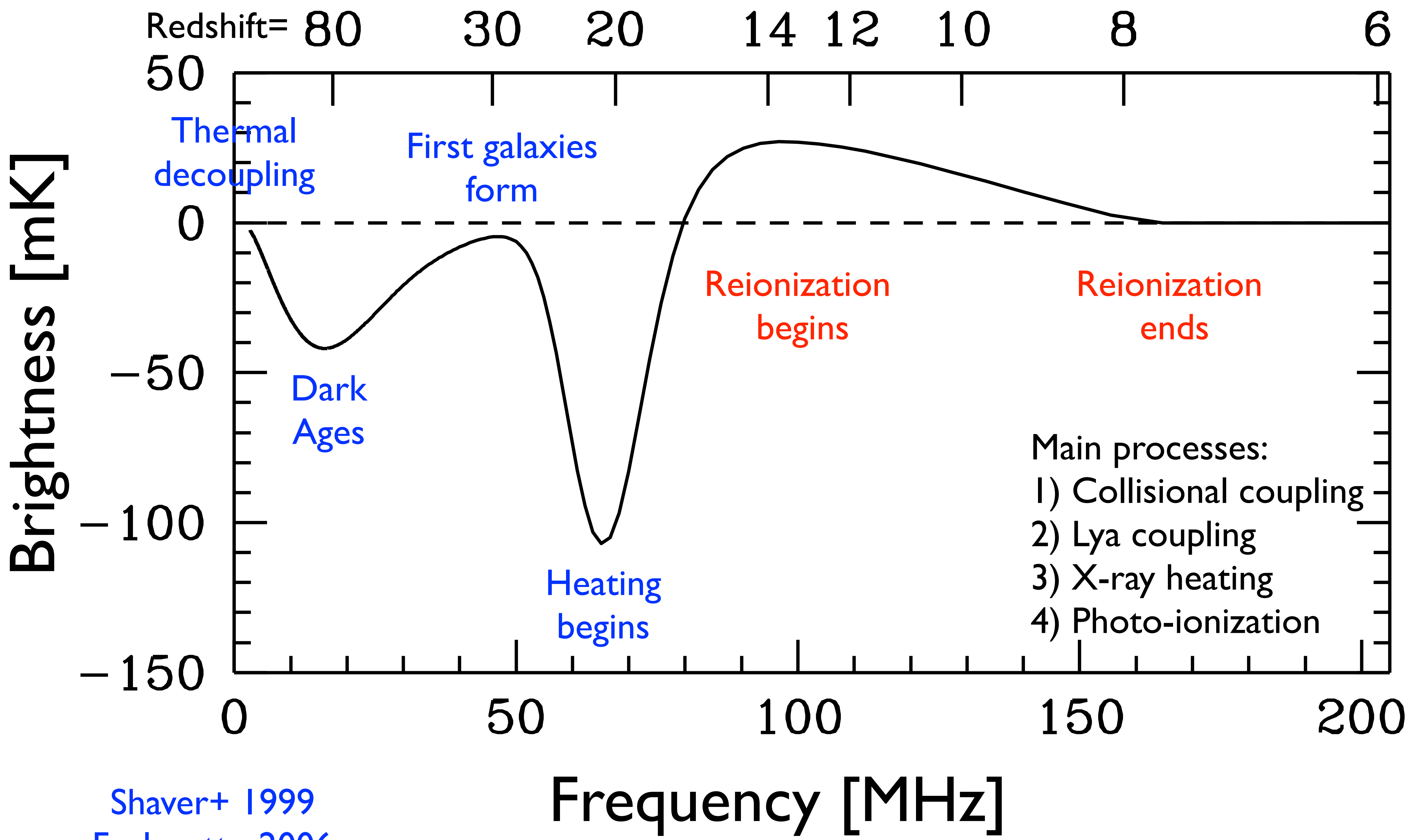

Shaver+ 1999
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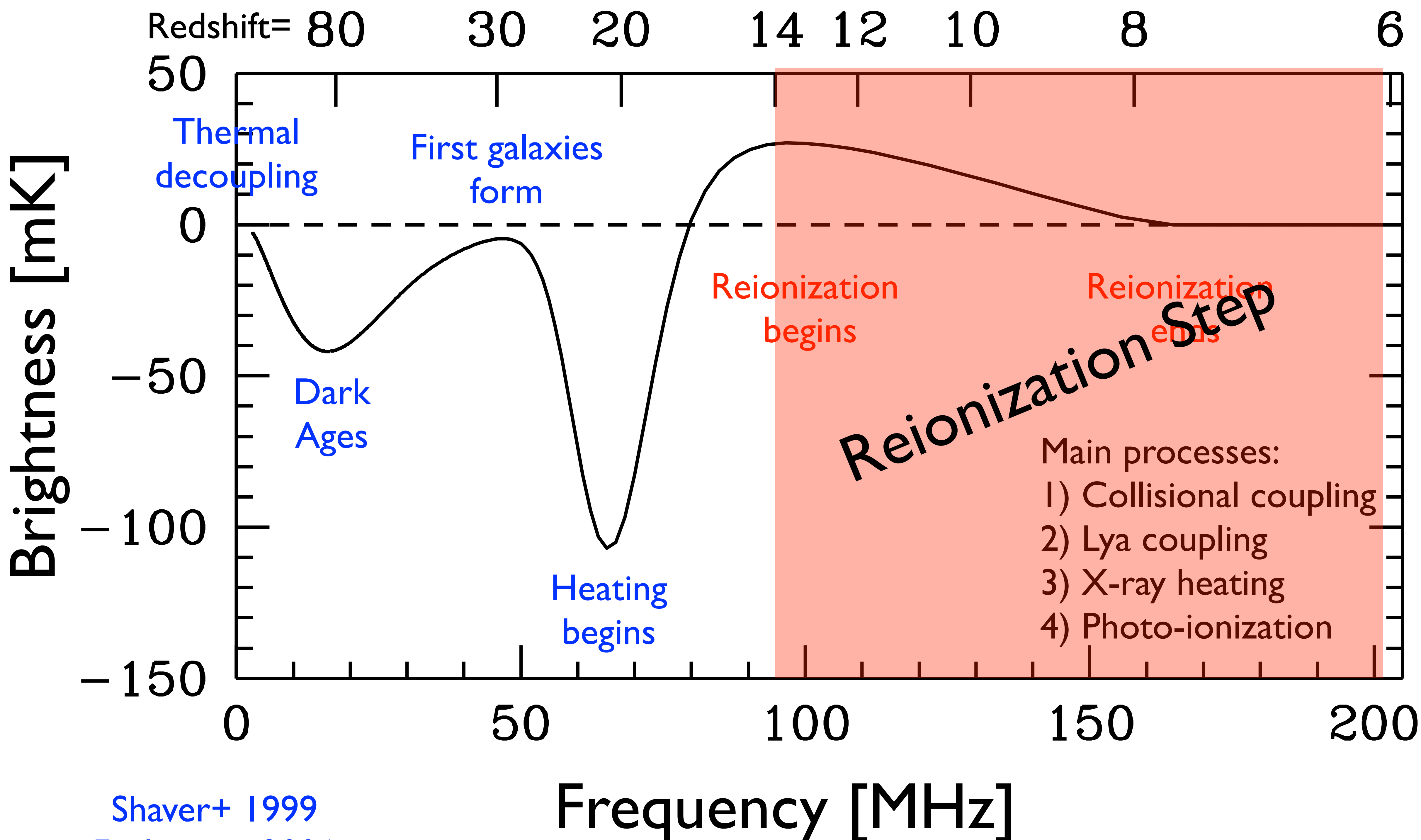
Pritchard & Loeb 2010

measurement would constrain basic features of first galaxies

21 cm global signal



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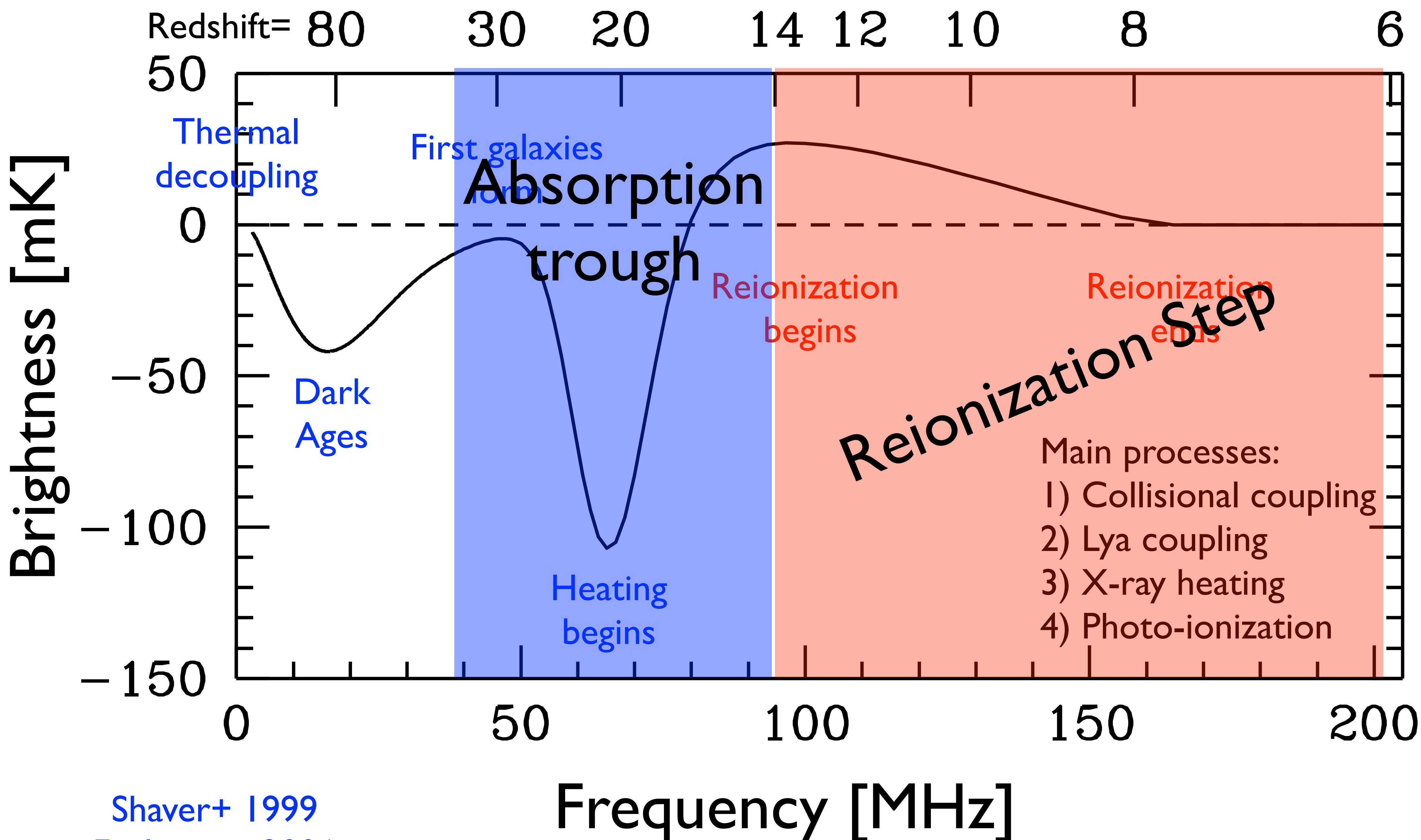

Shaver+ 1999
Furlanetto 2006
Pritchard & Loeb 2010

measurement would constrain basic features of first galaxies

SKA2 versus New baseline (50%)

Imperial College London