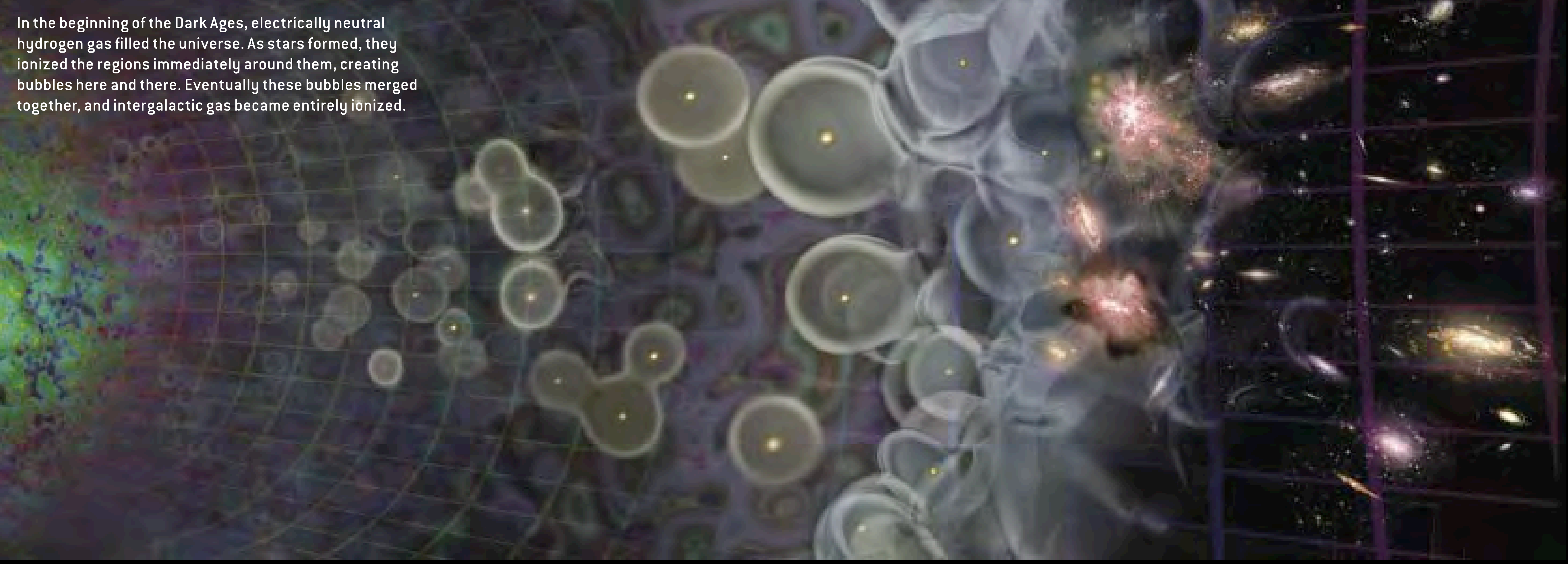


Latest developments in EoR Science and the Requirements for SKA Phase 1

Jonathan Pritchard

Imperial College London

Overview

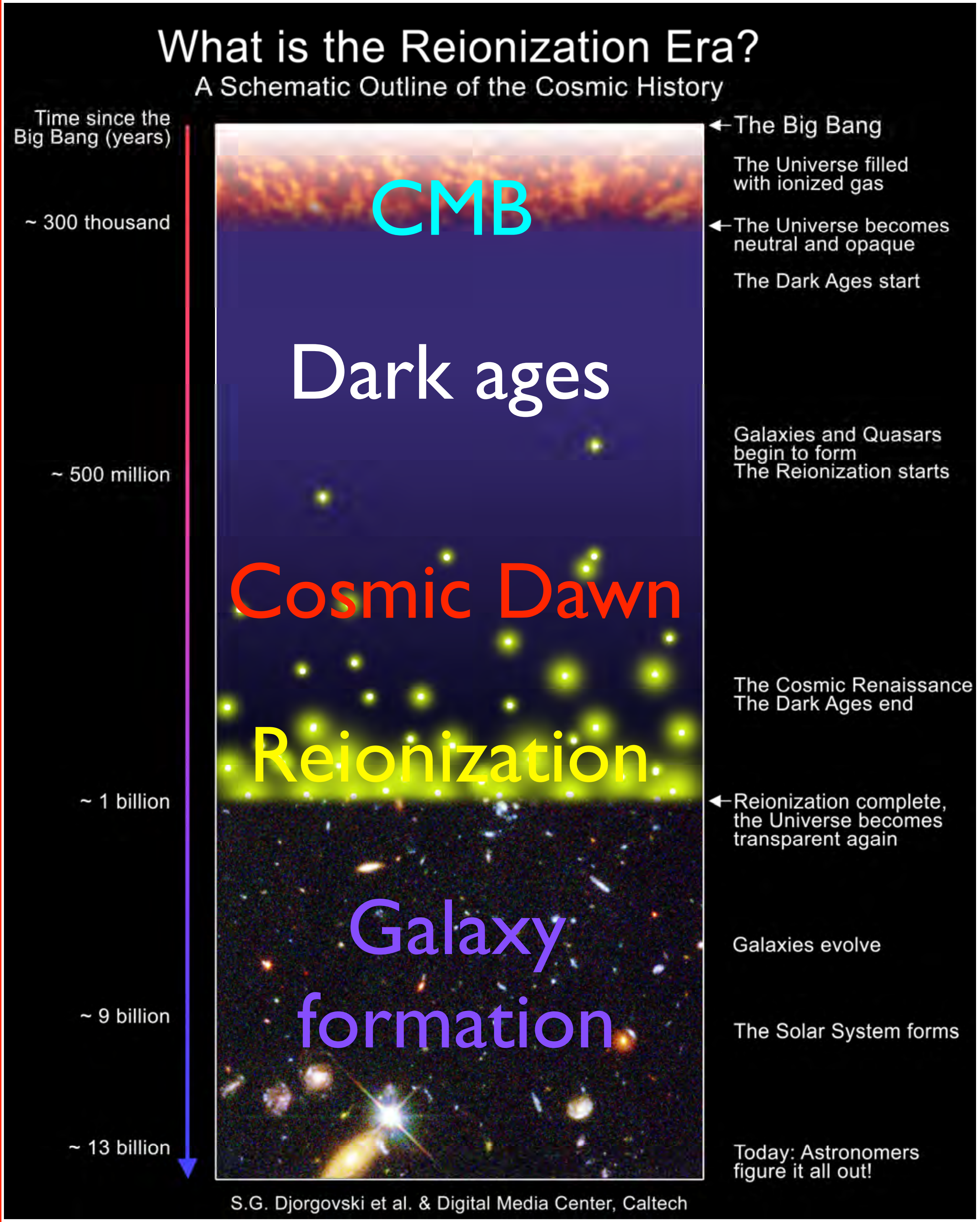
21 cm tomography

DRM Ch 2: Probing the Neutral Intergalactic Medium During the Epoch of Reionization

21 cm forest

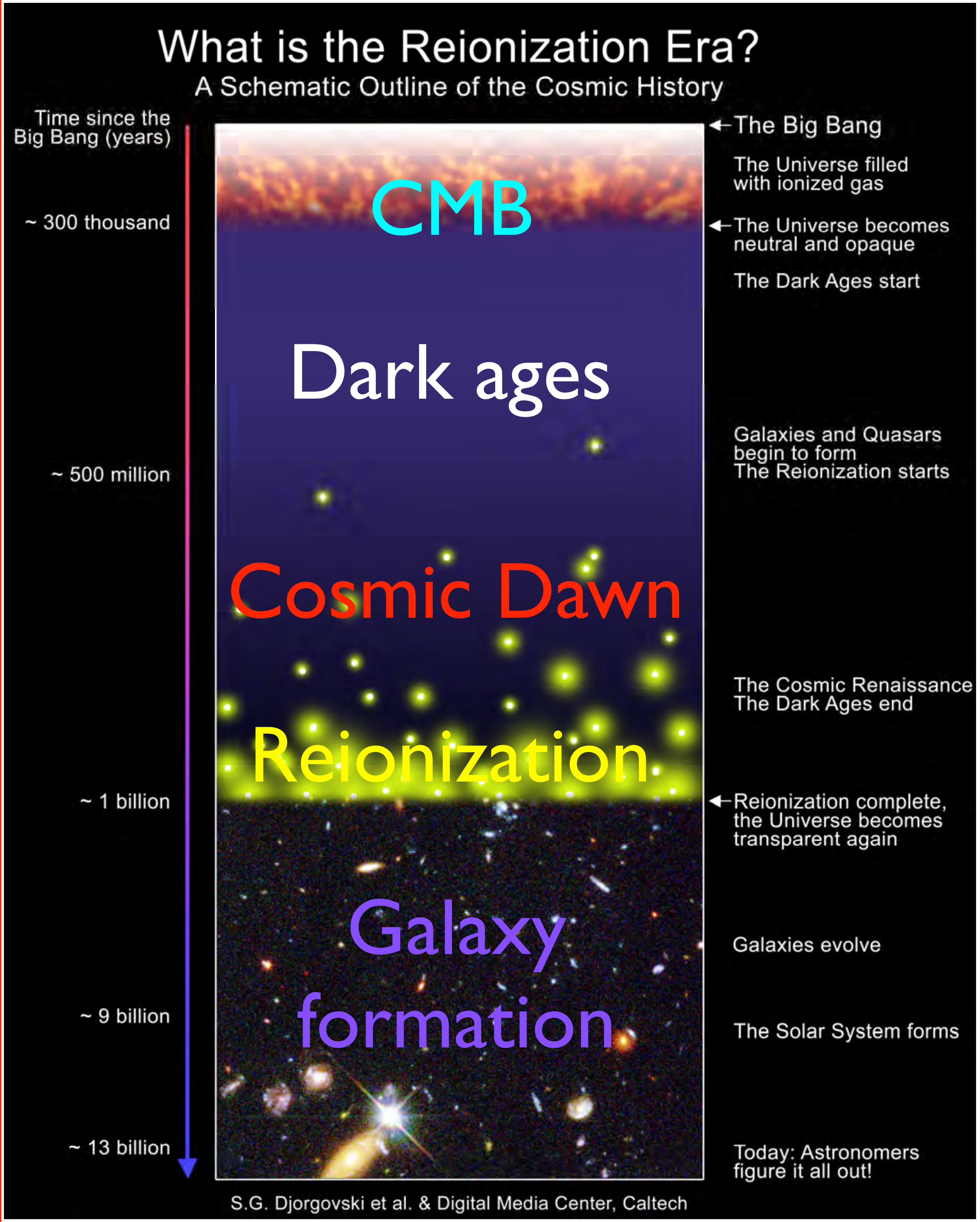
DRM Ch 4: Probing the Epoch of Reionization Using the 21-cm forest

The first billion years



Reionization marks the limits of current observations

The first billion years



Reionization marks the limits of current observations

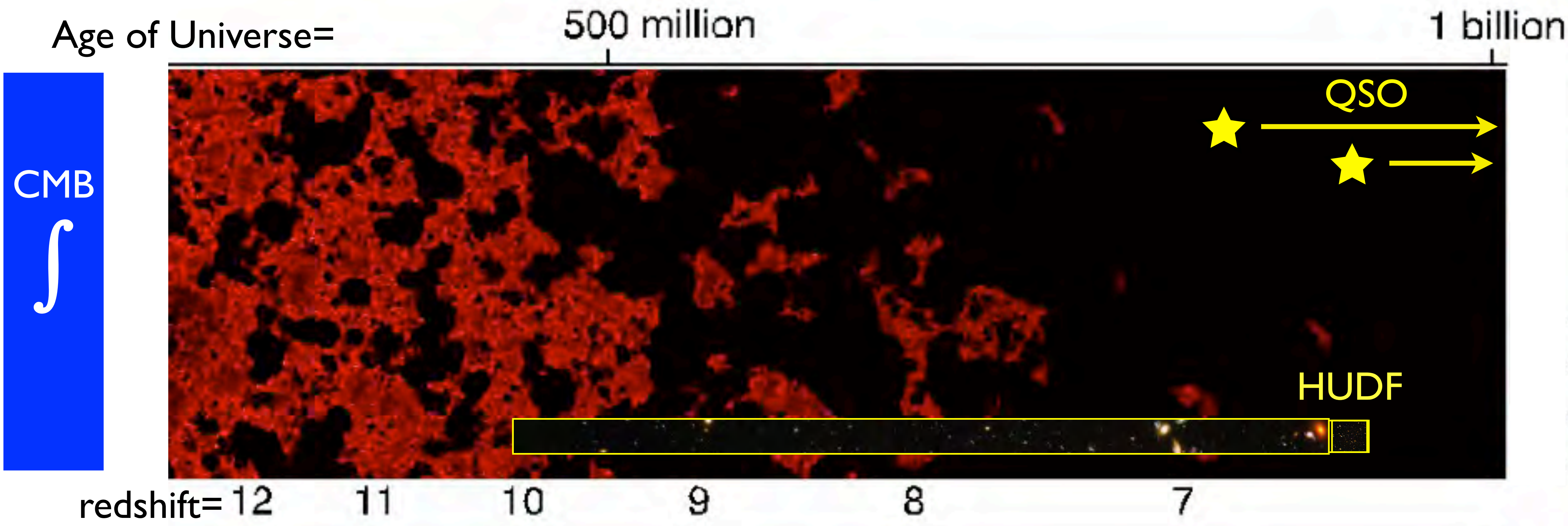
When did the first galaxies form?

When did the first black holes form?

How and when did reionization proceed?

How do galaxies form and evolve?

More data needed...



Existing observations leaves much unanswered:

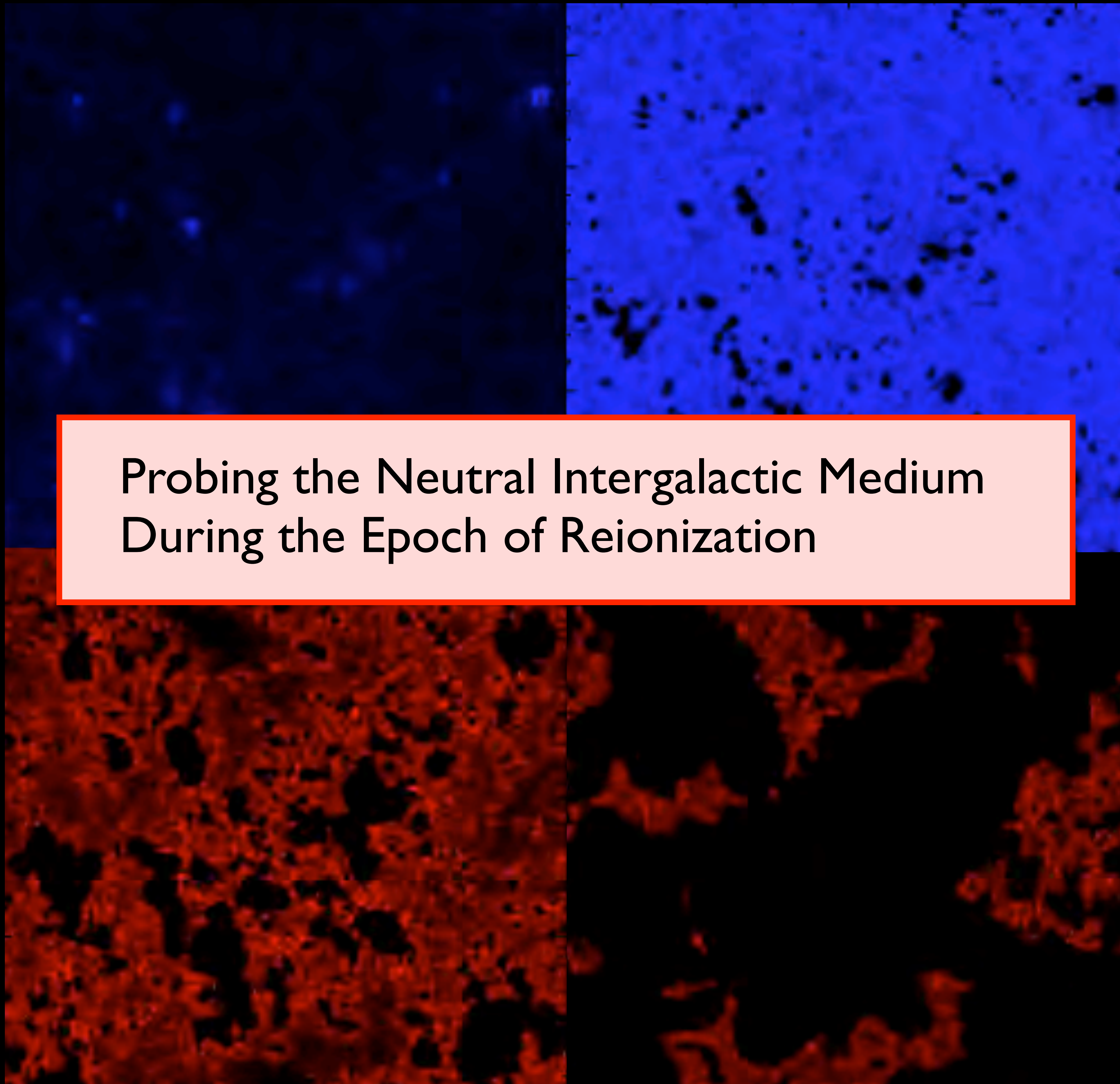
- CMB integral constraint only
- HST probes only brightest galaxies
- QSO spectra only probe small neutral fractions

Progress can be made by more consistently combining observations to constrain models

Pritchard, Wyithe, Loeb 2010; Mitra, Choudhury, Ferrara 2011

Fundamental need for new types of observation to understand details of reionization

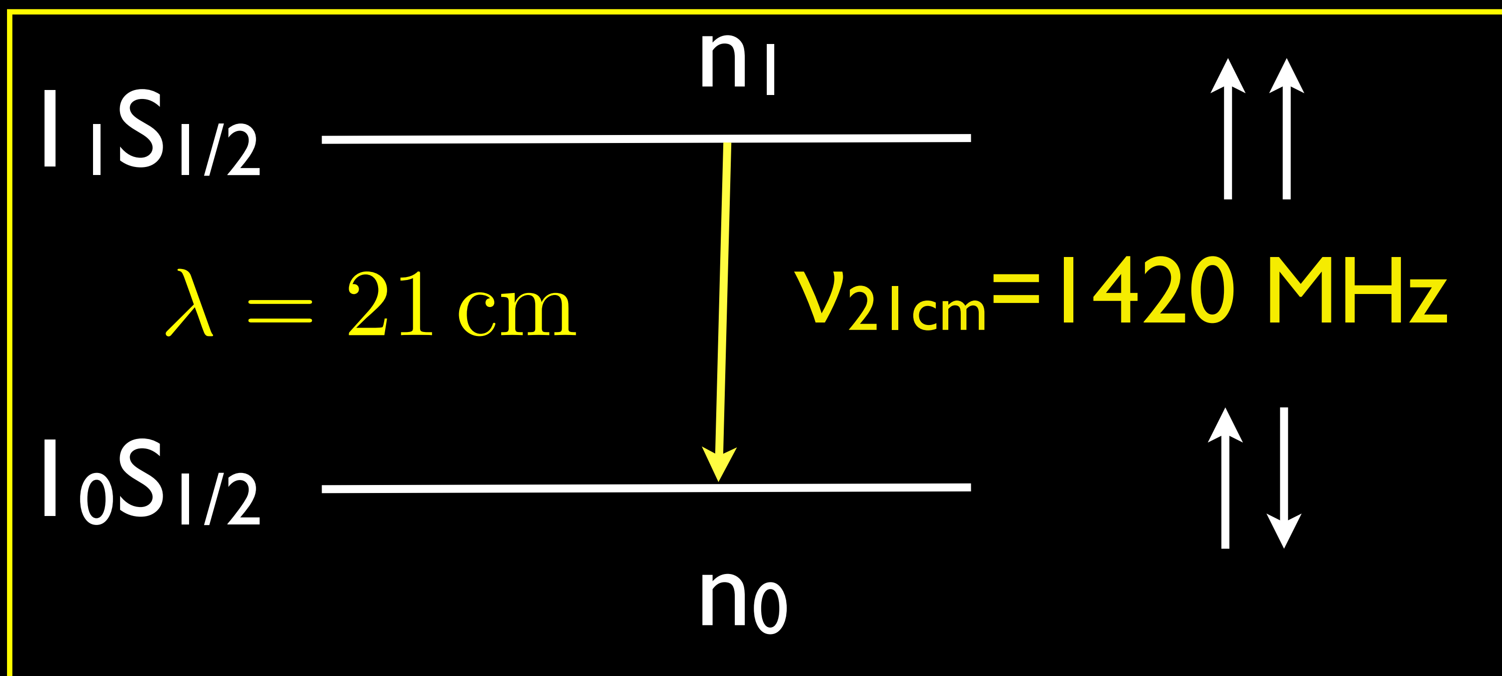
New observations needed to probe z>12 Universe



Probing the Neutral Intergalactic Medium During the Epoch of Reionization

21 cm basics

Hyperfine transition of neutral hydrogen



Useful numbers:

$$200\,\mathrm{MHz} \rightarrow z = 6$$
$$100\,\mathrm{MHz} \rightarrow z = 13$$
$$70\,\mathrm{MHz} \rightarrow z \approx 20$$

$$t_{\mathrm{Age}}(z=6) \approx 1\,\mathrm{Gyr}$$
$$t_{\mathrm{Age}}(z=10) \approx 500\,\mathrm{Myr}$$
$$t_{\mathrm{Age}}(z=20) \approx 150\,\mathrm{Myr}$$

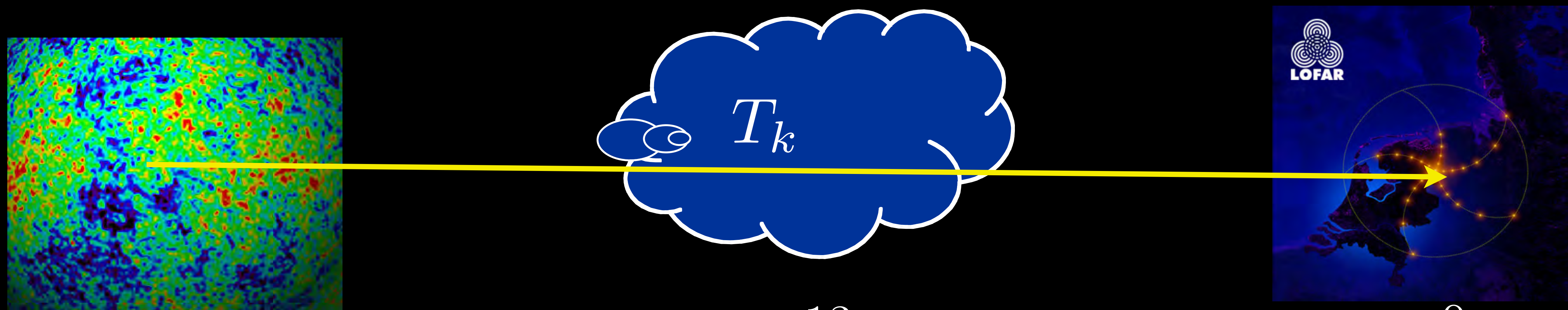
$$t_{\mathrm{Gal}}(z=8) \approx 100\,\mathrm{Myr}$$

Spin temperature describes relative occupation of levels

$$n_1/n_0 = 3\exp(-h\nu_{21\mathrm{cm}}/kT_s)$$

21 cm line in cosmology

T_γ T_S T_b



$z = 13$

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

$z = 0$

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

CMB acts as back light

Neutral gas imprints signal

Redshifted signal detected

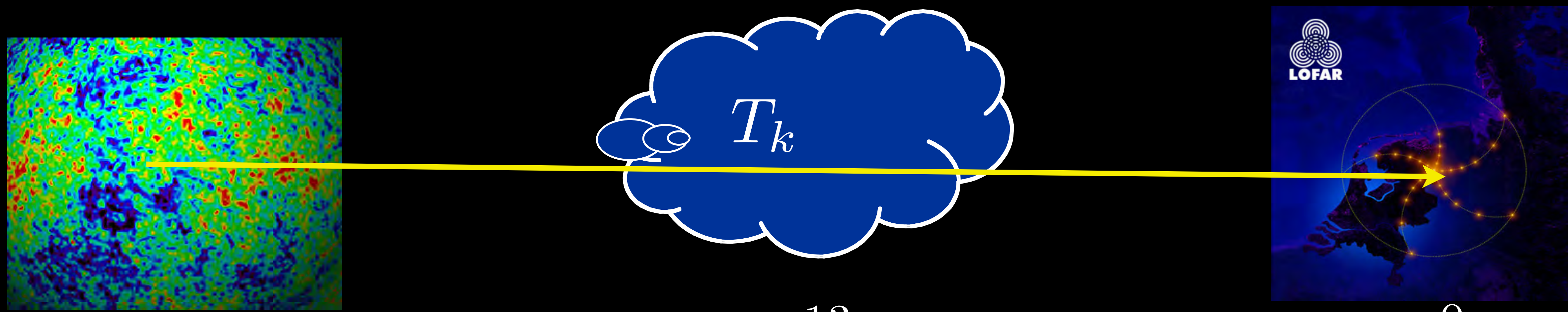
brightness temperature

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

spin temperature set by different mechanisms:
- Radiative transitions (CMB)
- Collisions
- Wouthysen-Field effect (resonant scattering of Lyα)

21 cm line in cosmology

T_γ | T_S | T_b



CMB	Neutral gas	Detected
	$z=13$	$z=0$
	$\nu = 1.4\,\mathrm{GHz}$	$\nu = 100\,\mathrm{MHz}$
CMB acts as back light	Neutral gas imprints signal	Redshifted signal detected

neutral fraction

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:
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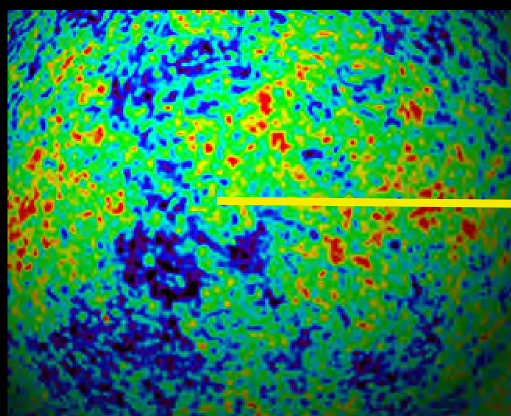
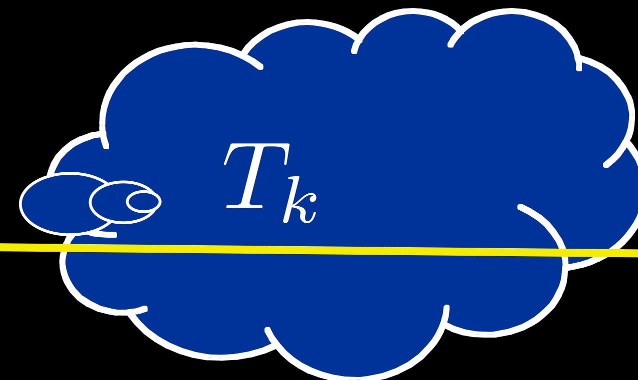
21 cm line in cosmology

T_γ



CMB acts as back light

T_S

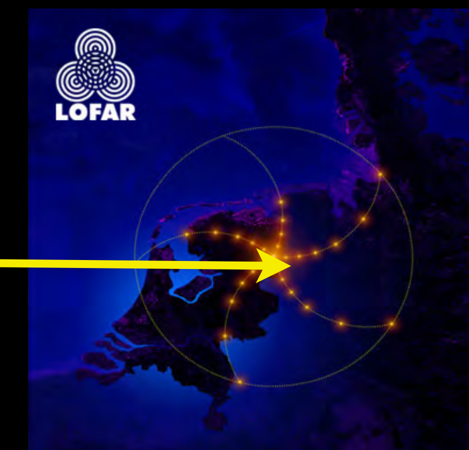


$z = 13$

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

Neutral gas imprints signal

T_b



$z = 0$

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

Redshifted signal detected

neutral fraction

baryon density

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

spin temperature set by different mechanisms:
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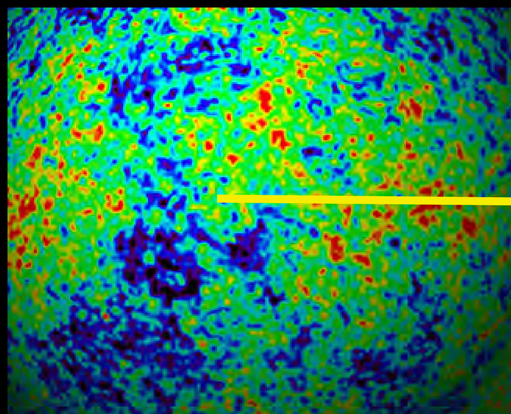
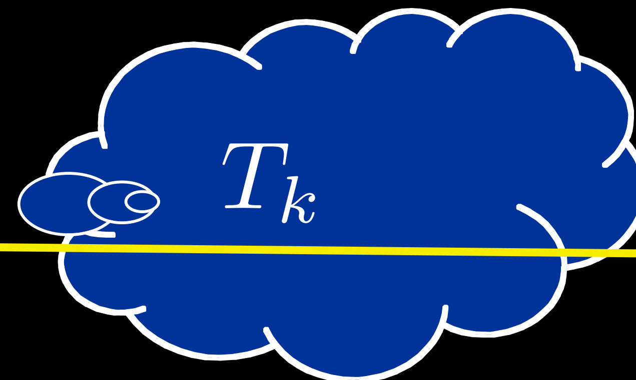
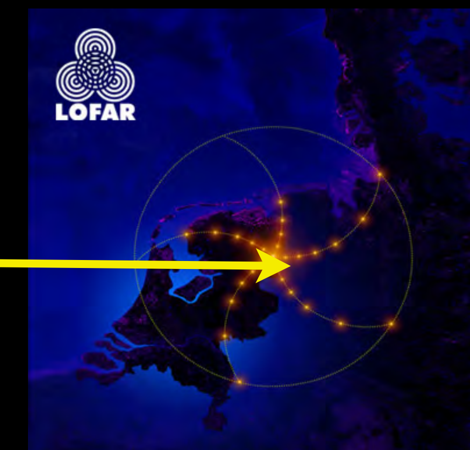
21 cm line in cosmology

T_γ $\qquad$ T_S $\qquad$ 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 $\quad$ baryon density $\quad$ spin temperature

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

spin temperature set by different mechanisms:
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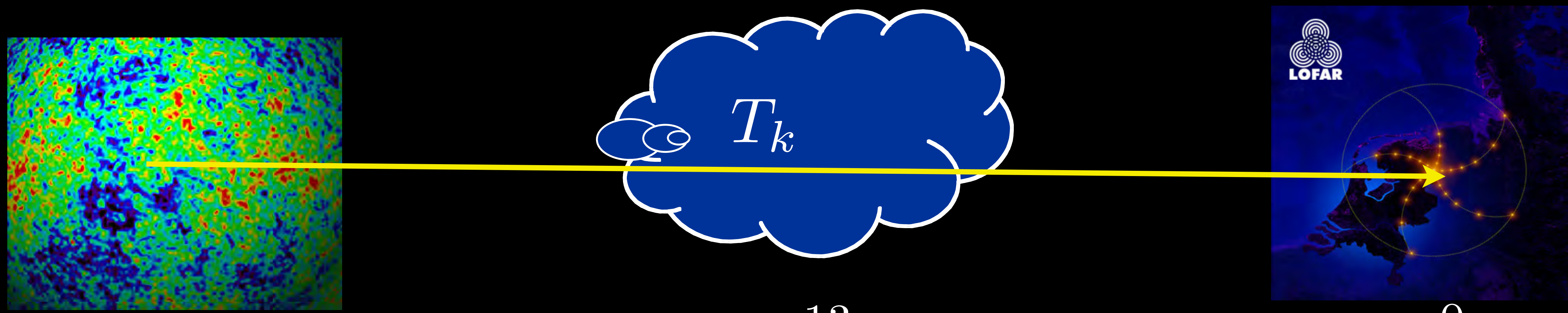
21 cm line in cosmology

T_γ T_S T_b



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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:
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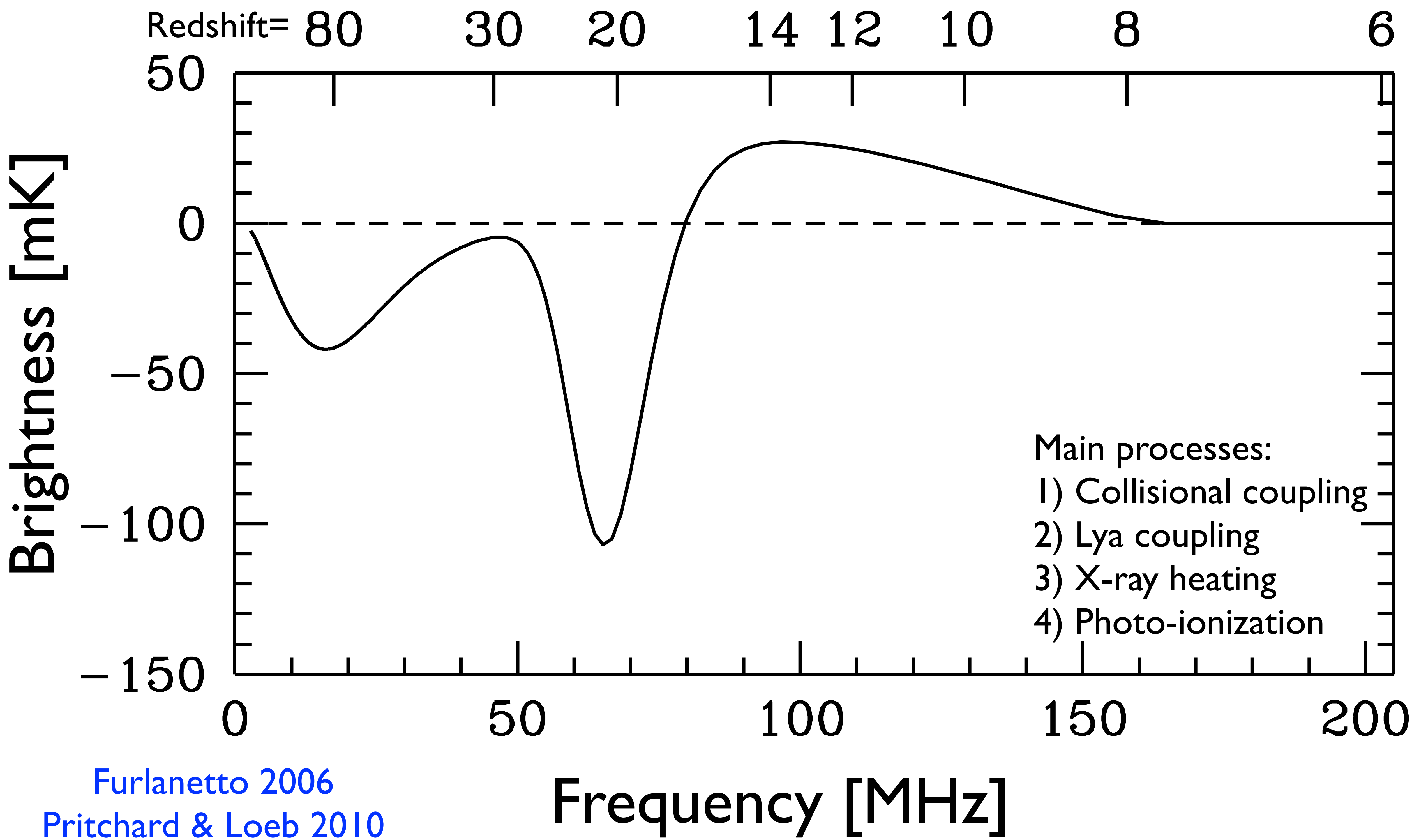
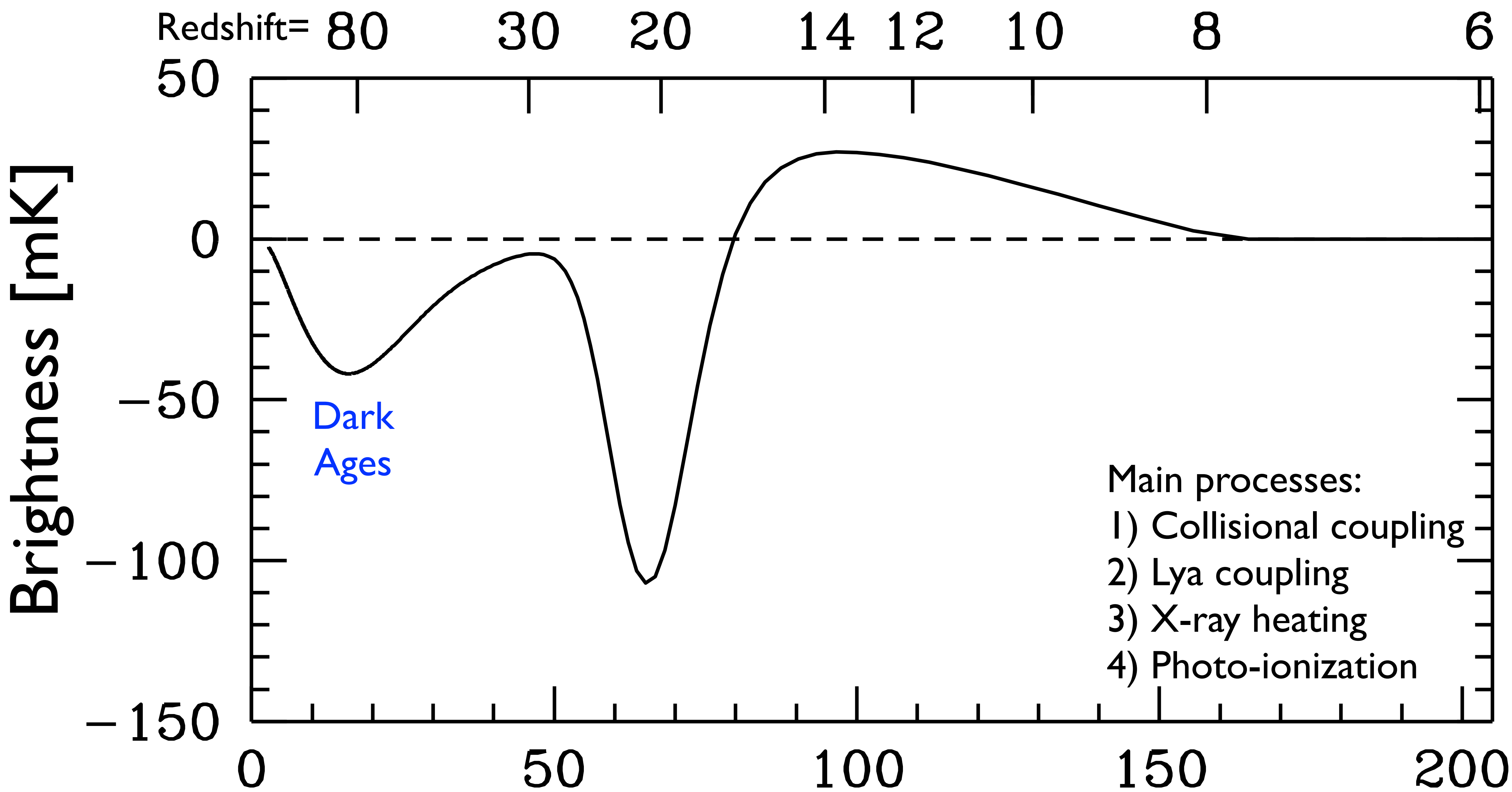
- Wouthysen-Field effect (resonant scattering of Lyα)

21 cm global signal



Furlanetto 2006
Pritchard & Loeb 2010

21 cm global signal



Furlanetto 2006
Pritchard & Loeb 2010

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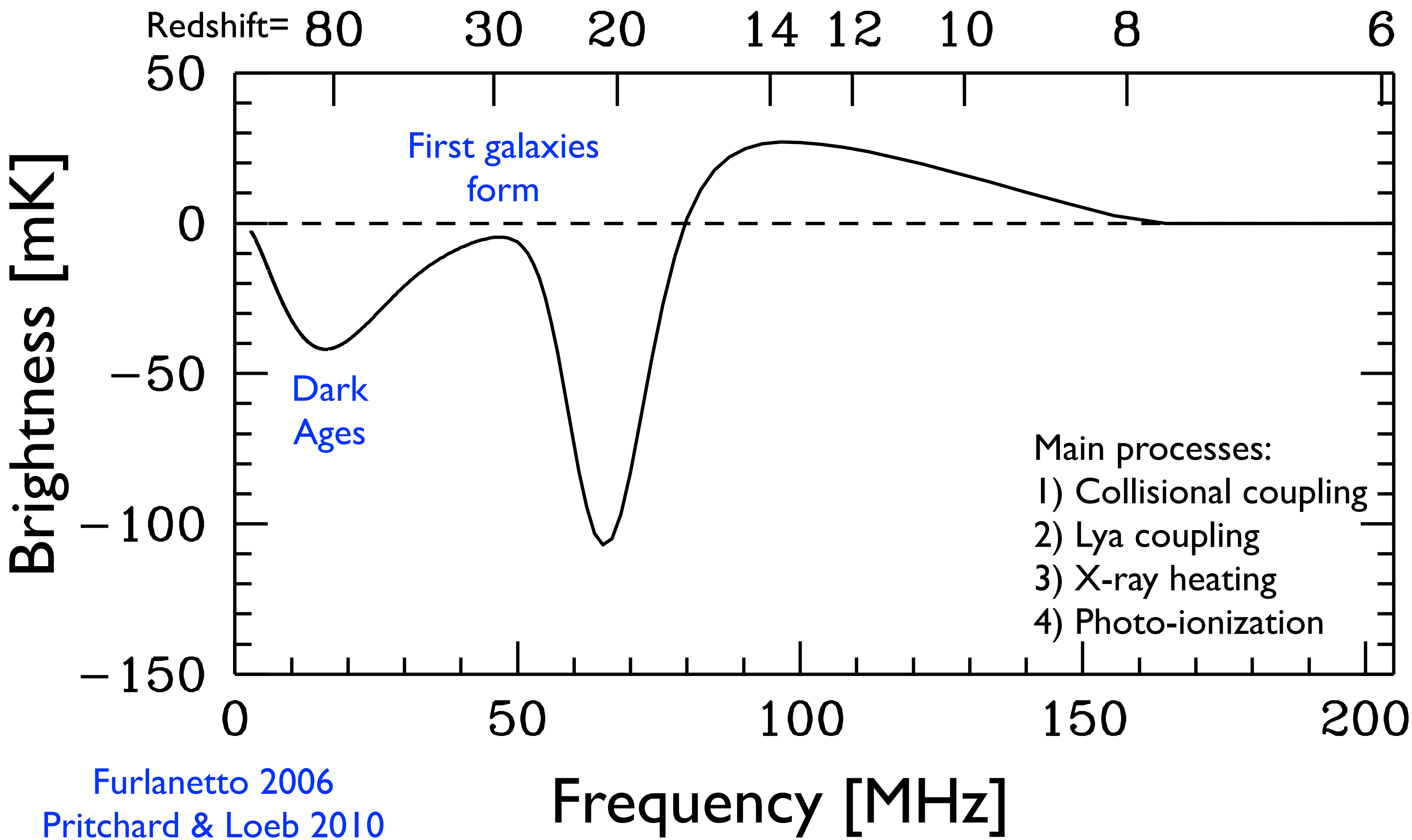
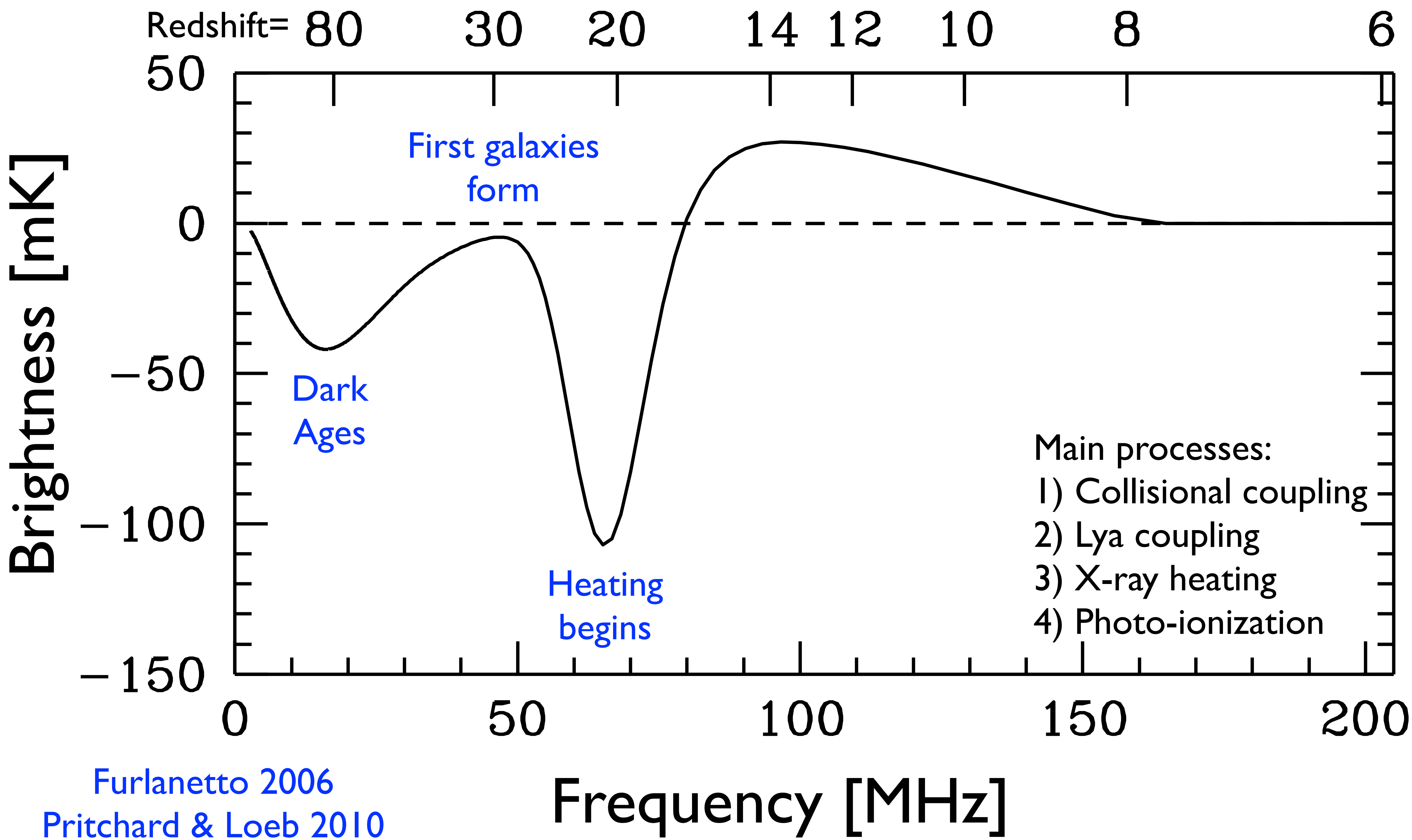


Furlanetto 2006
Pritchard & Loeb 2010

21 cm global signal



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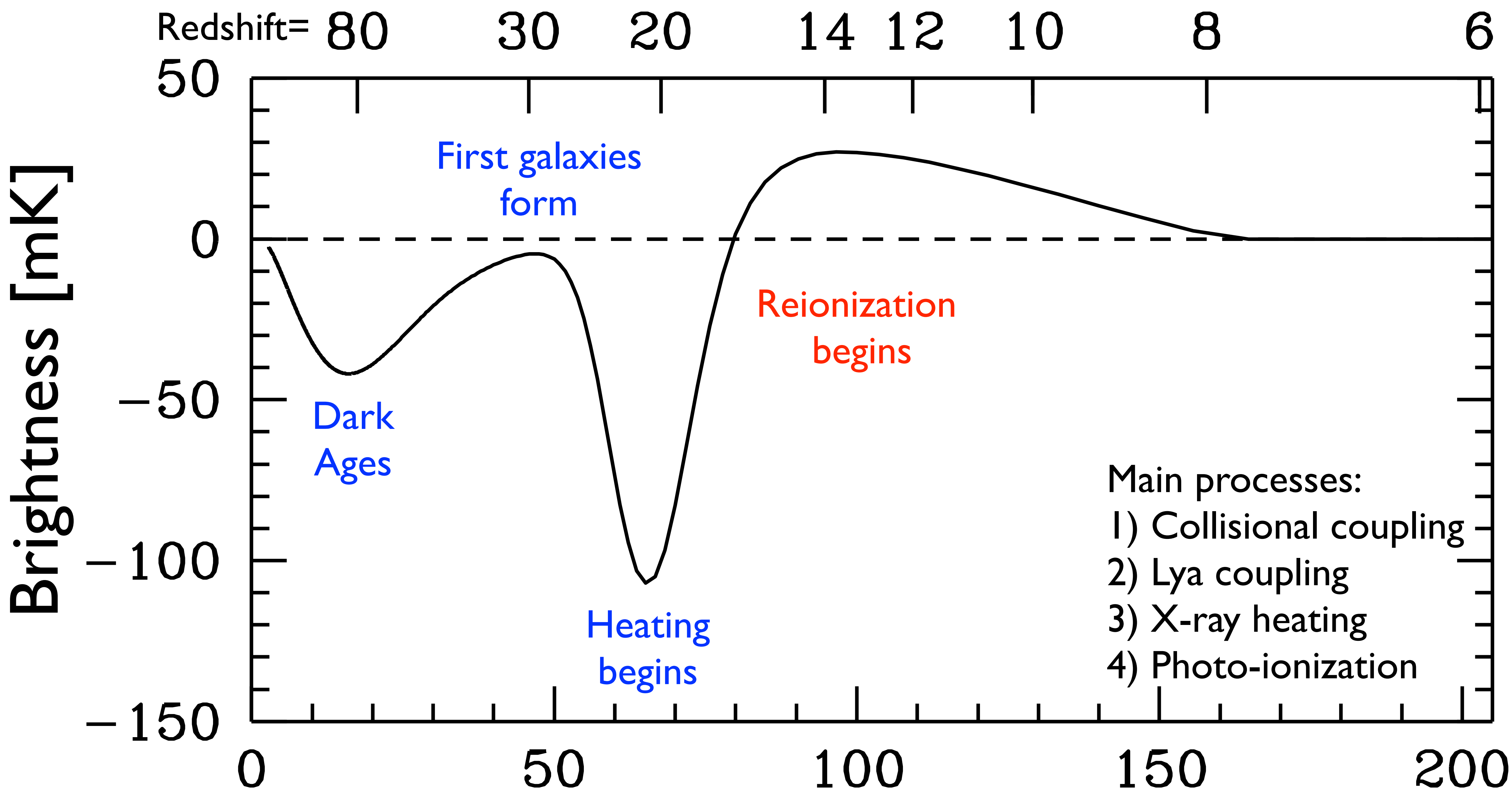
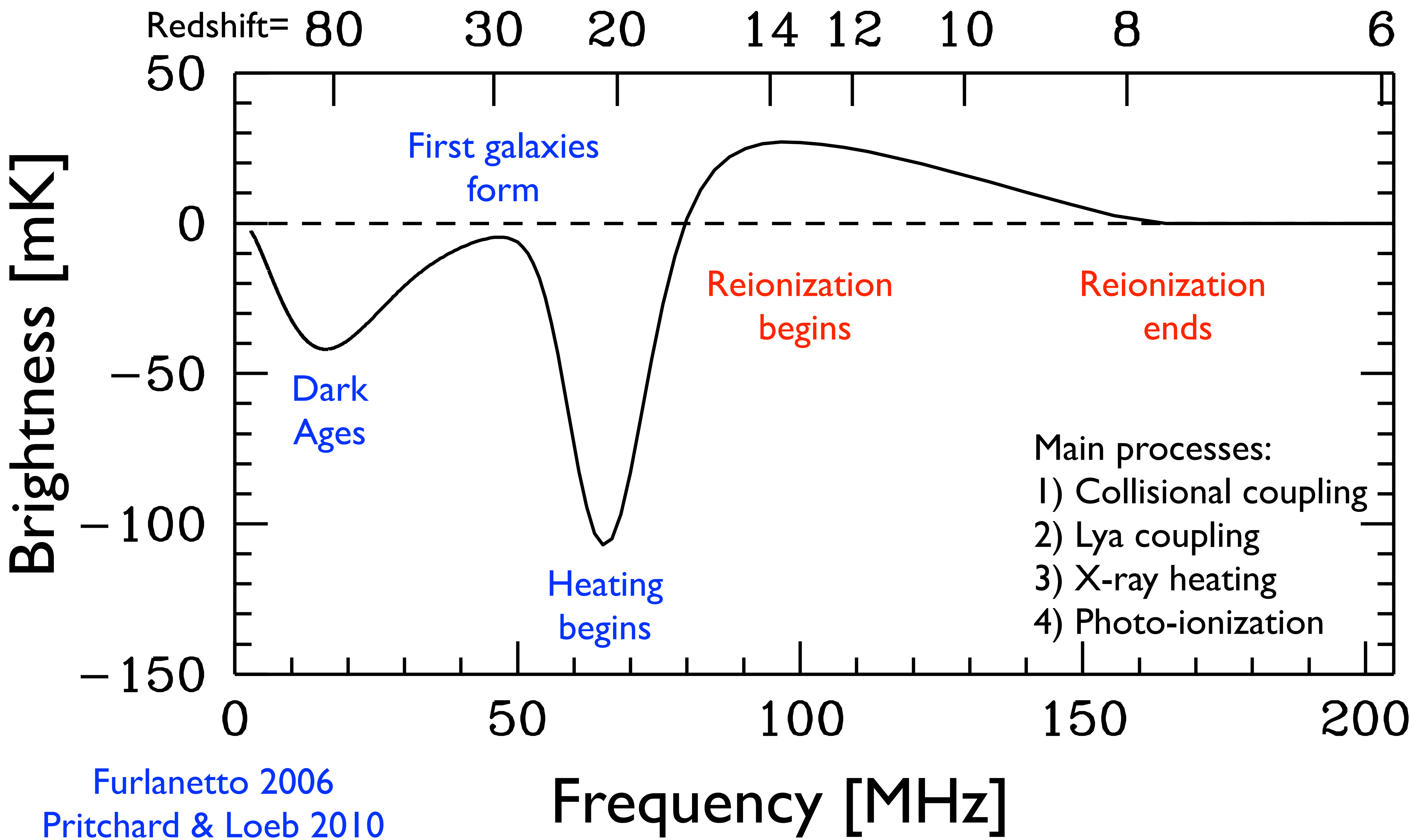
Pritchard & Loeb 2010

21 cm global signal



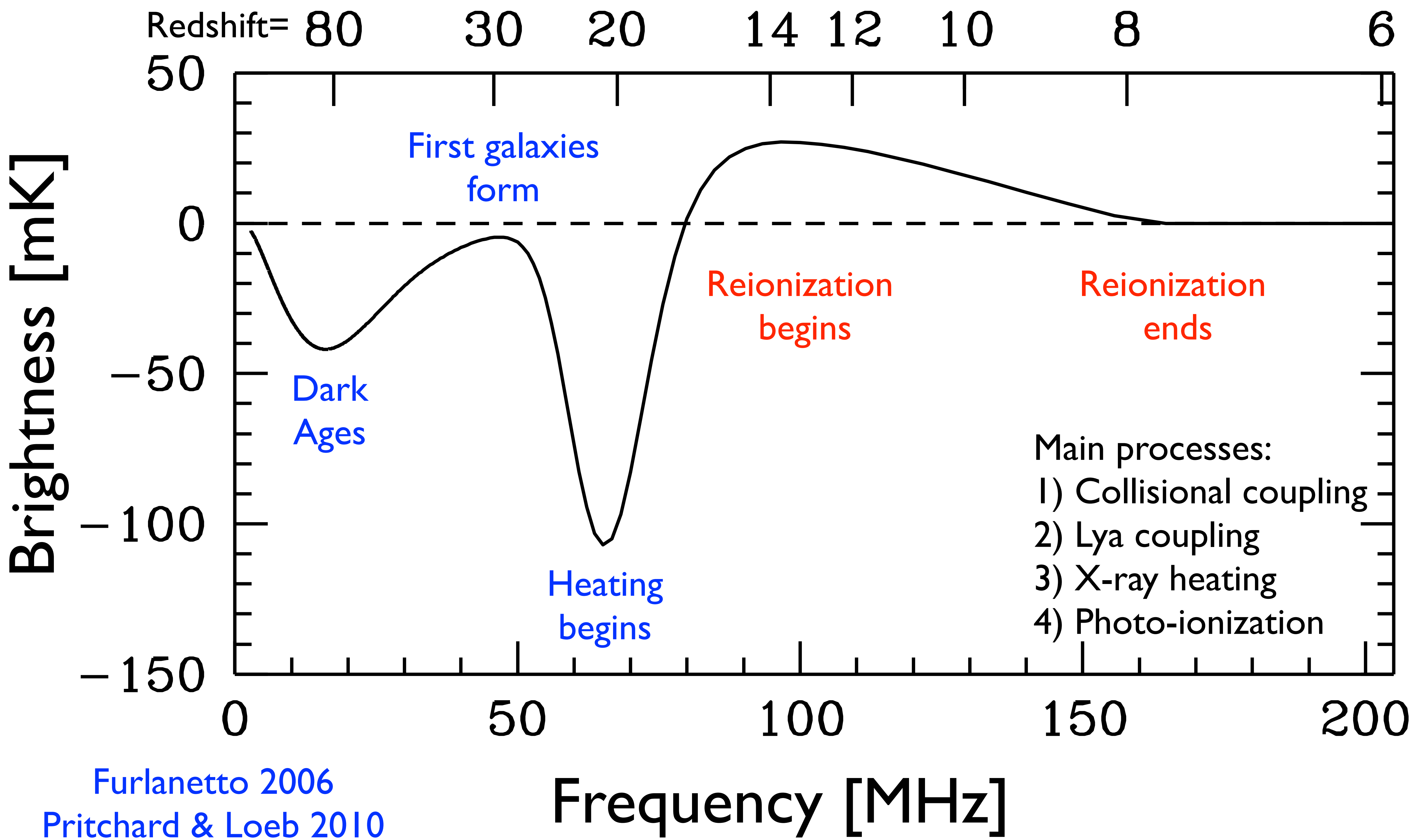
Furlanetto 2006
Pritchard & Loeb 2010

21 cm global signal



Furlanetto 2006
Pritchard & Loeb 2010

21 cm global signal

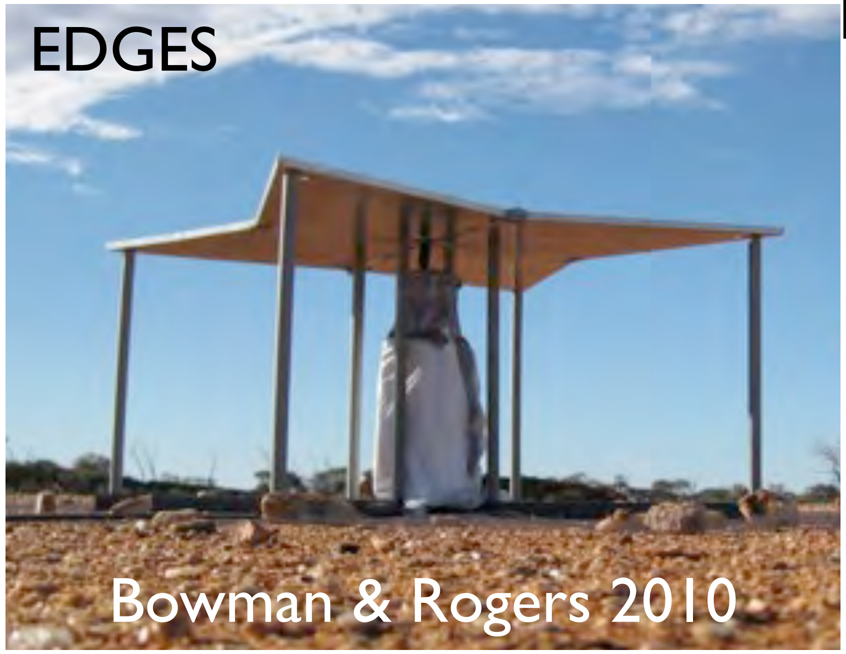


Furlanetto 2006
Pritchard & Loeb 2010

measurement would constrain basic features of first galaxies

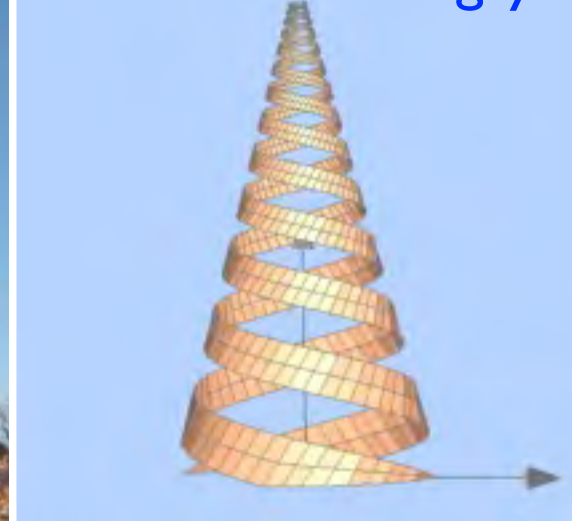
Absolute temperature measurements

EDGES



Bowman & Rogers 2010

BIGHORNS - Tingay+



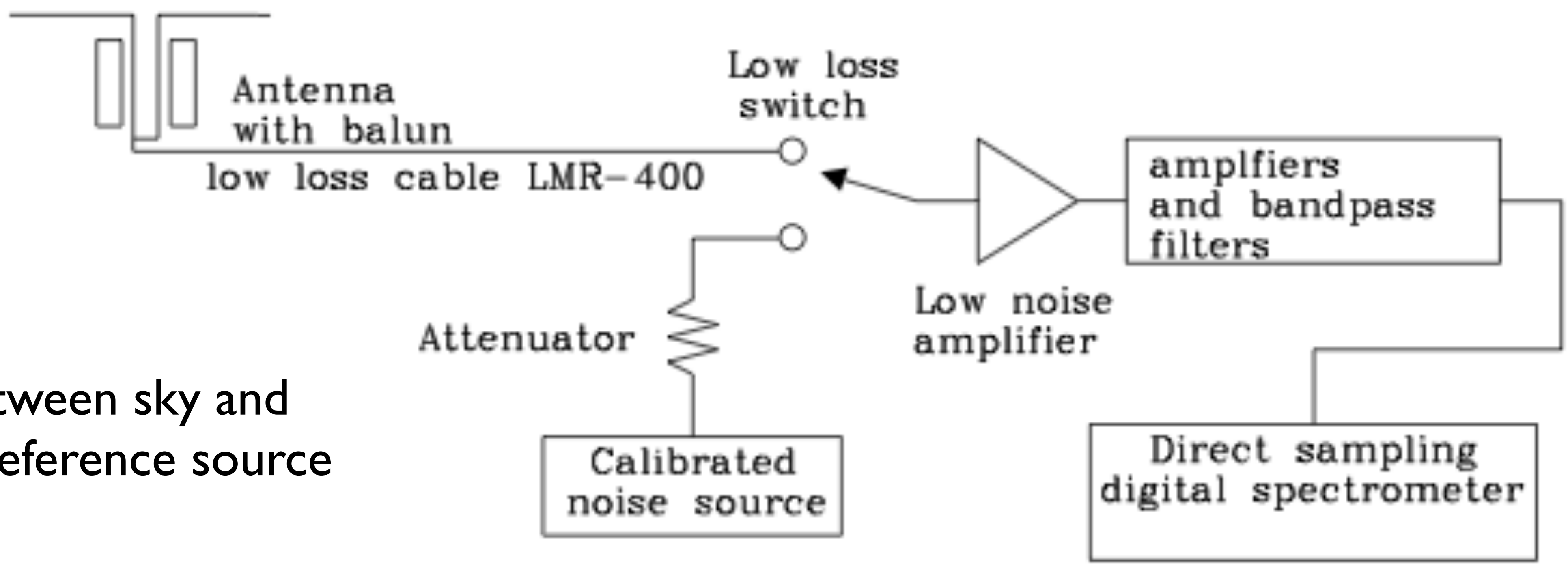
ZEBRA - Subrahmanyan+

DARK AGES RADIO EXPLORER

DARE

Burns+

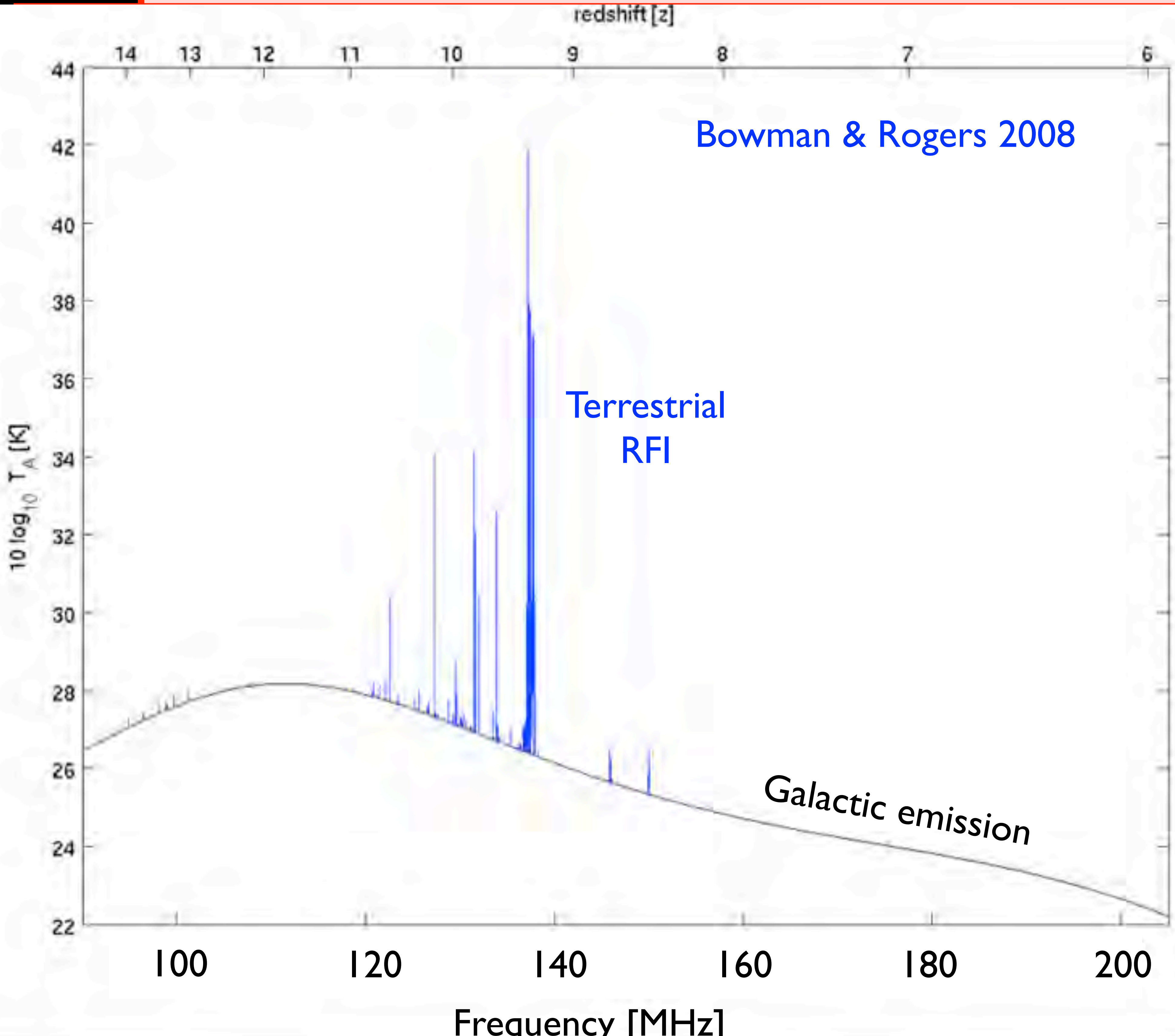
also CoRE - Ekers+



Switch between sky and calibrated reference source

Large (smooth) foregrounds must be removed <=> instrumental calibration is crucial

EDGES observations



~50 hours integration

100-200 MHz
in 2 MHz channels

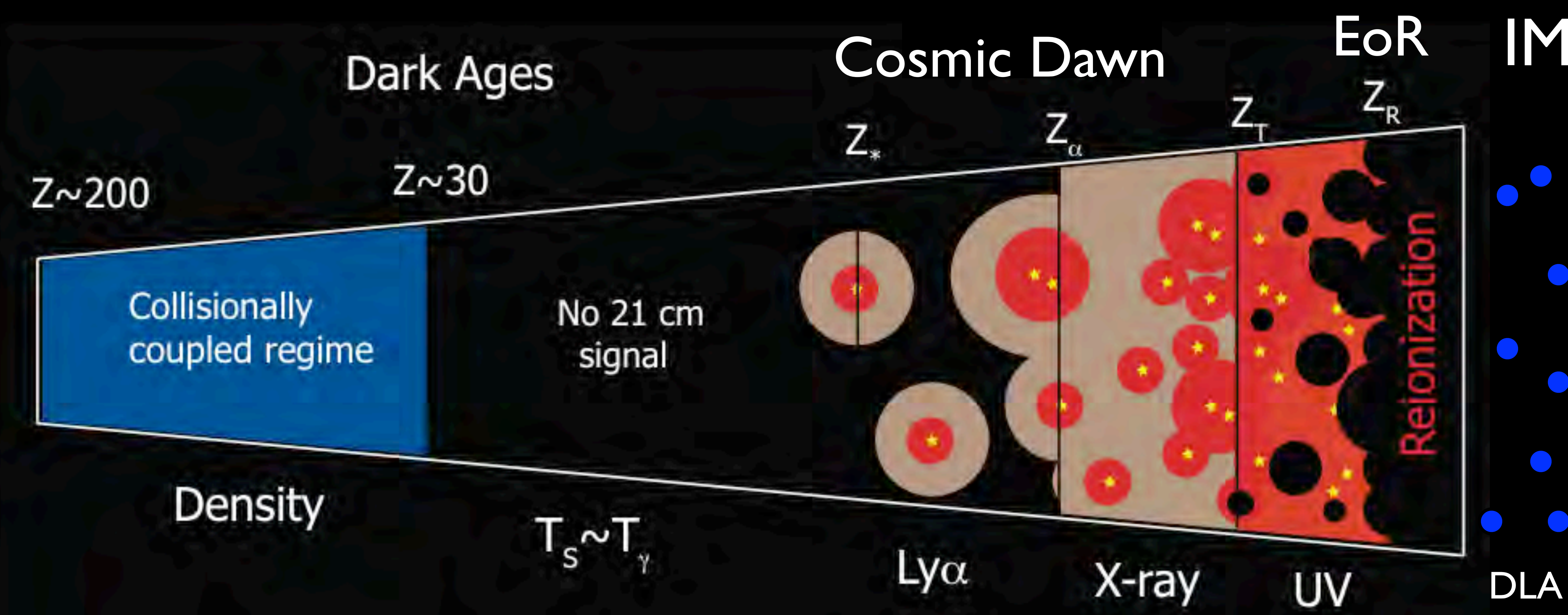
Absence of sharp features excludes reionization scenarios with duration $\Delta z<0.06$

Brightness Fluctuations

brightness temperature	density	neutral fraction	gas temperature	Lyman alpha flux	peculiar velocities

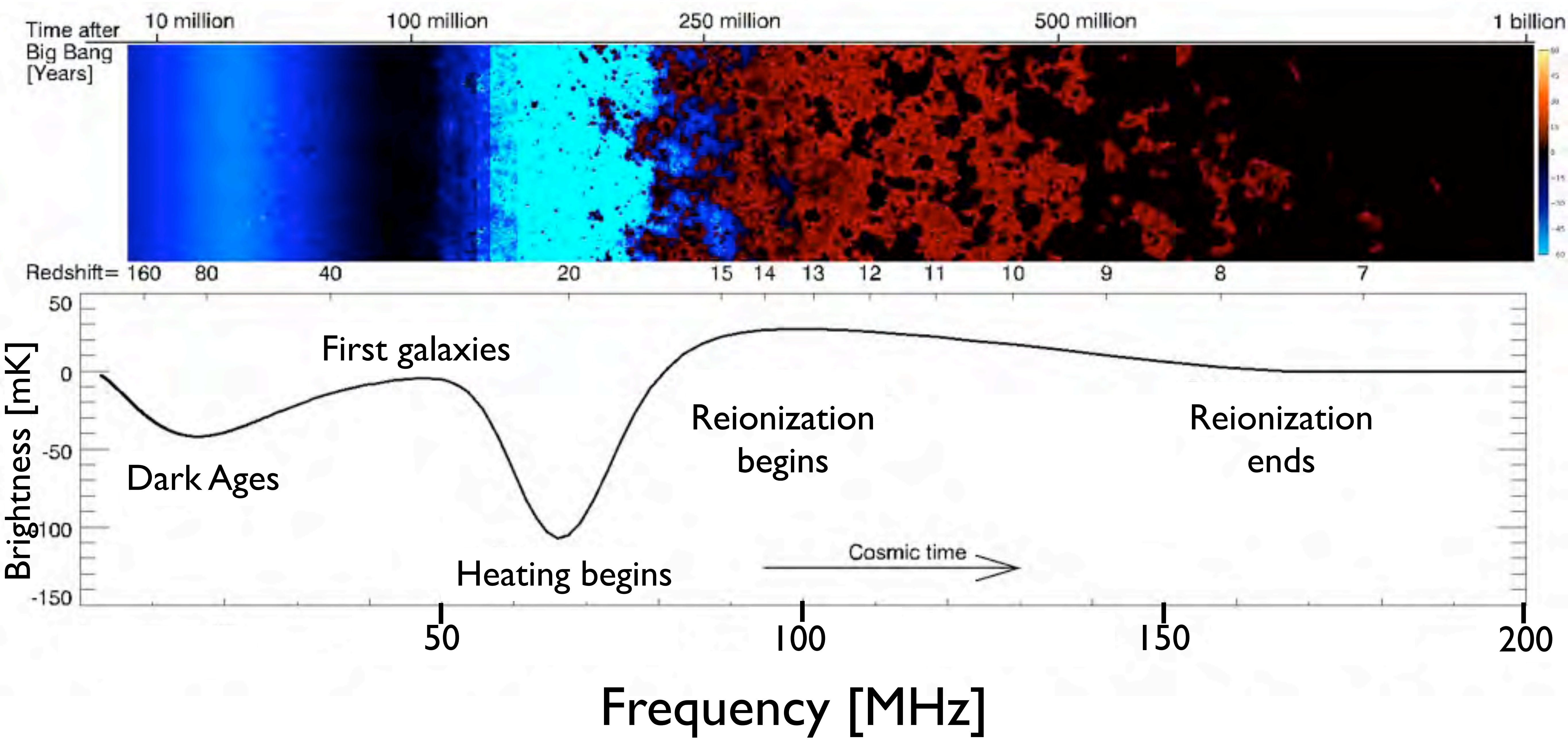
$$\delta_{T_b} = \beta\delta_b + \beta_x\delta_{x_{HI}} + \beta_T\delta_{T_k} + \beta_\alpha\delta_\alpha - \delta_{\partial v}$$

cosmology	reionization	X-ray heating	Lya sources	cosmology



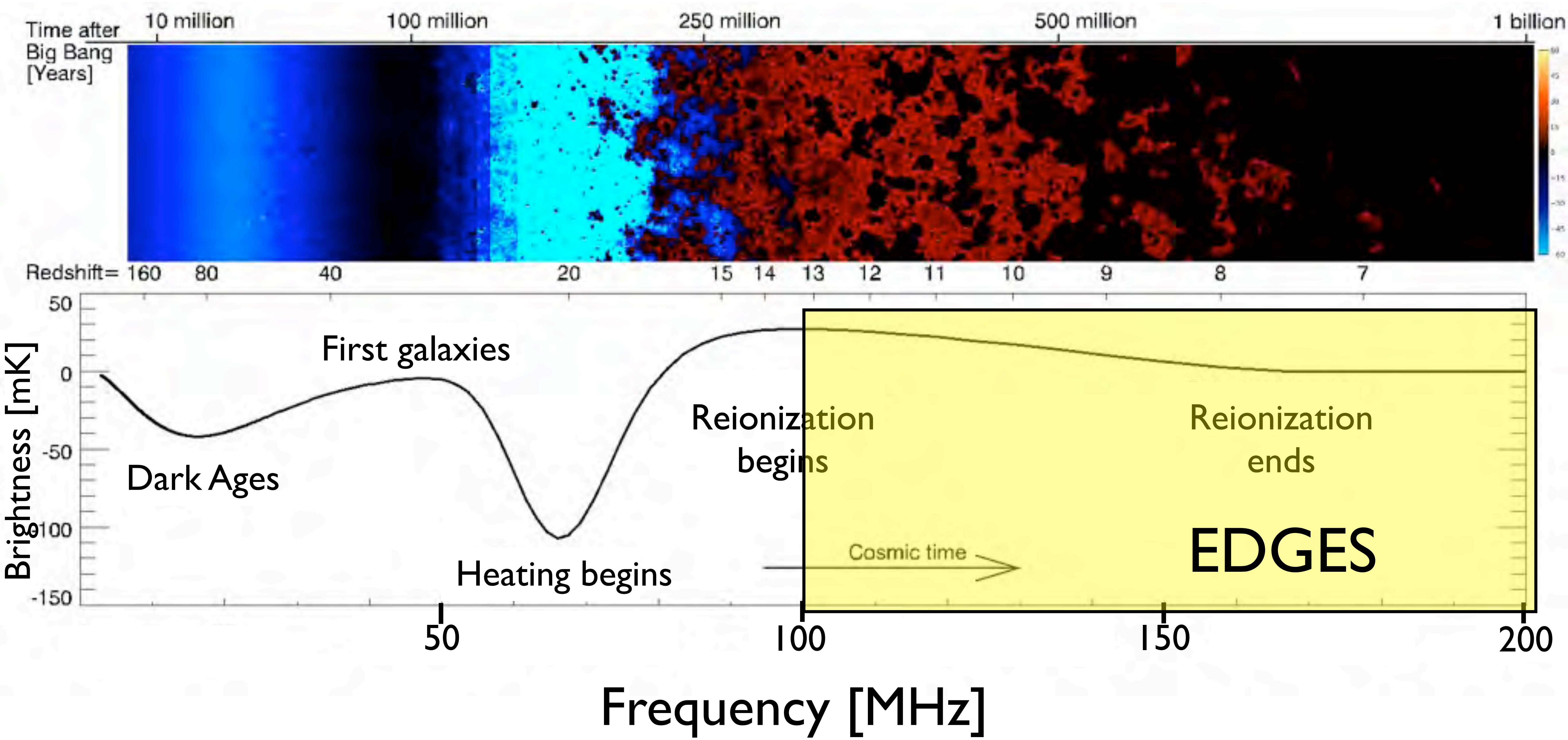
21 cm summary

Pritchard & Loeb 2010



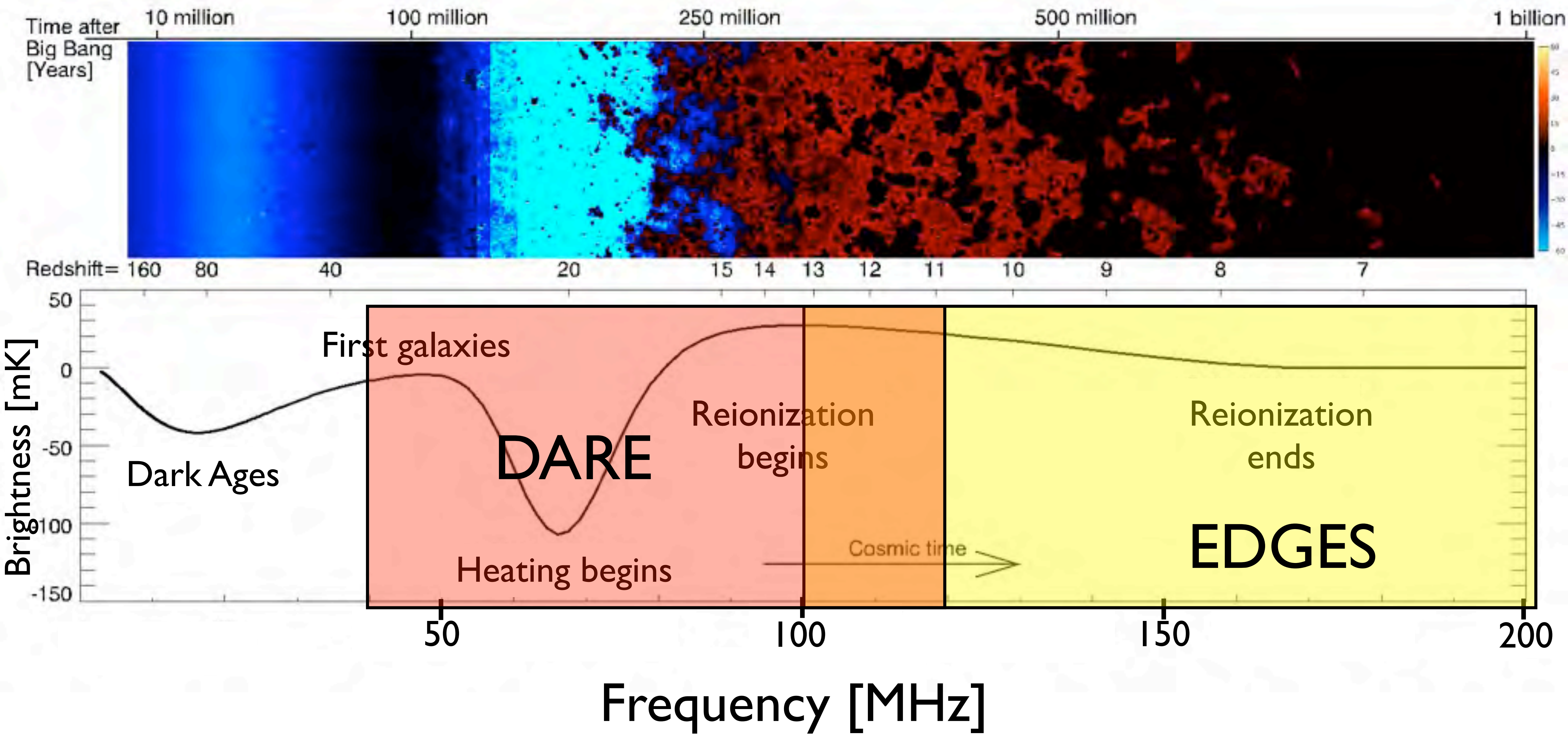
21 cm summary

Pritchard & Loeb 2010



21 cm summary

Pritchard & Loeb 2010



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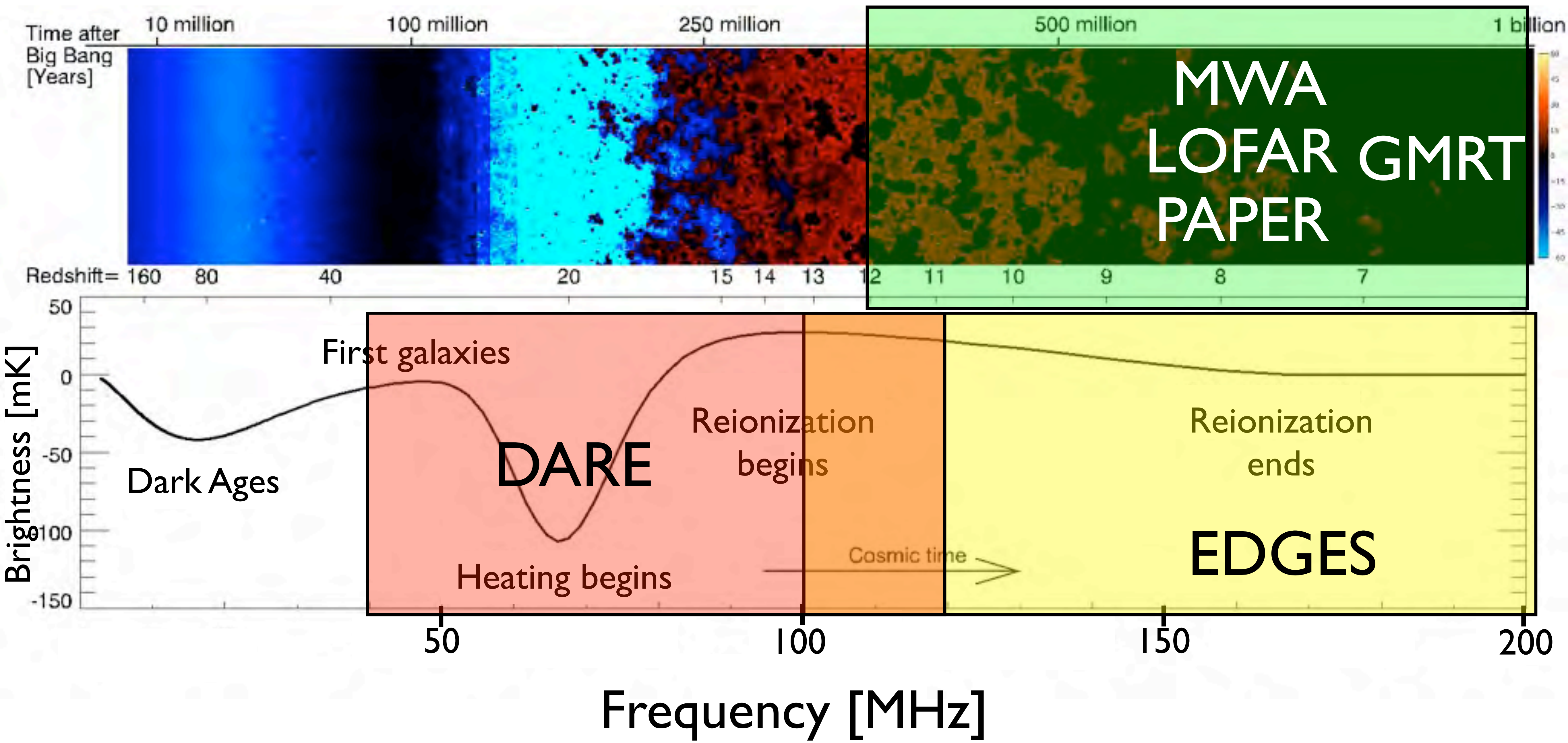

21 cm summary

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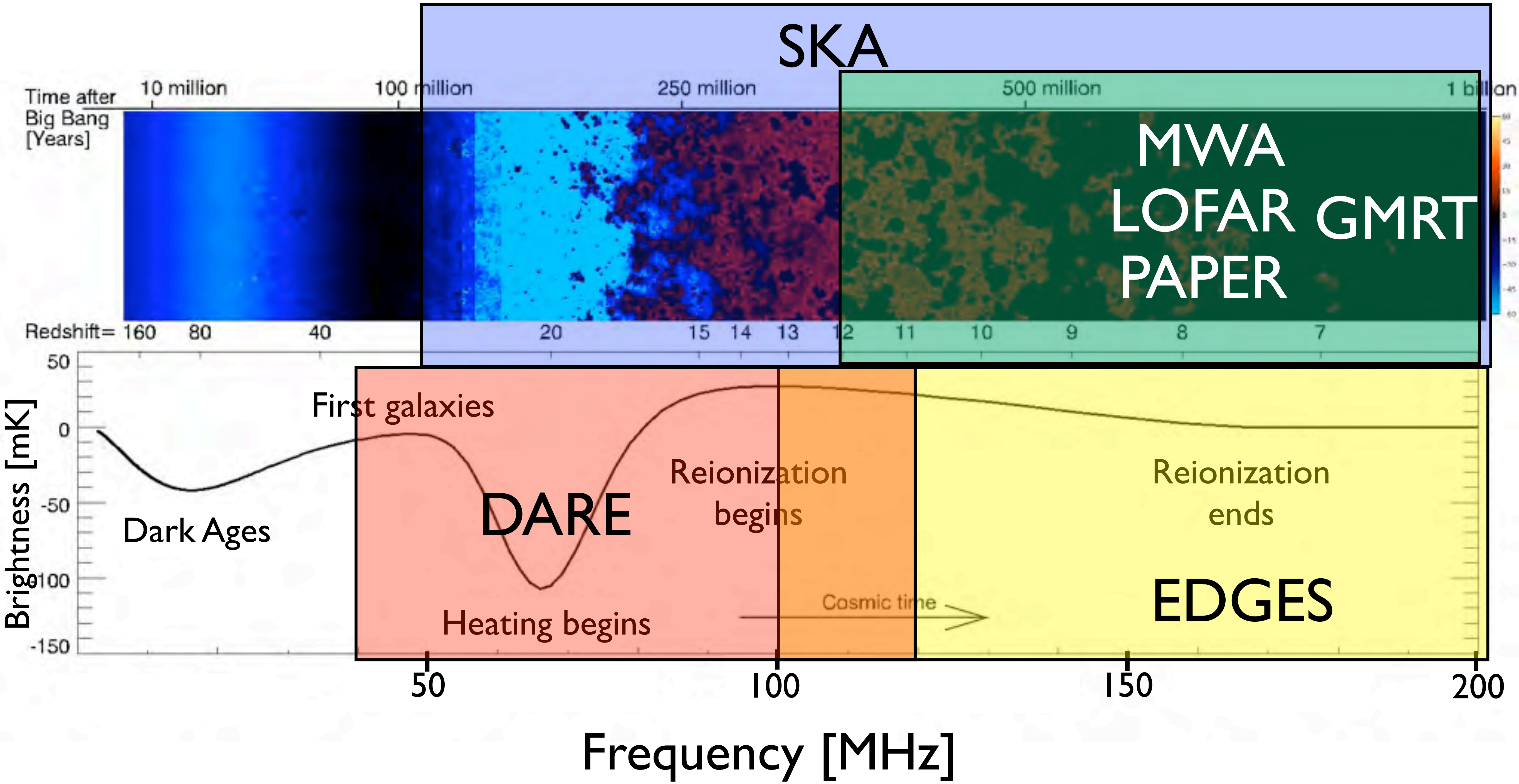

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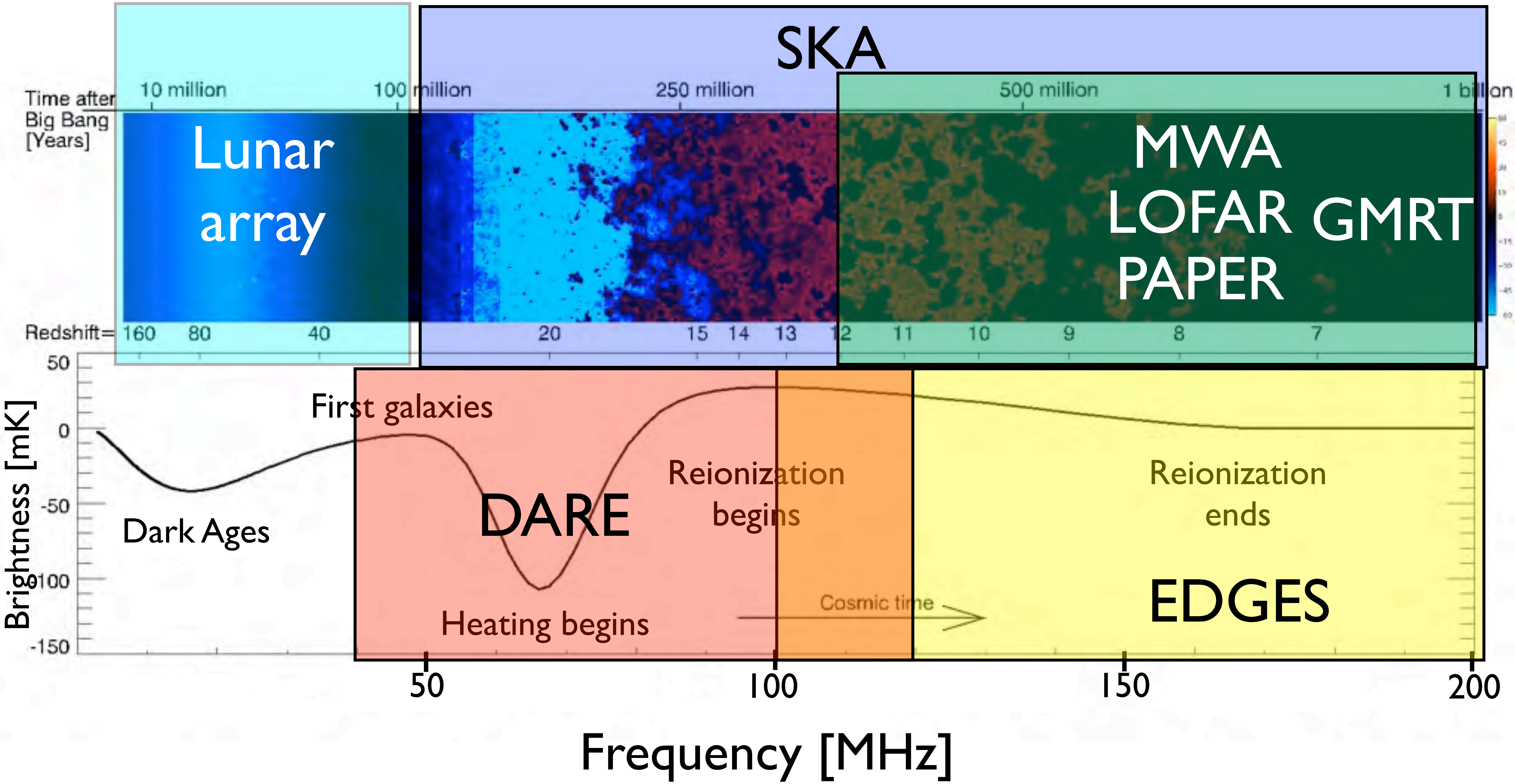
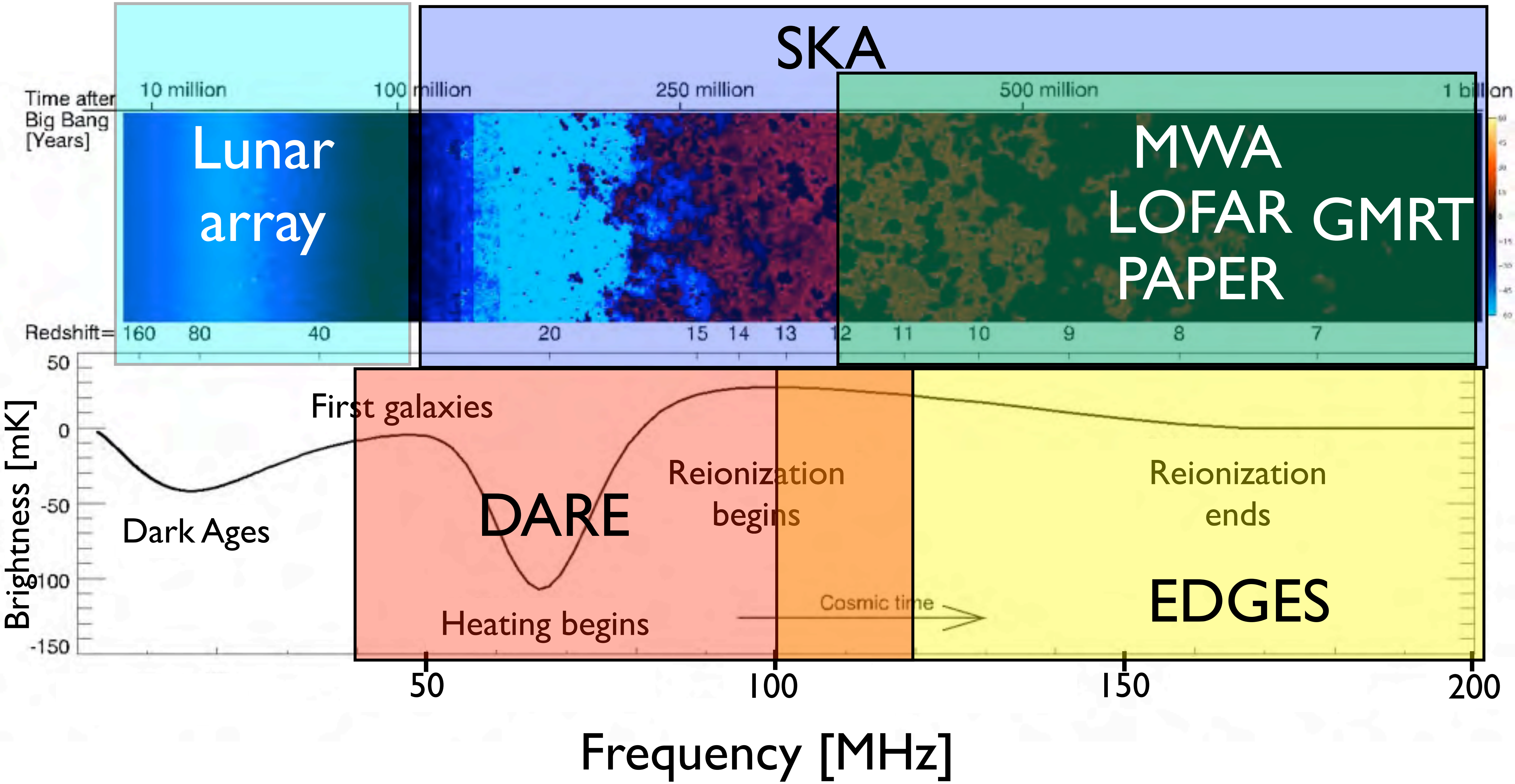
Pritchard & Loeb 2010



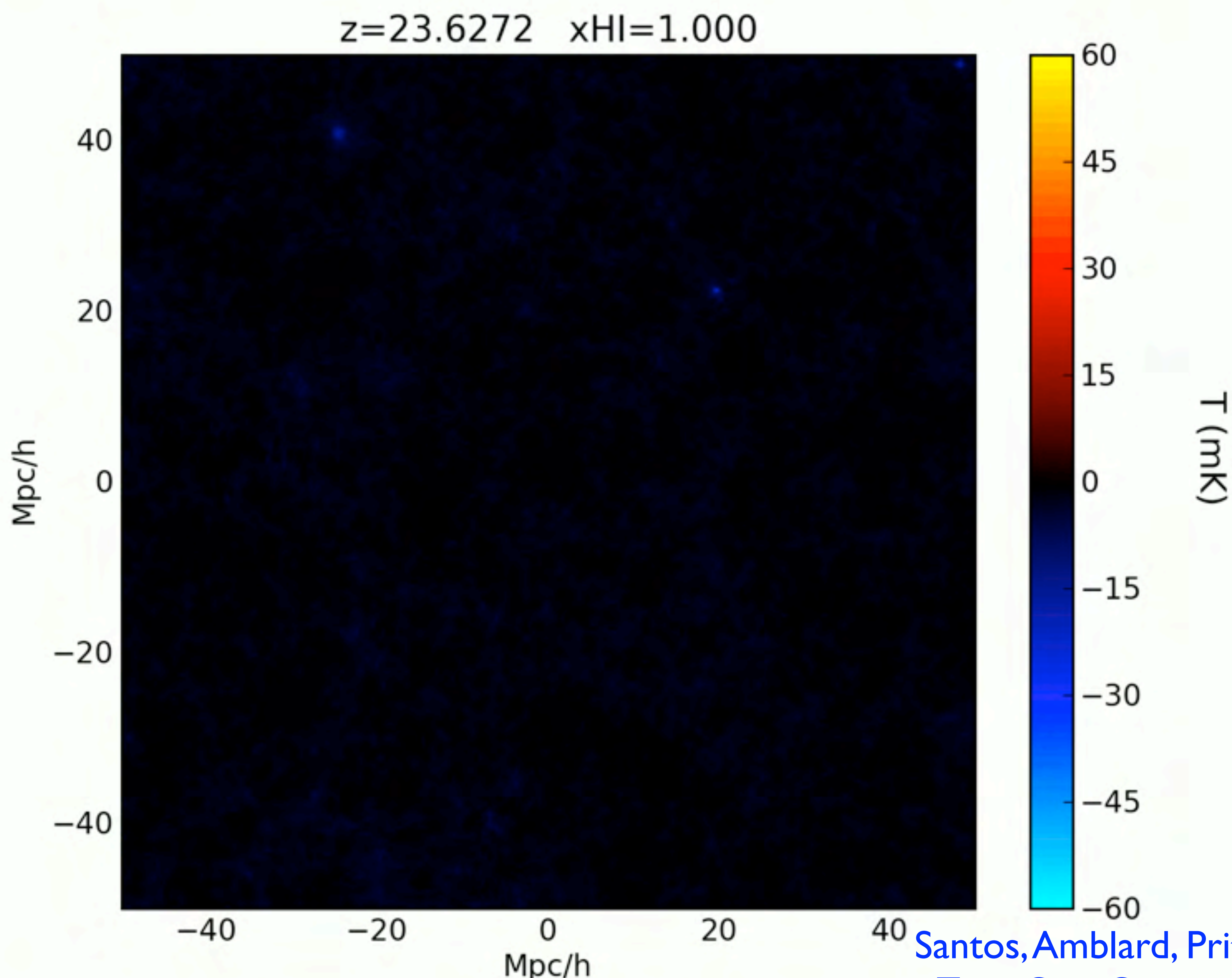
21 cm summary

Pritchard & Loeb 2010



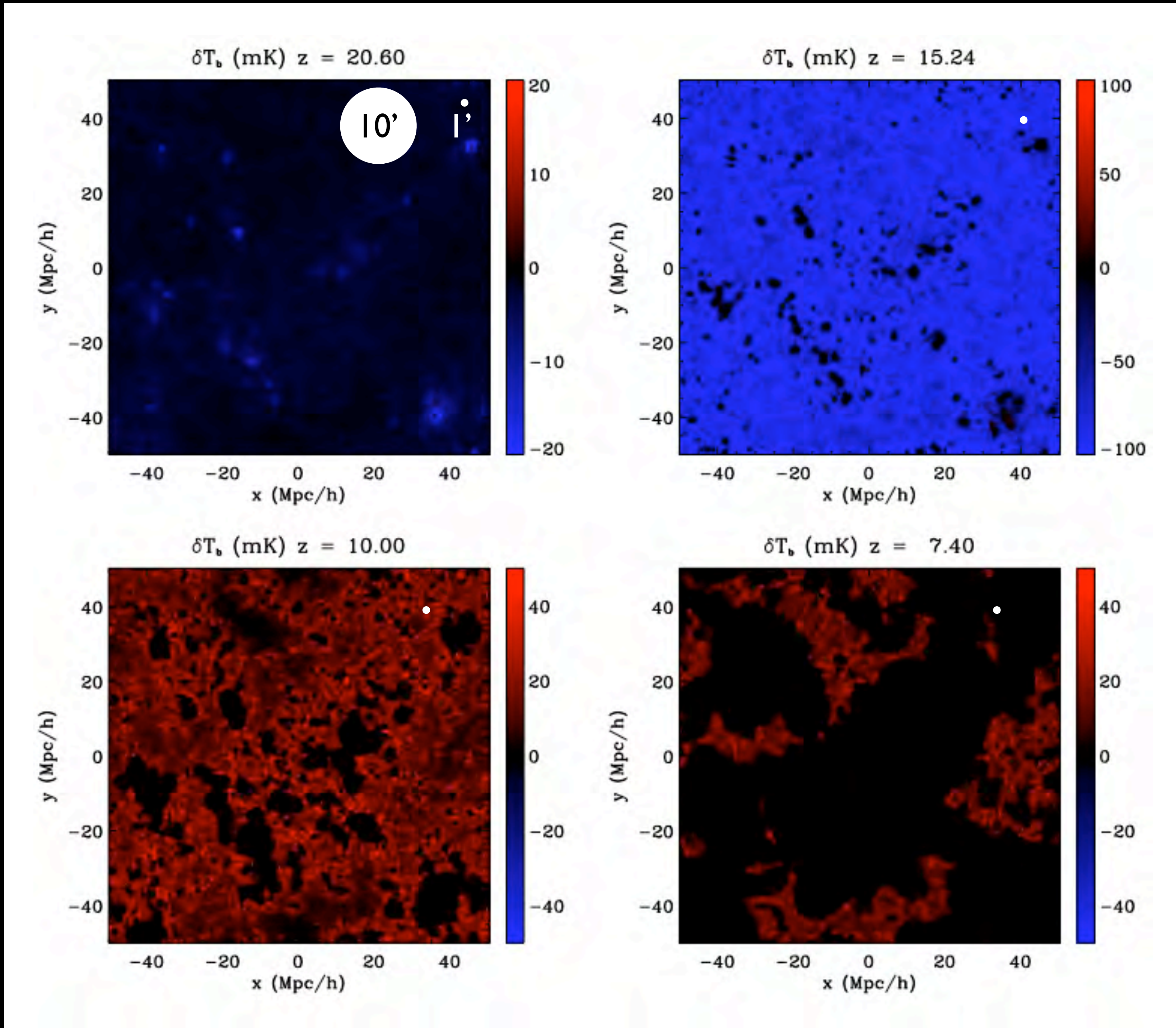
Science requirement 1: cover full redshift range accessible

Movie of the cosmic evolution



Santos, Amblard, Pritchard, Trac, Cen, Cooray 2008

Imaging brightness fluctuations



At z=8 (150 MHz)

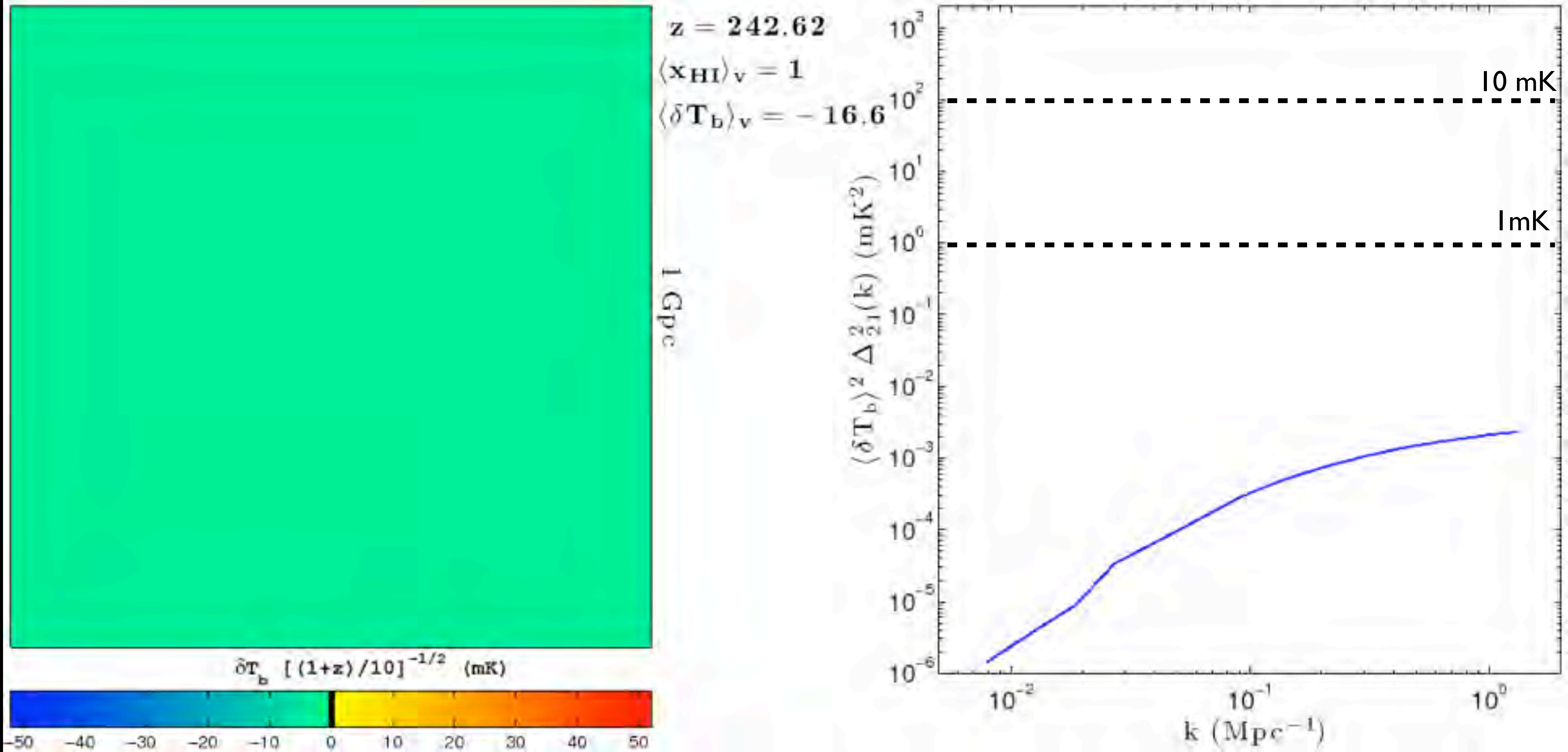
1 arcmin~0.3 pMpc
~2 cMpc

0.1 MHz~0.3 pMpc
~2 cMpc

Imaging requires S/N>1 per mode

Science requirement 3+4: Resolve bubbles in 3D

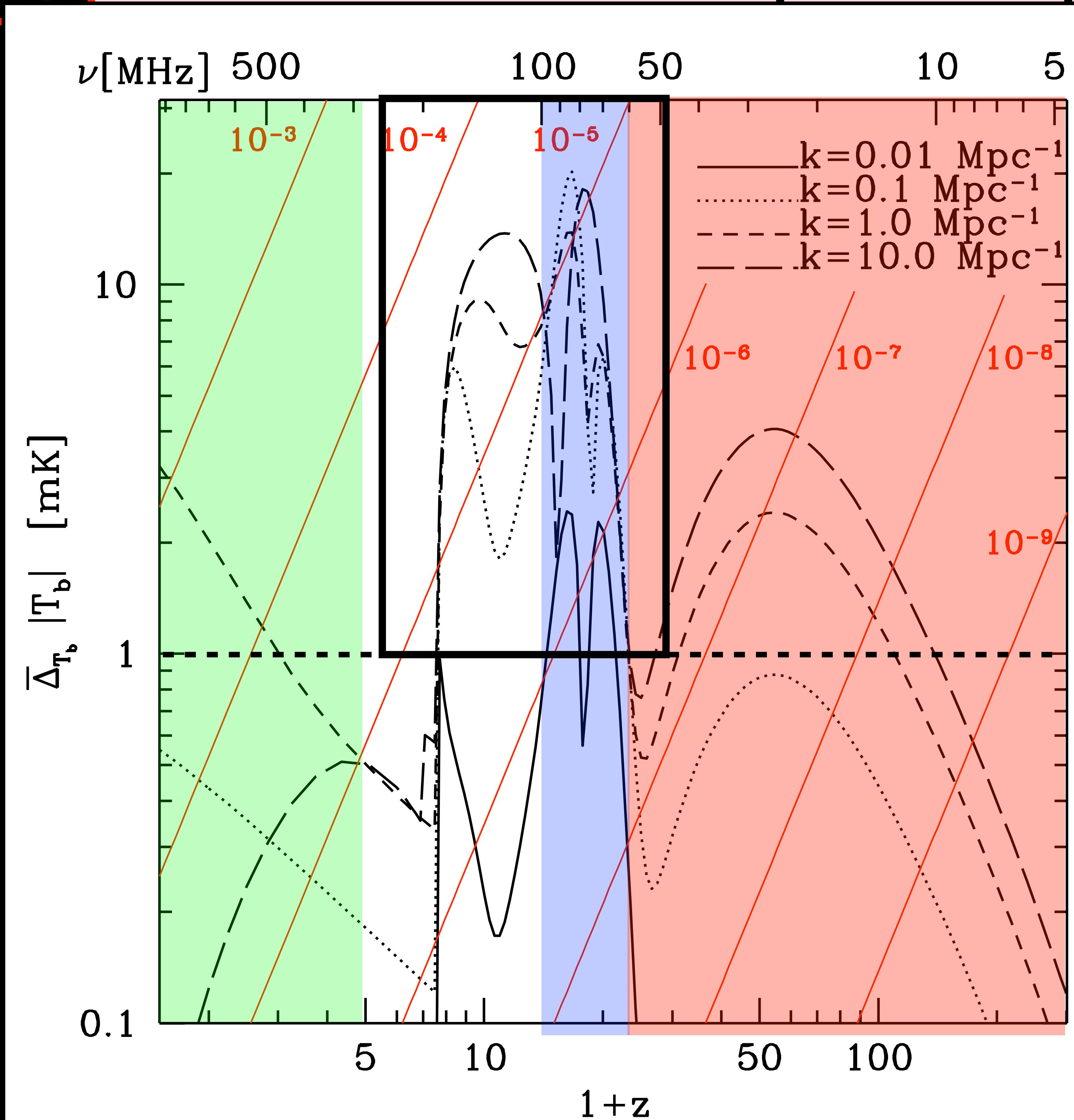
Evolution of the power spectrum



Science requirement 2: 1 mK sensitivity on arcmin scales for imaging and power spectrum

Mesinger+ 2010

Evolution of power spectrum



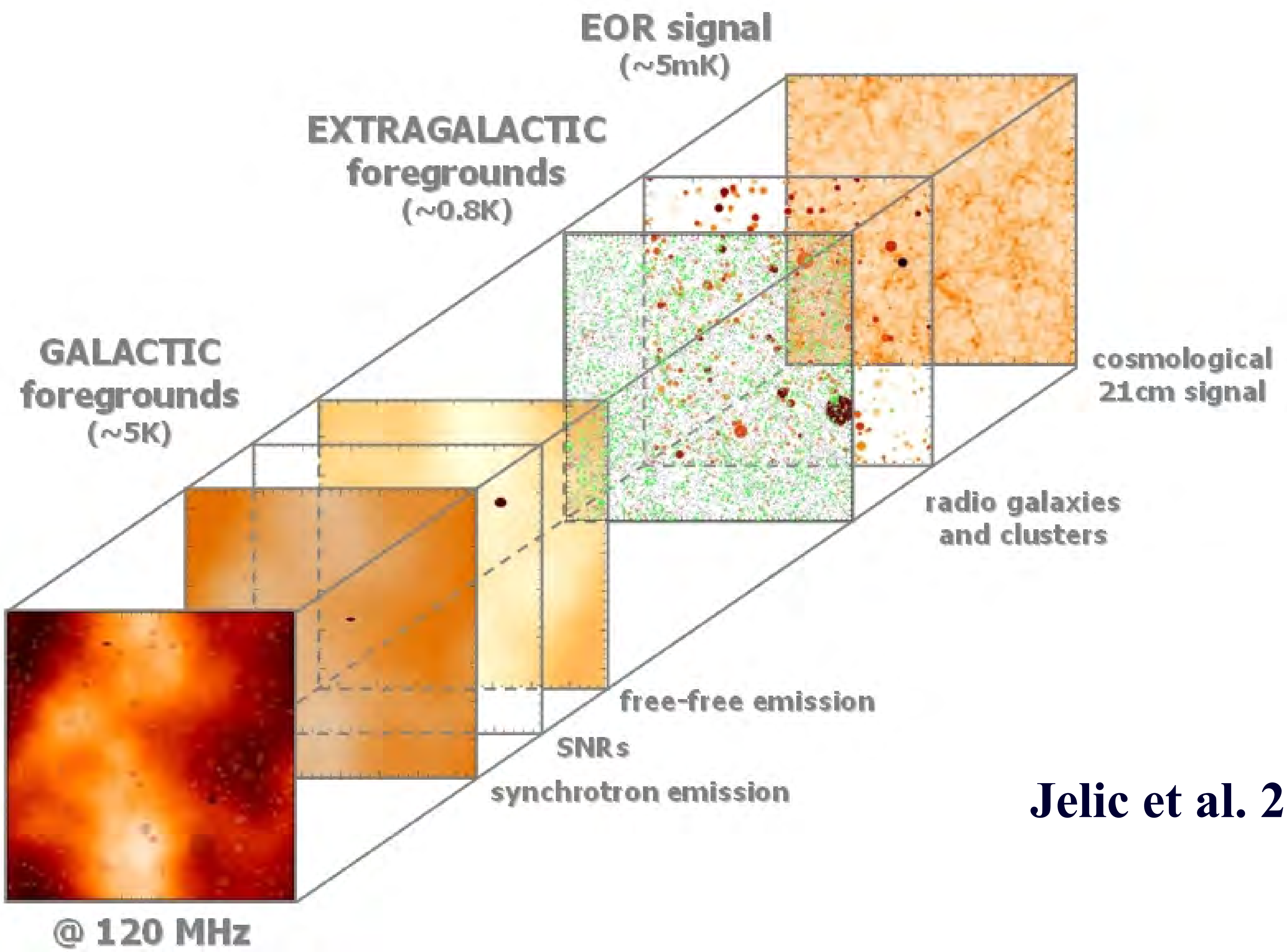
Evolution of signal means dynamic range requirements ~1:100,000 similar between z=6 and z=20

1 mK sensitivity at 1 arcmin scale enough to probe full range

Pritchard & Loeb 2008

Foreground removal

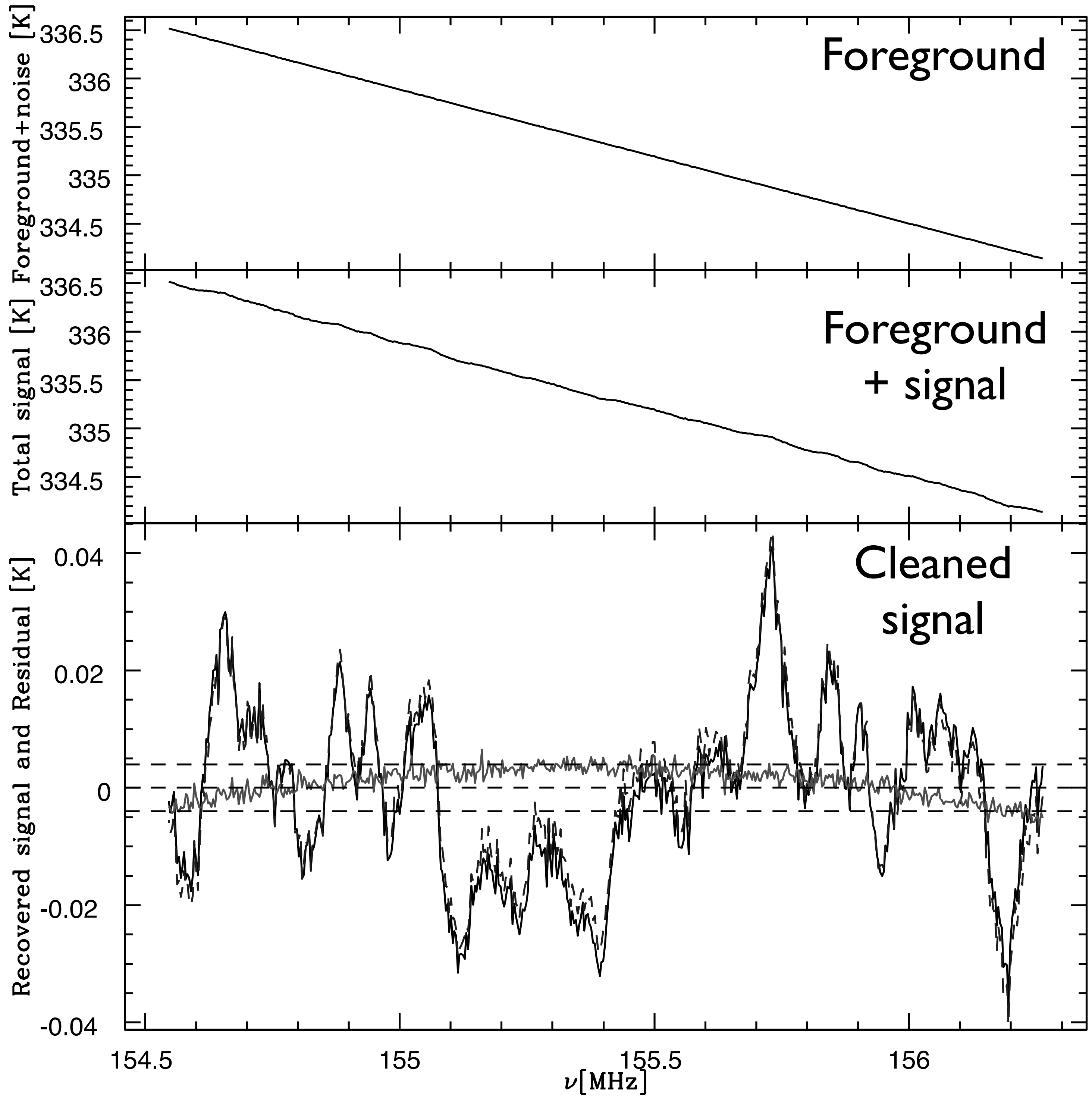
Foregrounds ~ 10^3-10^5 signal



Jelic et al. 2008

Diffuse foregrounds

Diffuse foregrounds readily removed if spectrally smooth
e.g. galactic synchrotron emission



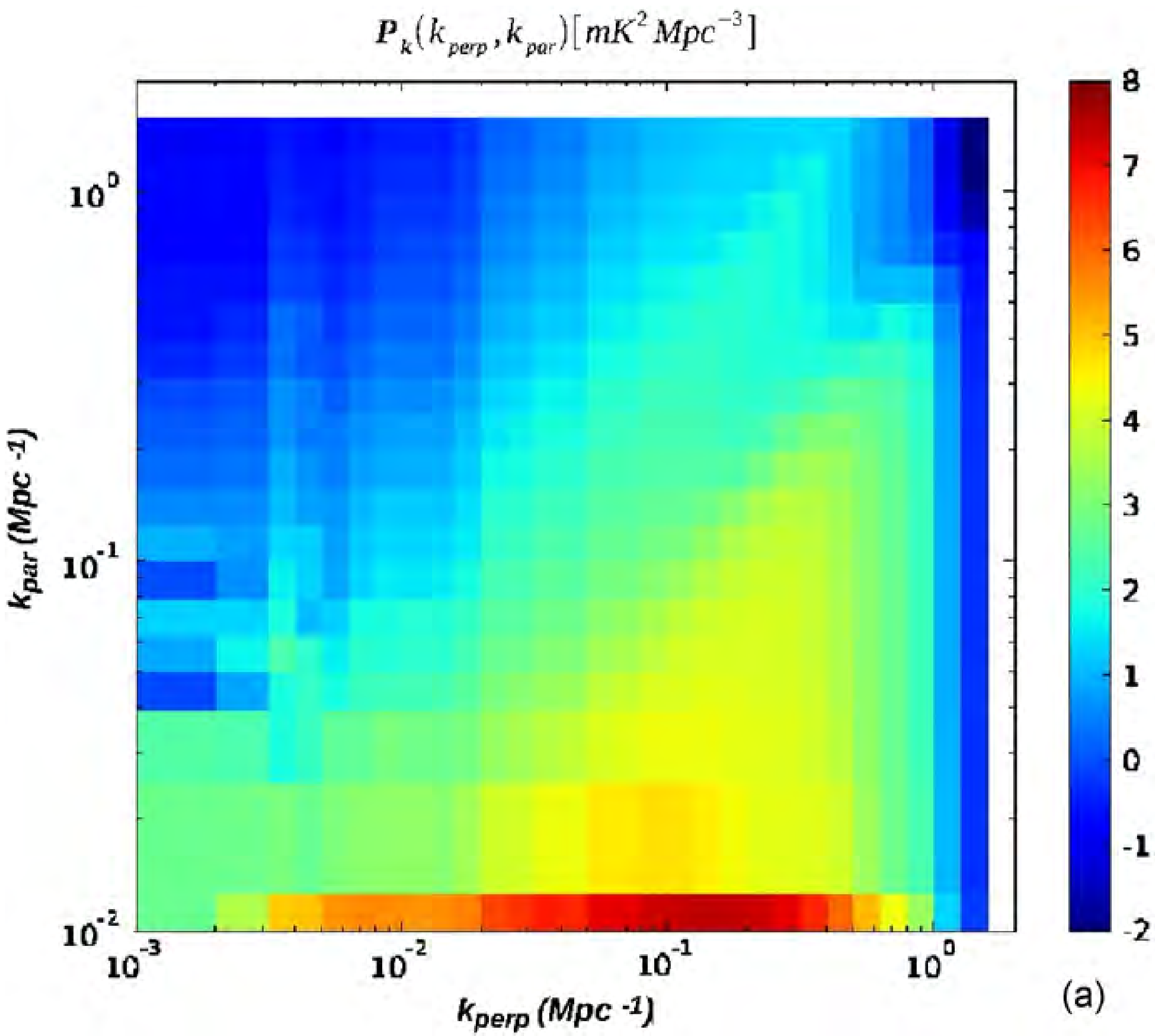
Wang+ 2006

Point source subtraction/ionosphere

Confusion floor from point source removal needs to be below sensitivity

Point source modeling of extended e.g. double lobe sources maybe important

Ionospheric corrections across field of view ~10" across 5 deg field



Point source localisation errors at 1" Datta+ 2010

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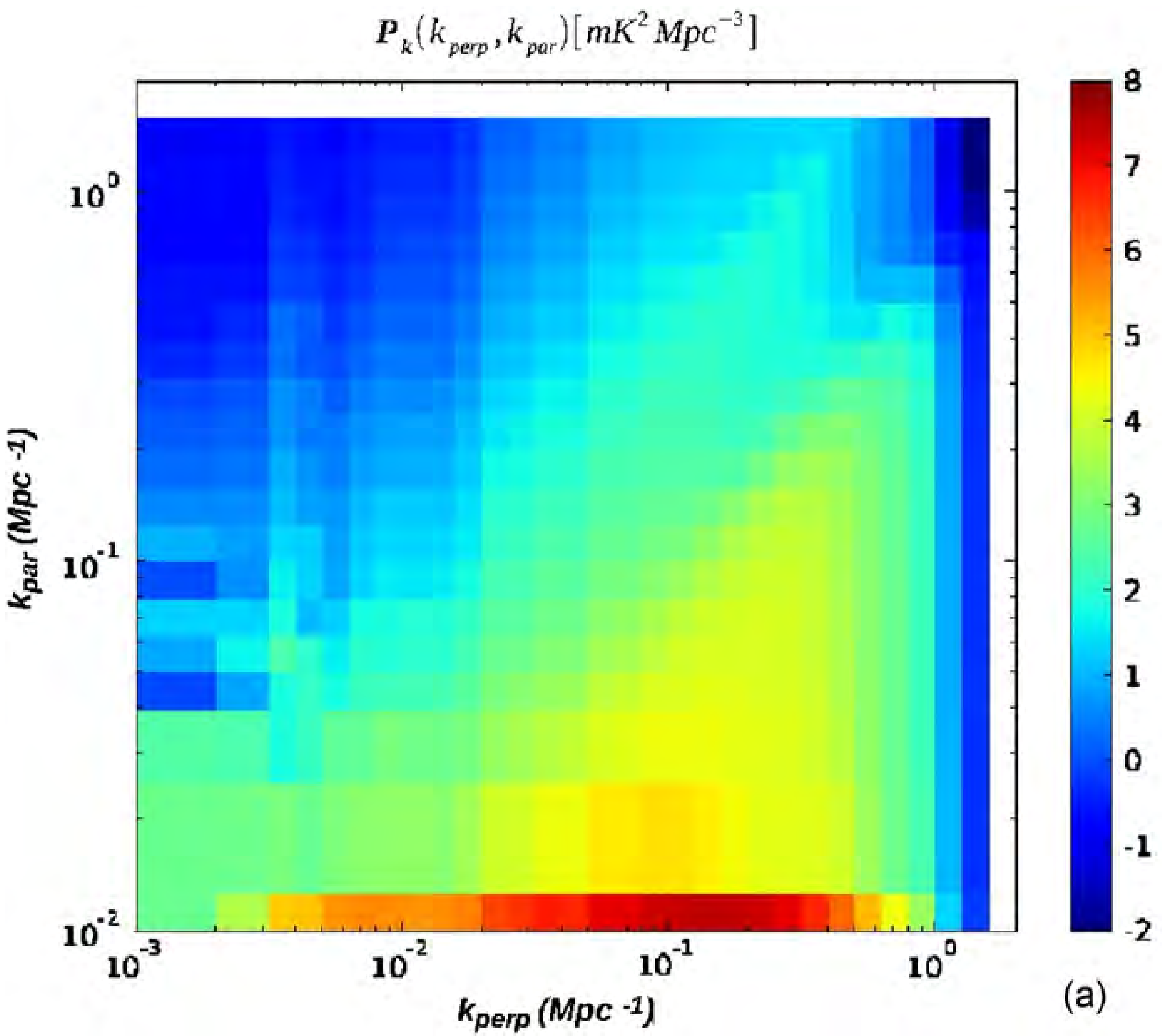


Point source localisation errors at 1” Datta+ 2010

Tech. 3: Outer baselines >5km (maybe as long as 50km)

21 cm pathfinders

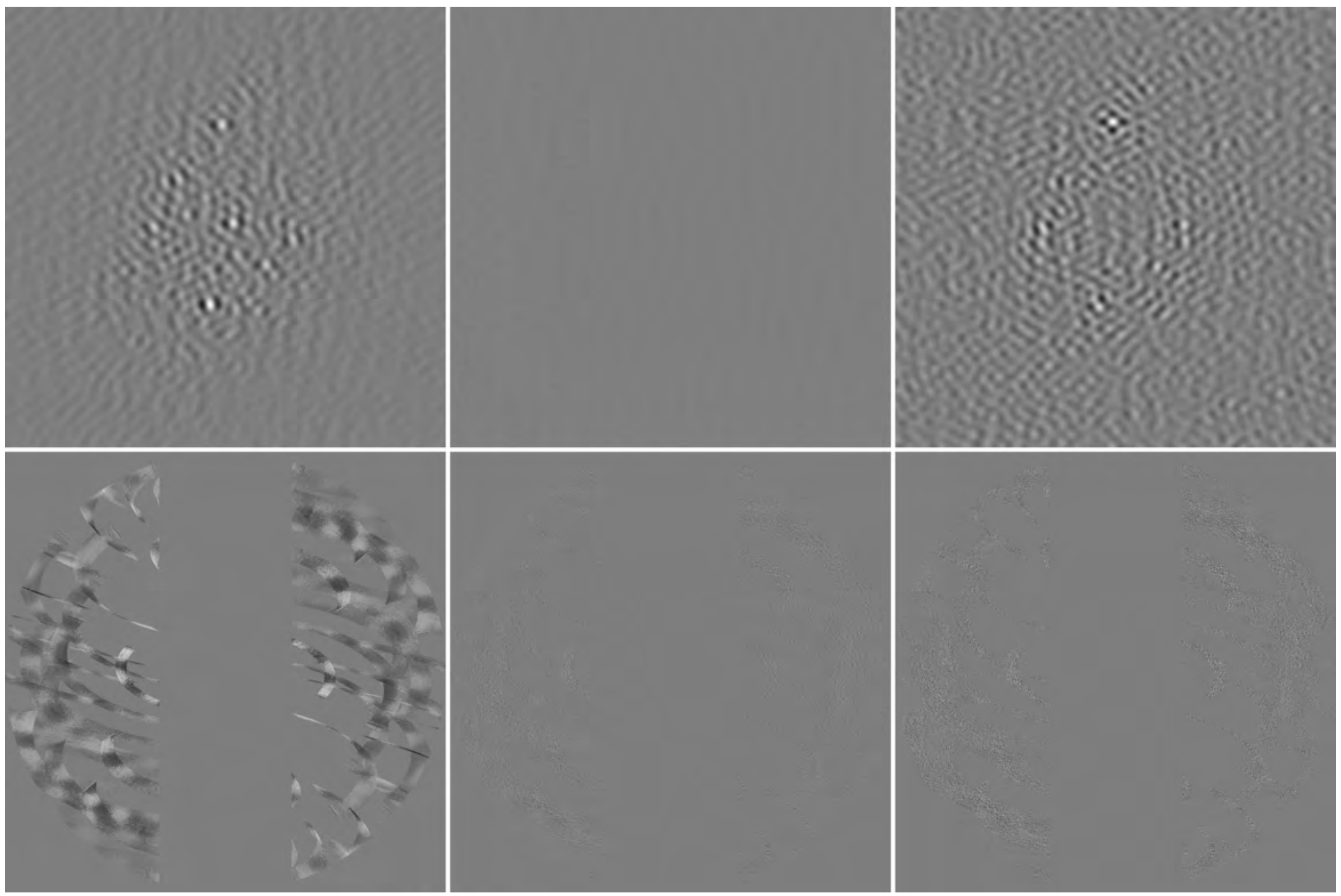
Several interferometers taking data to probe reionization ($z<12$)

GMRT

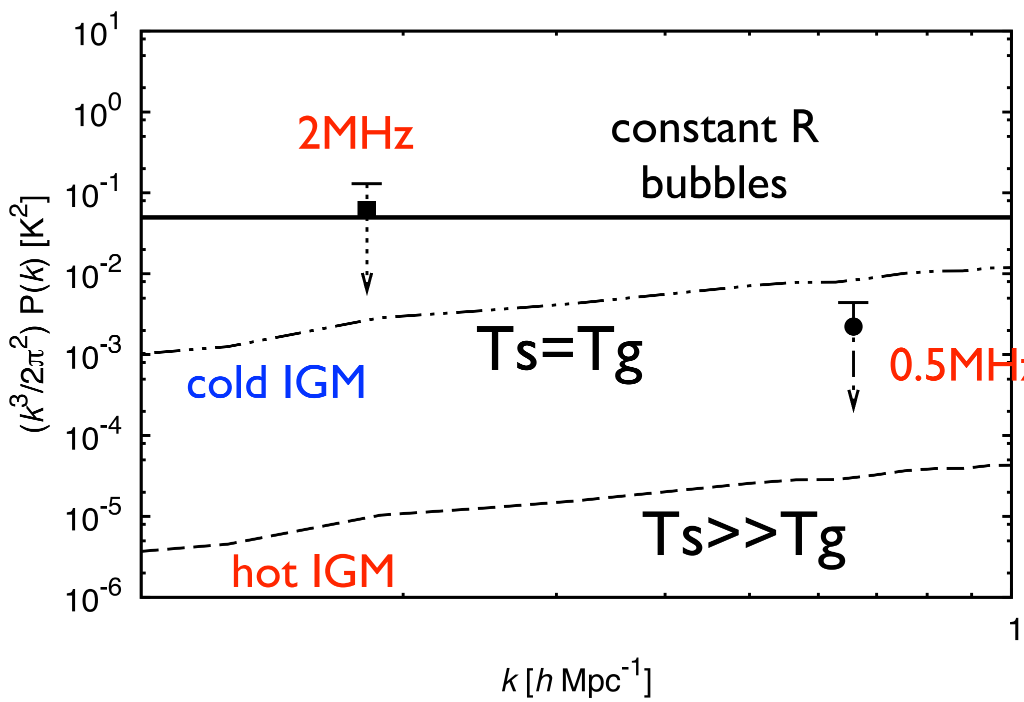
Sky map

Sky map
- foregrounds

Sky map-foregrounds
zoom



Upper limits
on power spectrum of
cold IGM



50 hours integration
~50 mK uncertainties

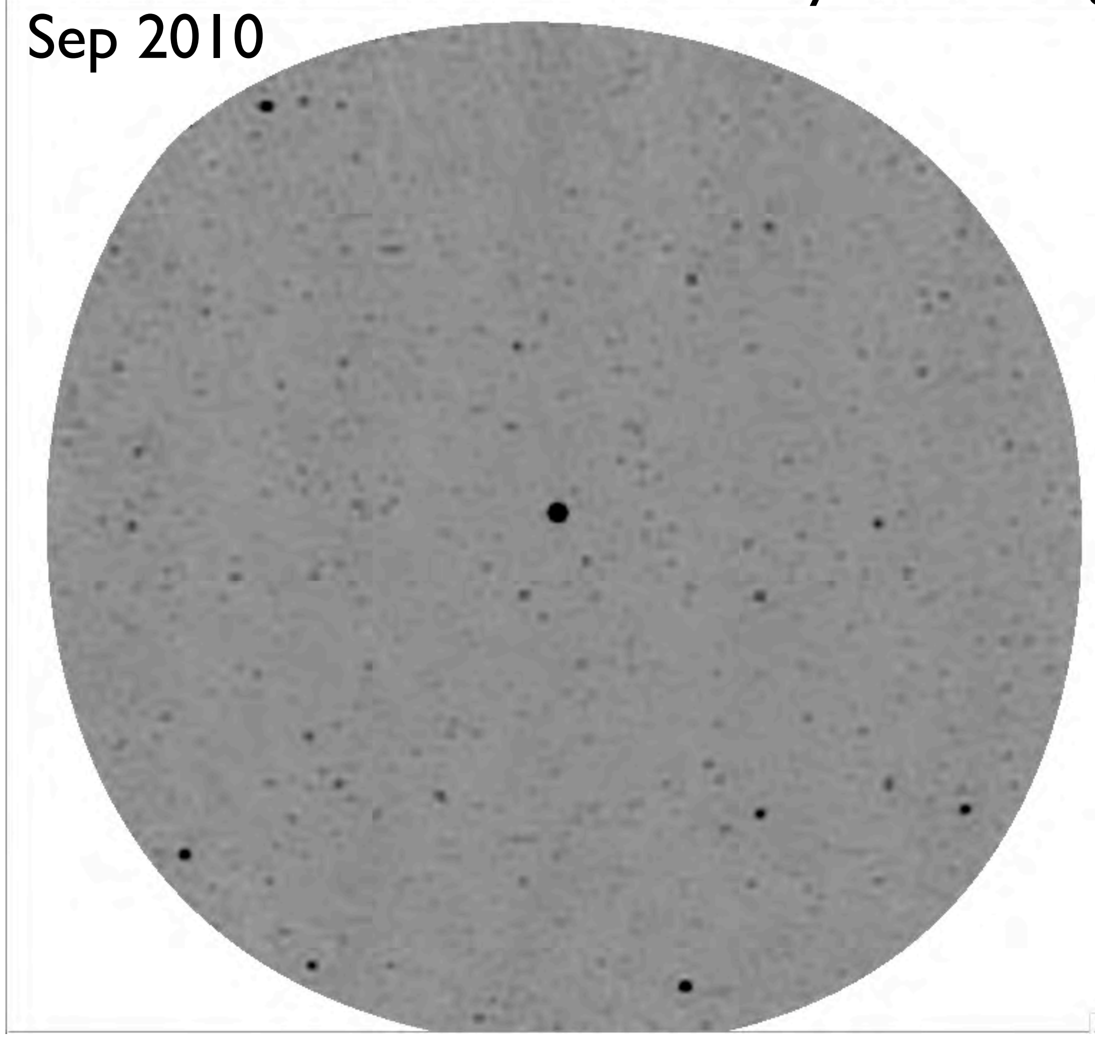
Data of the required sensitivity acquired with GMRT
=> first serious limits on 21 cm signal at z~8.5

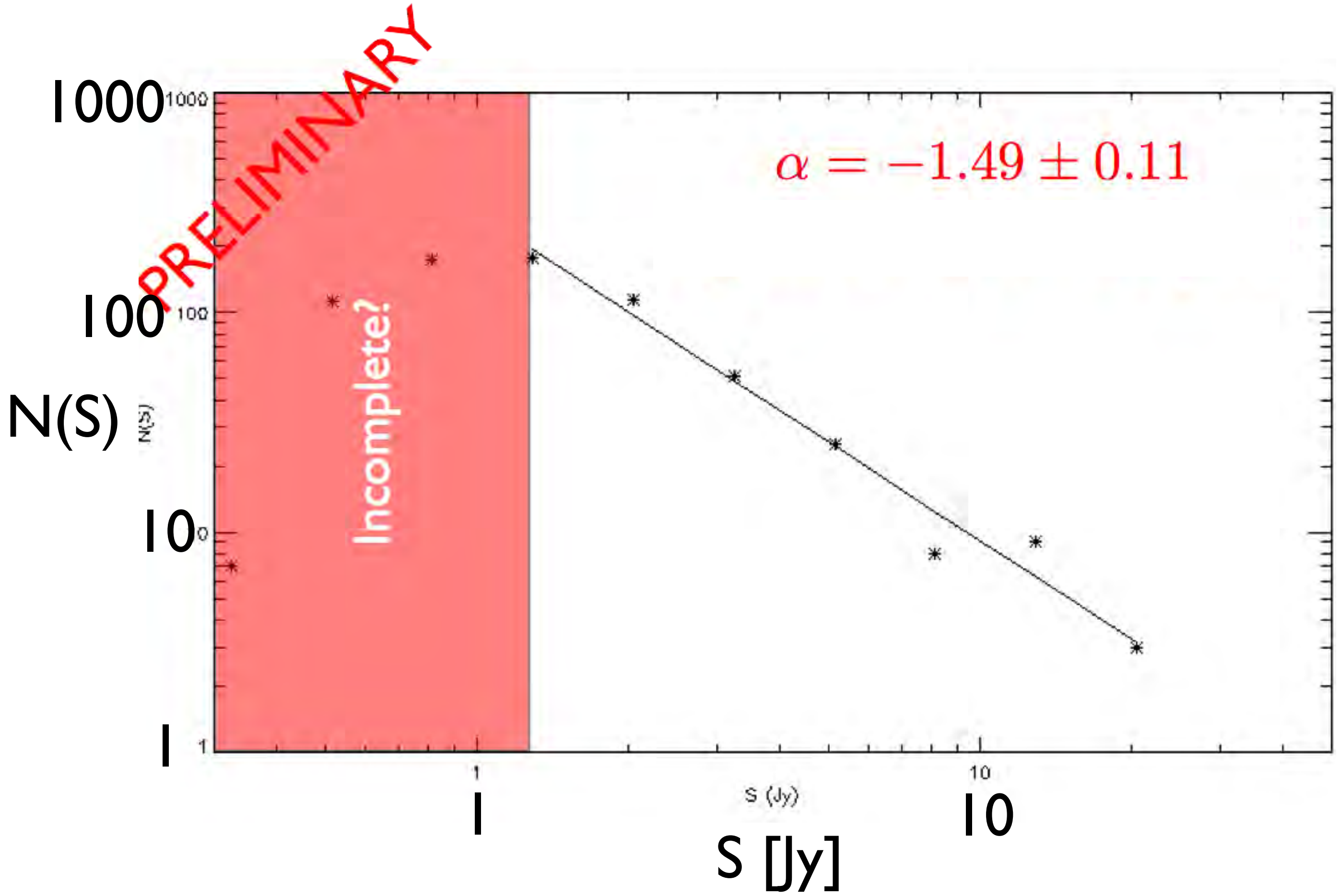
Paciga+ 2010

MWA

Hydra A
121 MHz
Sep 2010

Confusion limited maps
7000:1 dynamic range



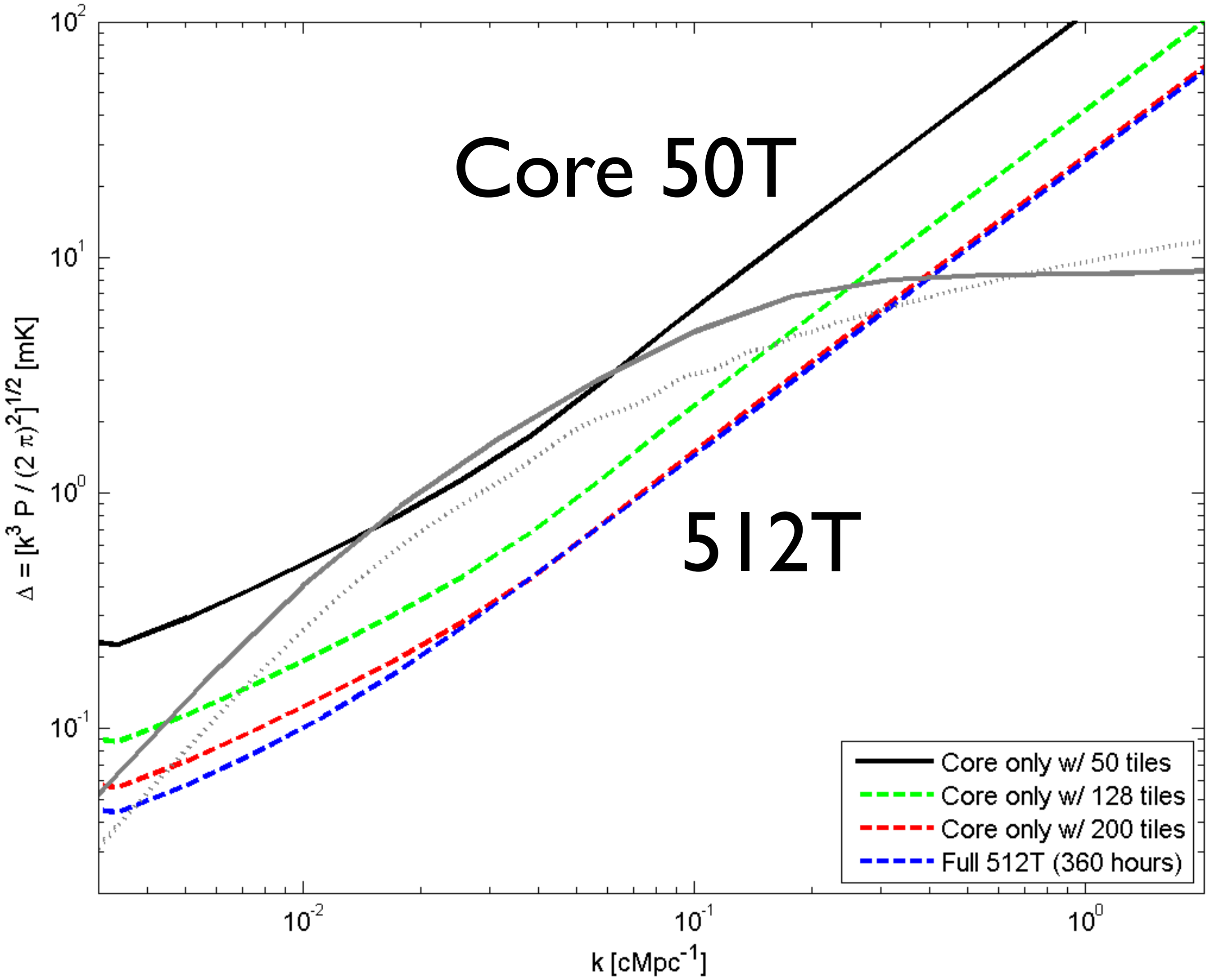


Chris Williams & MWA Collaboration

MWA build out to 128T

- Funding constraints prevent build out to 512T.
  Rescoped to 128T (infrastructure allows extension to 256T)

- 128T construction to be completed Sep 2012



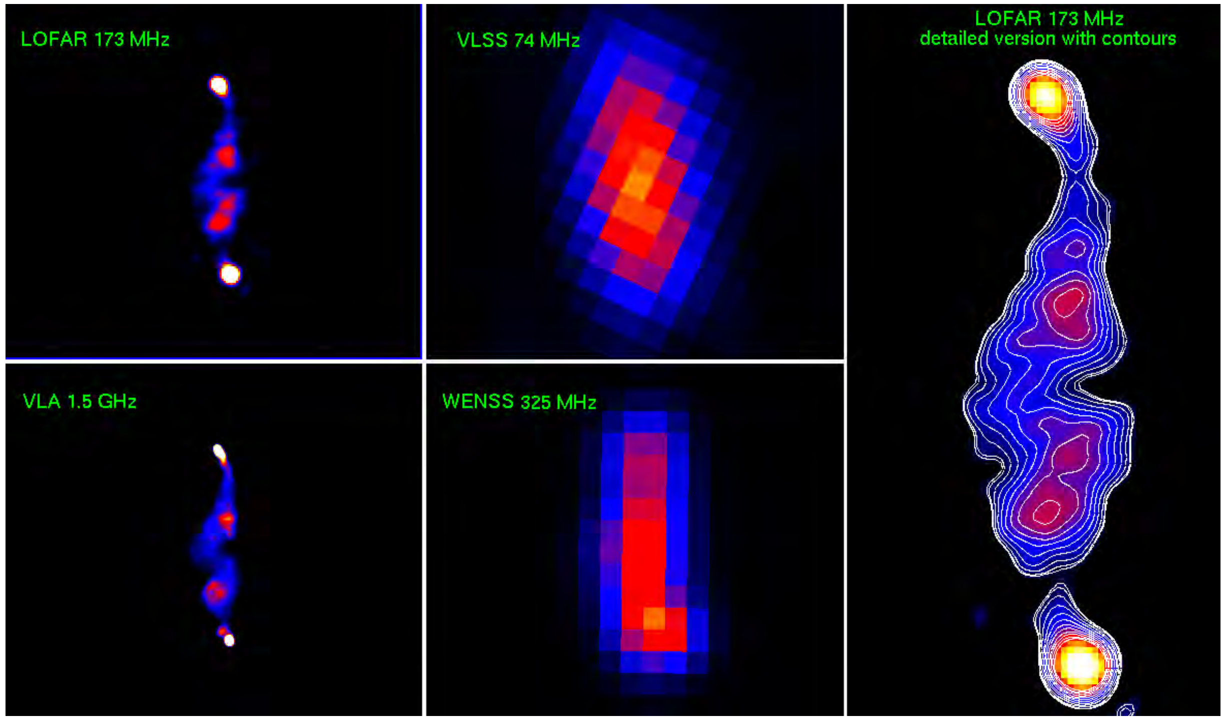
Limited ability to detect EoR. Strong constraints.

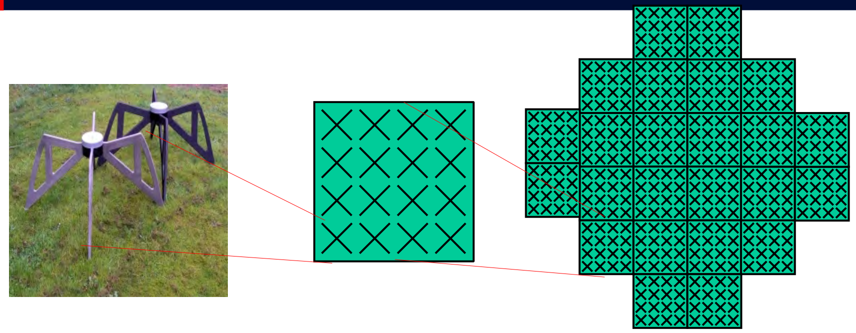
Test bed for large N, small D concept

Lots of other science...

J. Bowman & MWA collaboration

LOFAR





Core	2 km	23+ stations
NL	80 km	18+ stations
Europe	>1000 km	8+ stations

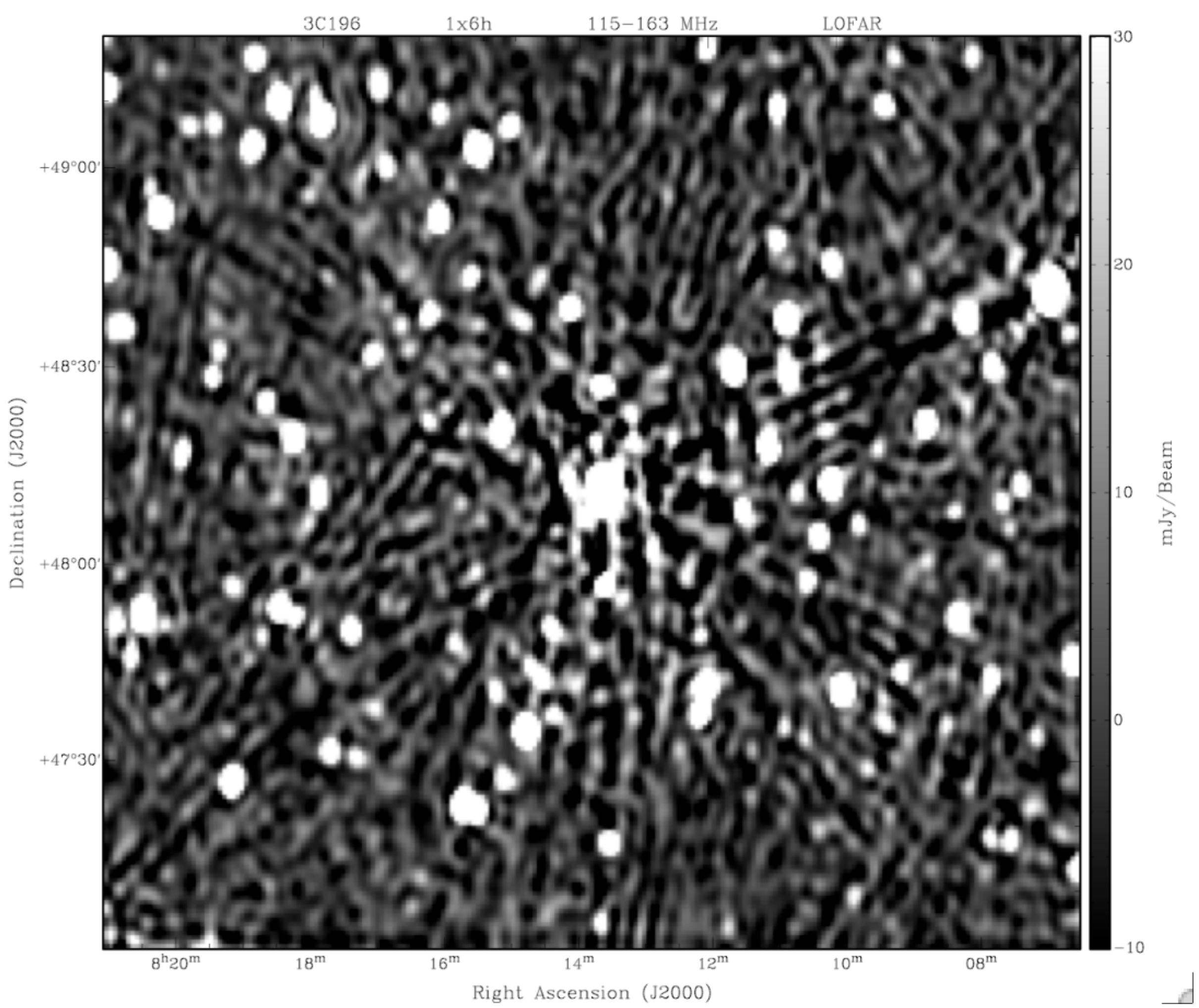
Total # of HBA dipoles: ~ 50000.

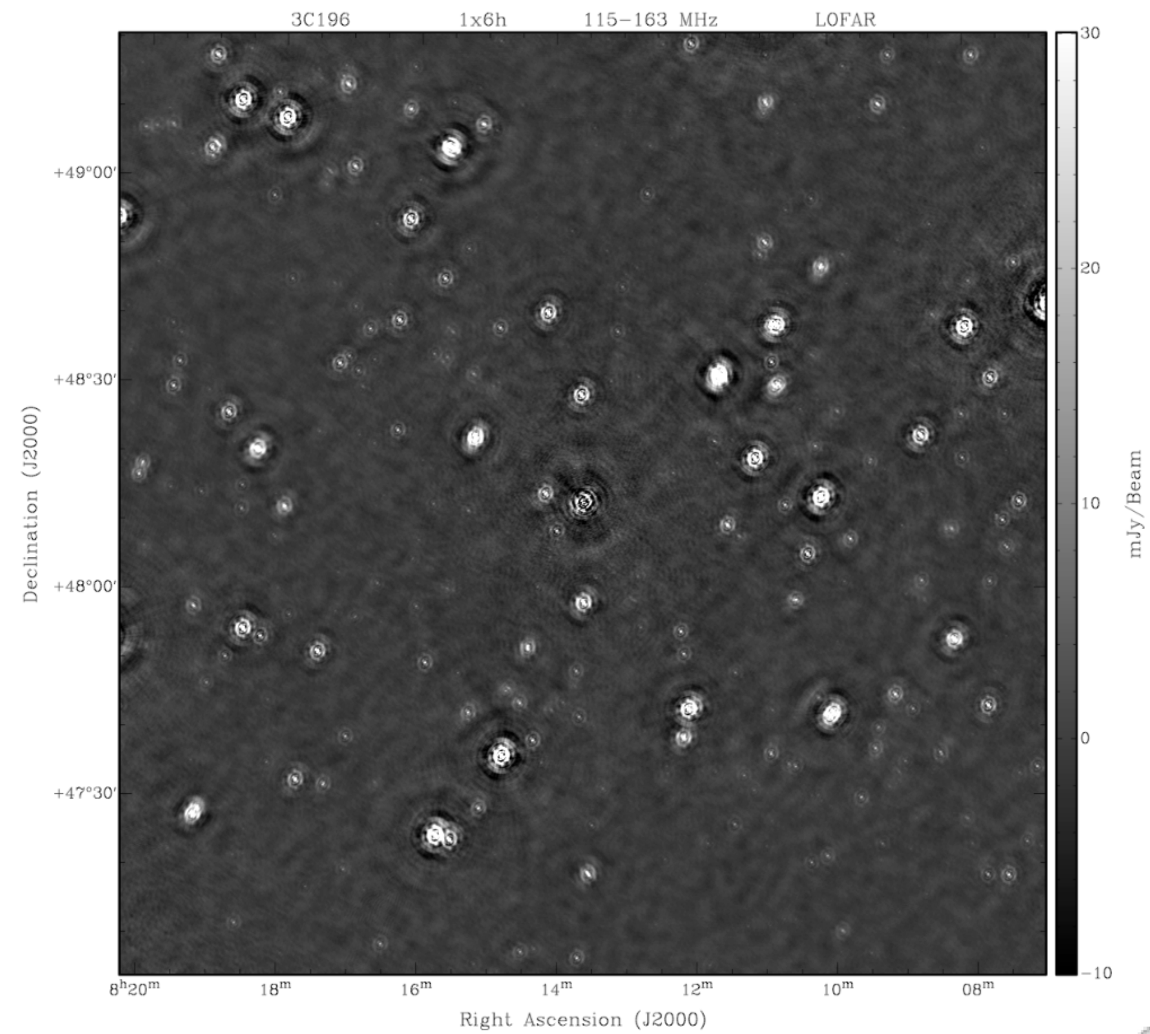
Timeline:
1. Official opening: June 2010
2. Data for our project starts: Jan. 2011
3. First results (hopefully) mid 2012

Slide from S. Zaroubi

LOFAR images

3C196: WSRT versus LOFAR 115-163 MHz





LOFAR **6h** thermal noise ~ 0.1 mJy
image noise ~ 0.3-0.7 mJy
CS +RS, ~ 30 km ! 244 subbands
DR ~ 83 Jy/0.5 mJy ~ 200,000:1 average

(300.000:1 edges, 180.000:1 close to brightest sources)

WSRT **72 h** thermal noise 0.6 mJy
confusion noise 3 mJy

Gianni Bernardi et al (2010)

Labropoulos et al., in prep.

Slide from
P. Labropoulos

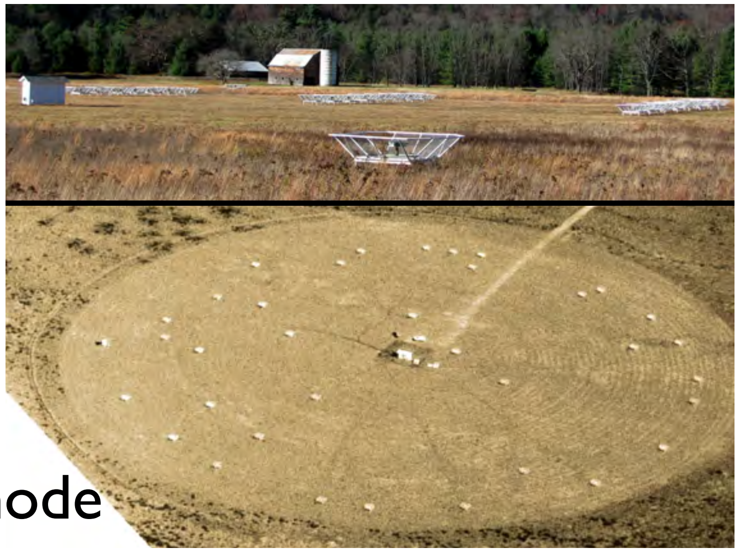
PAPER

PGB: PAPER Green Bank

- PGB-4: 2004
- PGB-8: 2006
- PGB-16: 2008
- PGB-32: 2010

PSA: PAPER South Africa

- PSA-16: 2009
- PSA-32: 2010
- PSA-64: 2011
- (PSA-128: 2012)

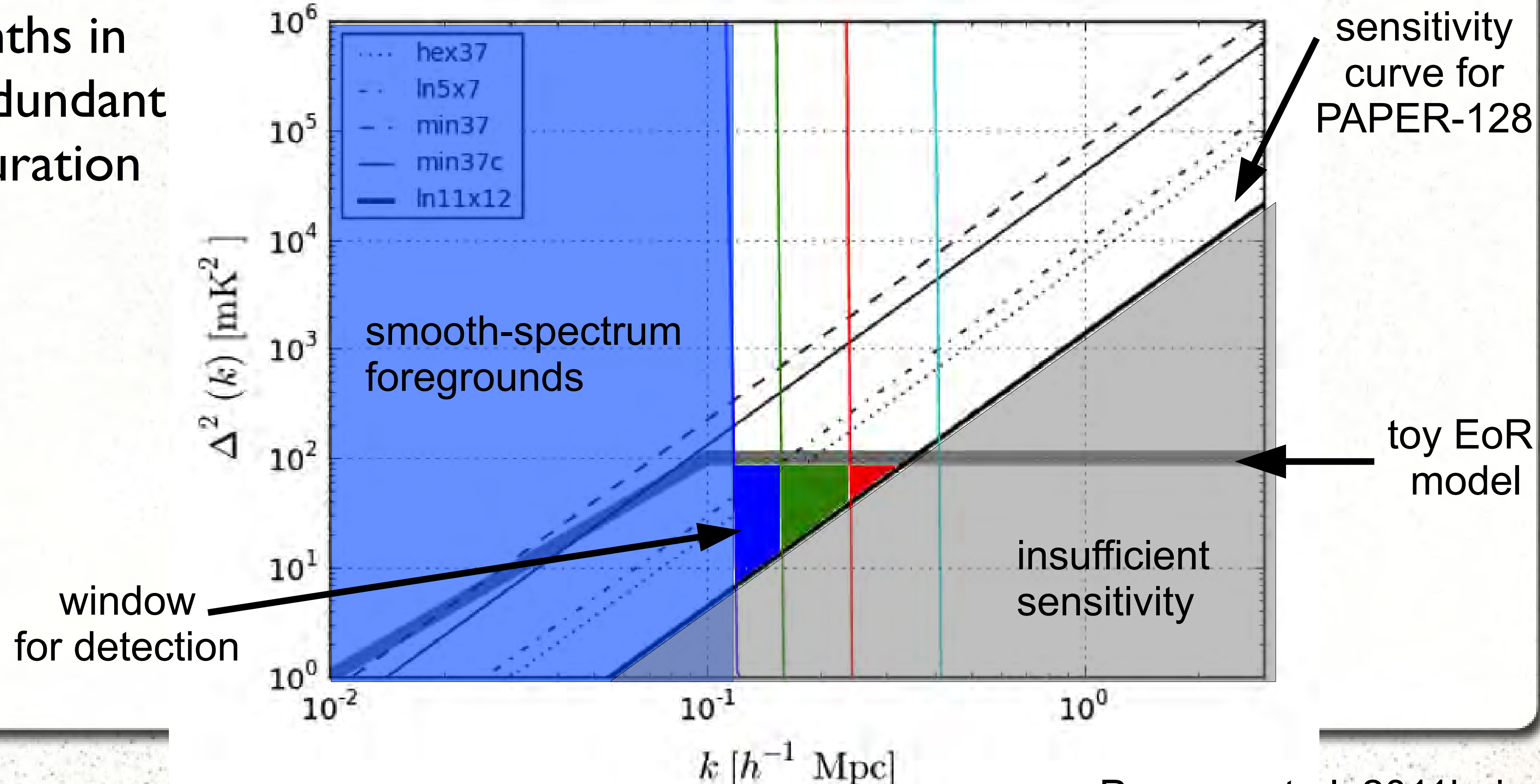


PAPER is producing maps of the radio sky in both hemispheres

Maximum redundant array to maximise sensitivity to single UV mode

4 months in max. redundant configuration

150 MHz



Redshift evolution key to proving detection

From J. Pober IoA talk

Parsons et al. 2011b, in prep

Scientific requirements for Phase 1

Track evolution of IGM through reionization to the first galaxies

SCI-S-REQ-0010: The SKA Phase 1 shall be able to observe the H I line over at least the redshift range of 6–19, with the goal of observing over the redshift range of 6–30.

Achieve S/N for power spectrum and imaging

SCI-S-REQ-0020: The SKA Phase 1 shall provide a brightness temperature noise level, typically taken as the root-mean-square value, of 1 mK on arcminute angular scales.

Resolve ionized bubbles in angle and depth

SCI-S-REQ-0030: The SKA Phase 1 shall provide an angular resolution at least as high as 1′.

SCI-S-REQ-0040: The SKA Phase 1 shall provide a radial resolution over the required frequency range for these observations of 0.1 Mpc.

Probe representative volumes of Universe

SCI-S-REQ-0050: The SKA Phase 1 shall provide a field of view large enough to mitigate cosmic variance.

Technical requirements for Phase 1

Ensure desired redshift range is covered

SCI-T-REQ-0010: The SKA Phase 1 shall provide frequency coverage of at least 70 to 200 MHz, with a goal of covering 50 to 200 MHz.

Resolve bubbles in depth direction (RFI excision...)

SCI-T-REQ-0020: The SKA Phase 1 shall provide a frequency resolution of at least as fine as 100 kHz.

Resolve bubbles in angle (longer baselines for ionospheric calibration + point source removal)

SCI-T-REQ-0030: The SKA Phase 1 shall provide a maximum baseline of at least 5 km, and potentially as large as 50 km (TBC).

Polarised foreground removal (e.g. to prevent polarisation leaking into intensity)

SCI-T-REQ-0040: The SKA Phase 1 shall provide full polarization capabilities.

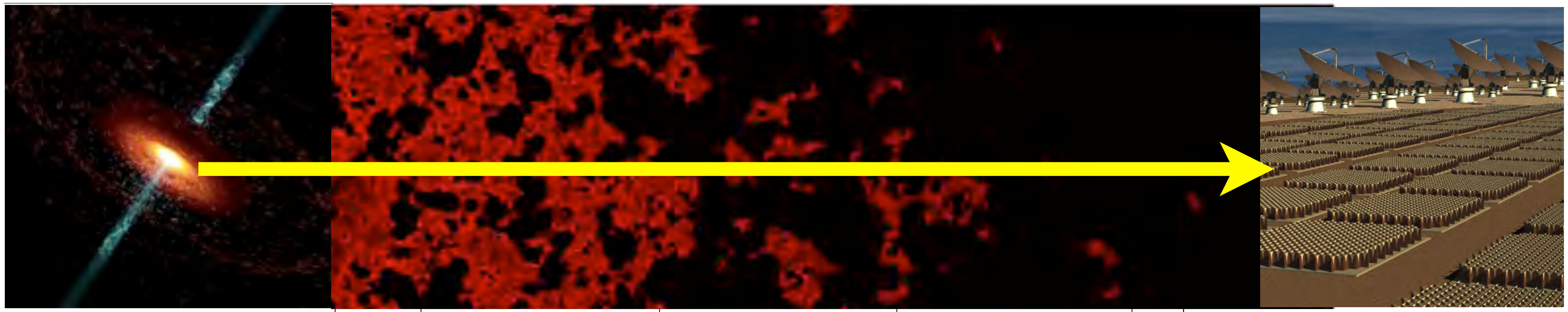
Integration time: More the better... > 1000 hrs

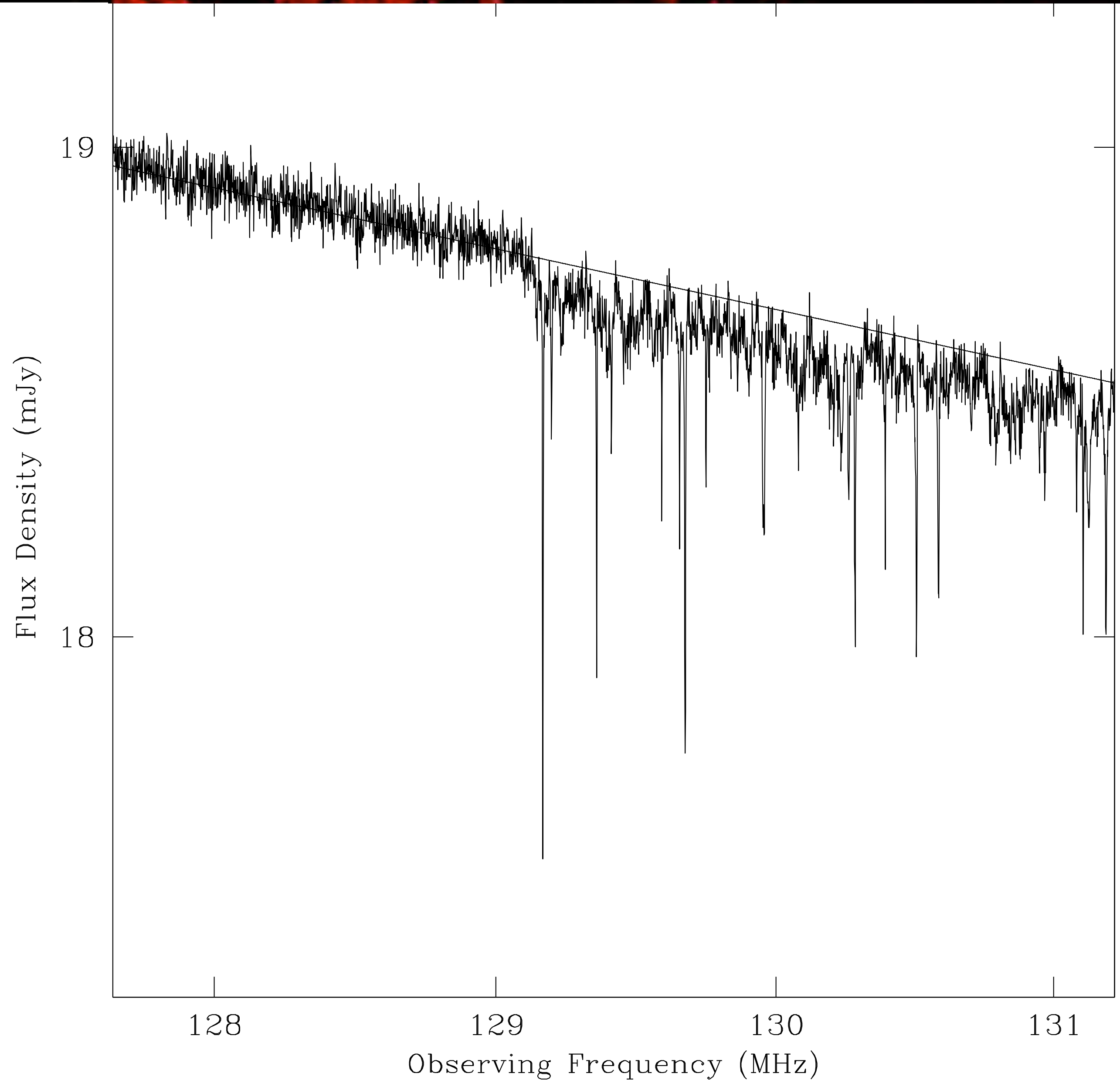
SCI-T-REQ-0050: TBD

Limit instrumental systematics to less than desired 1 mK sensitivity

SCI-T-REQ-0060: The SKA Phase 1 shall be designed so that any spatial structure within the sky area of interest that results from an instrumental contribution is much less than 1 mK on arcminute scales.

Probing the Epoch of Reionization Using the 21-cm forest





Physics of 21 cm forest

Radio bright point source as backlight => Targeted 1 dimensional skewer through IGM

Absorption by neutral hydrogen => flux decrement

Foregrounds much less of a problem - different systematics from 21 cm tomography

Size of decrement determined by optical depth
1) gas density
2) neutral fraction
3) gas temperature

$$\tau_{\nu_0}(z) \approx 0.009\underbrace{(1+\delta)}_{\text{density}}(1+z)^{3/2}\frac{\overbrace{x_{\rm HI}}^{\text{neutral fraction}}}{\underbrace{T_S}_{\text{spin temperature}}}$$

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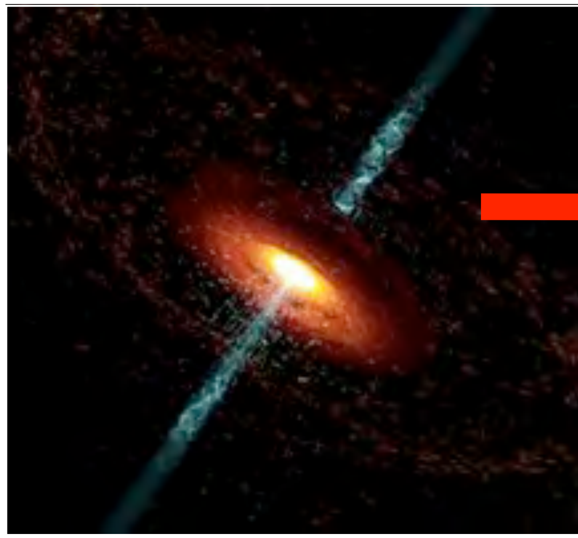
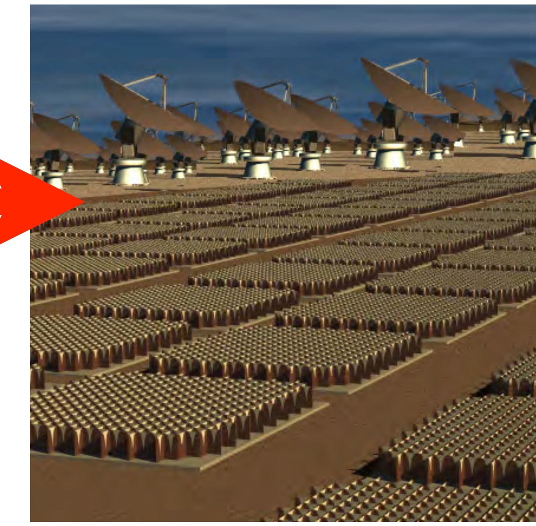
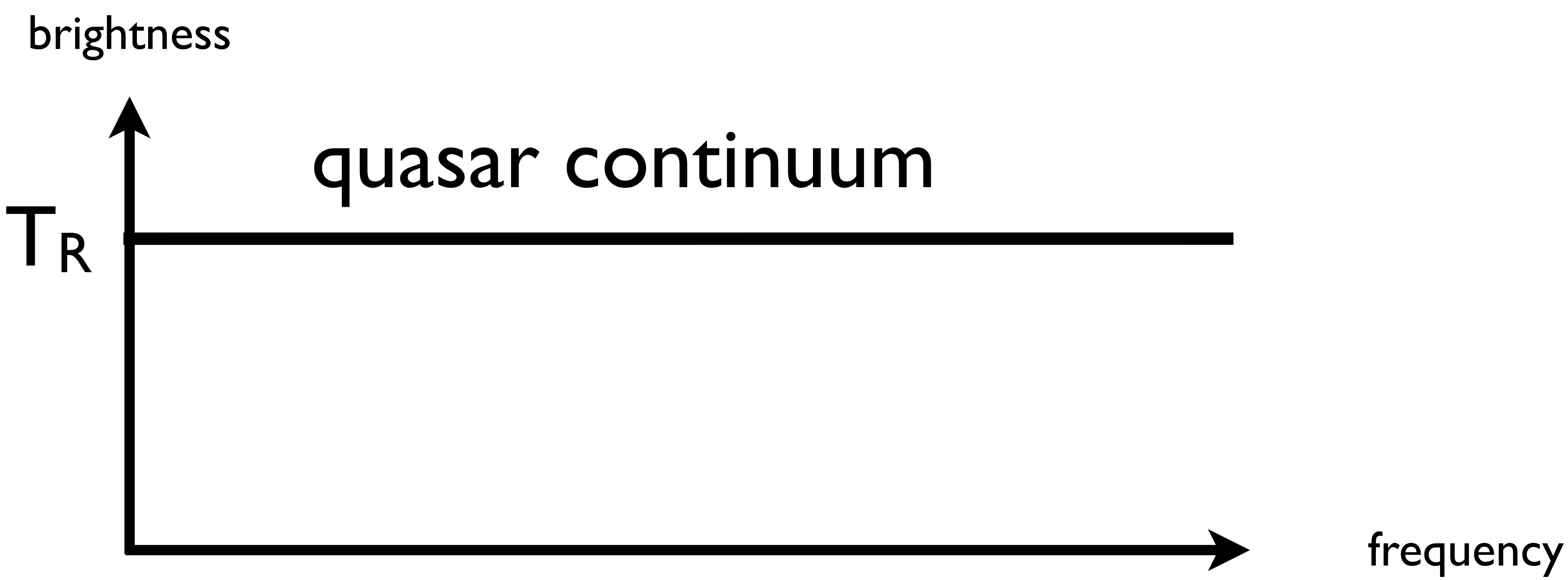
Science requirement 3: detect tau=0.001 or lower

21 cm forest

z=10

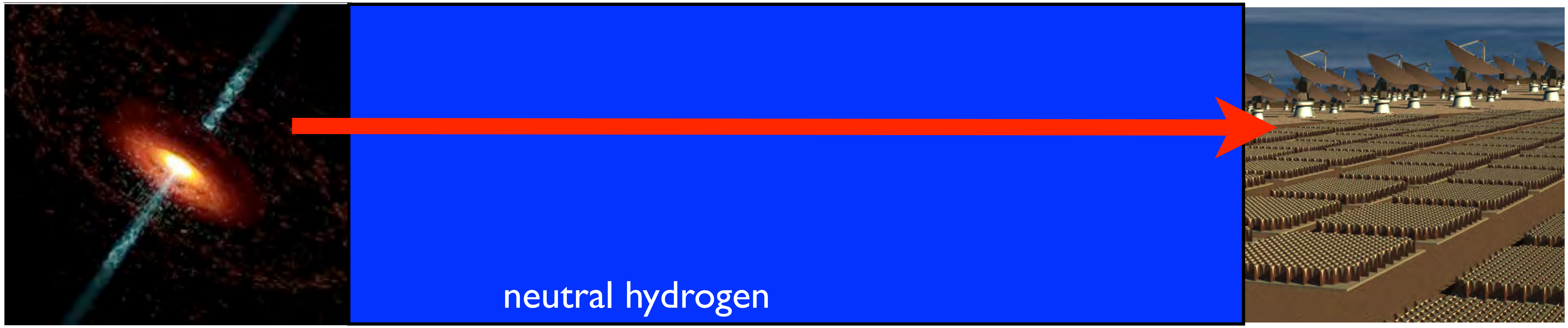






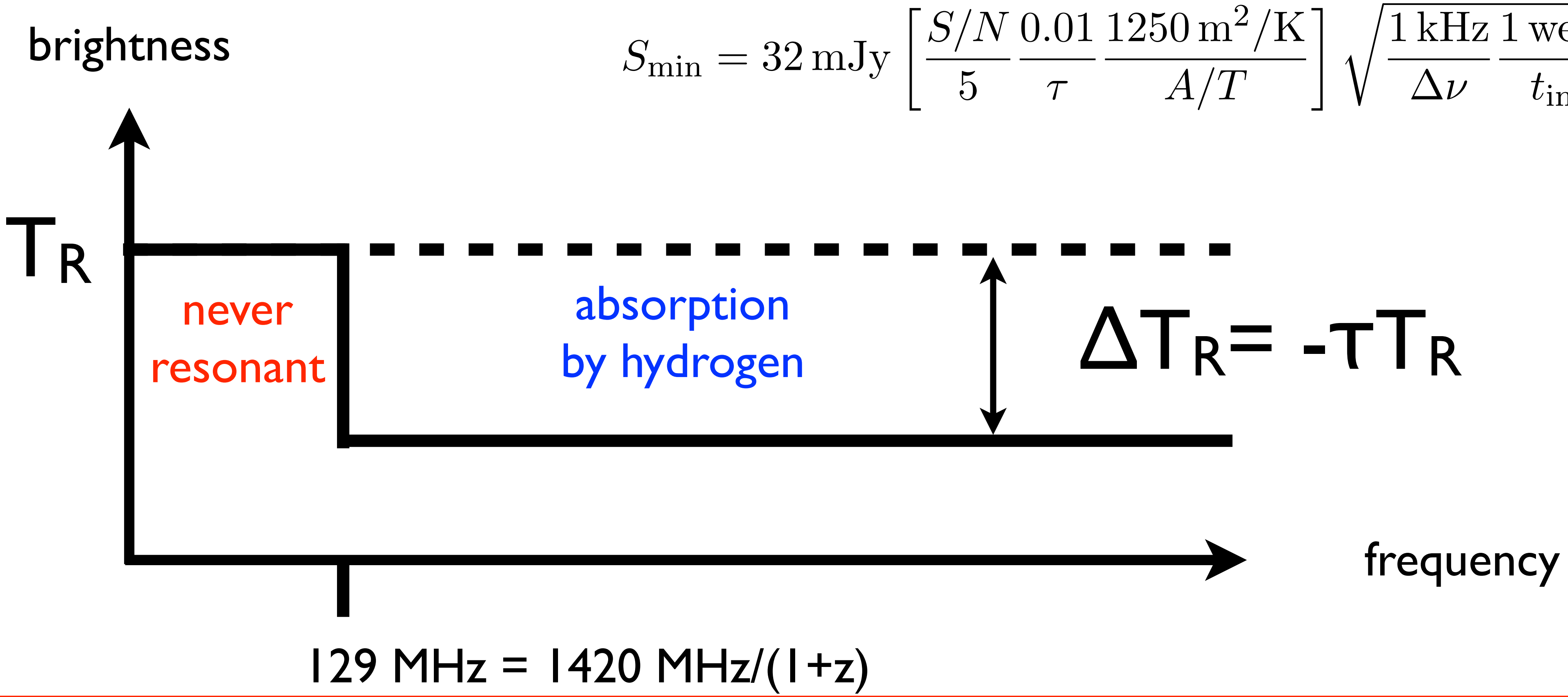
Absorption by hydrogen

z=10



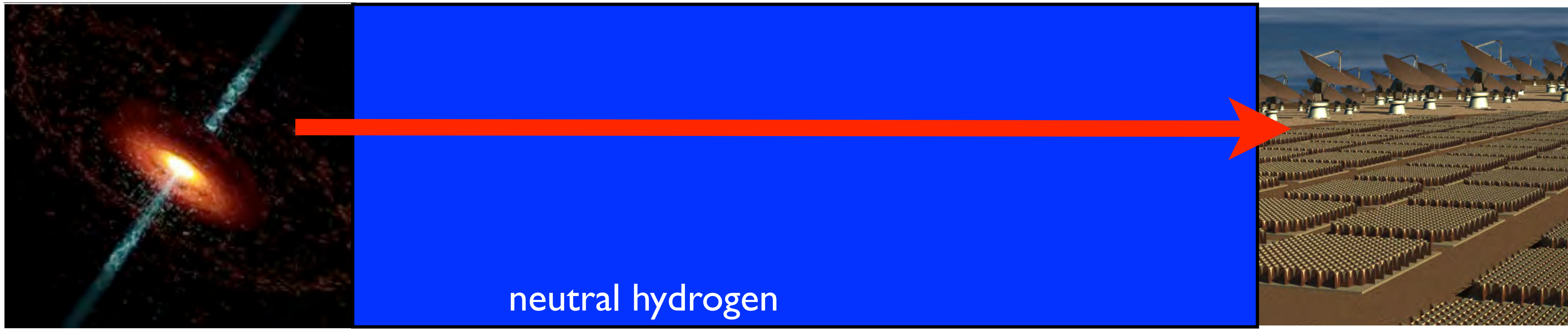
Forest easier to detect in brighter sources

$$S_{\rm min} = 32\,{\rm mJy}\left[\frac{S/N}{5}\,\frac{0.01}{\tau}\,\frac{1250\,{\rm m}^2/{\rm K}}{A/T}\right]\sqrt{\frac{1\,{\rm kHz}}{\Delta\nu}\,\frac{1\,{\rm week}}{t_{\rm int}}},$$



Absorption by hydrogen

z=10



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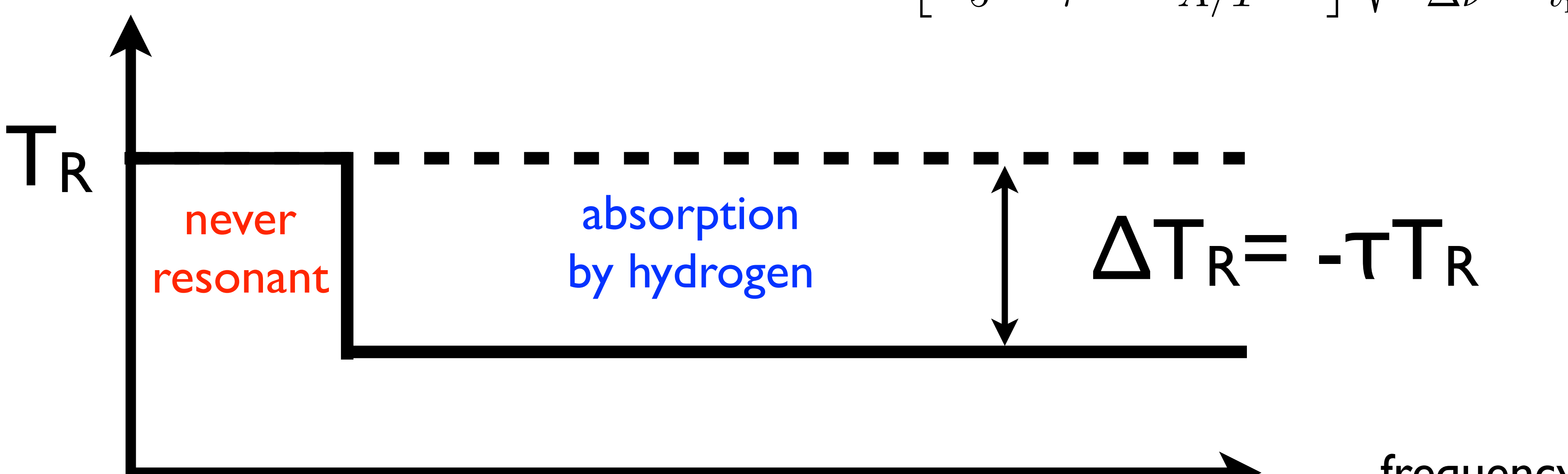
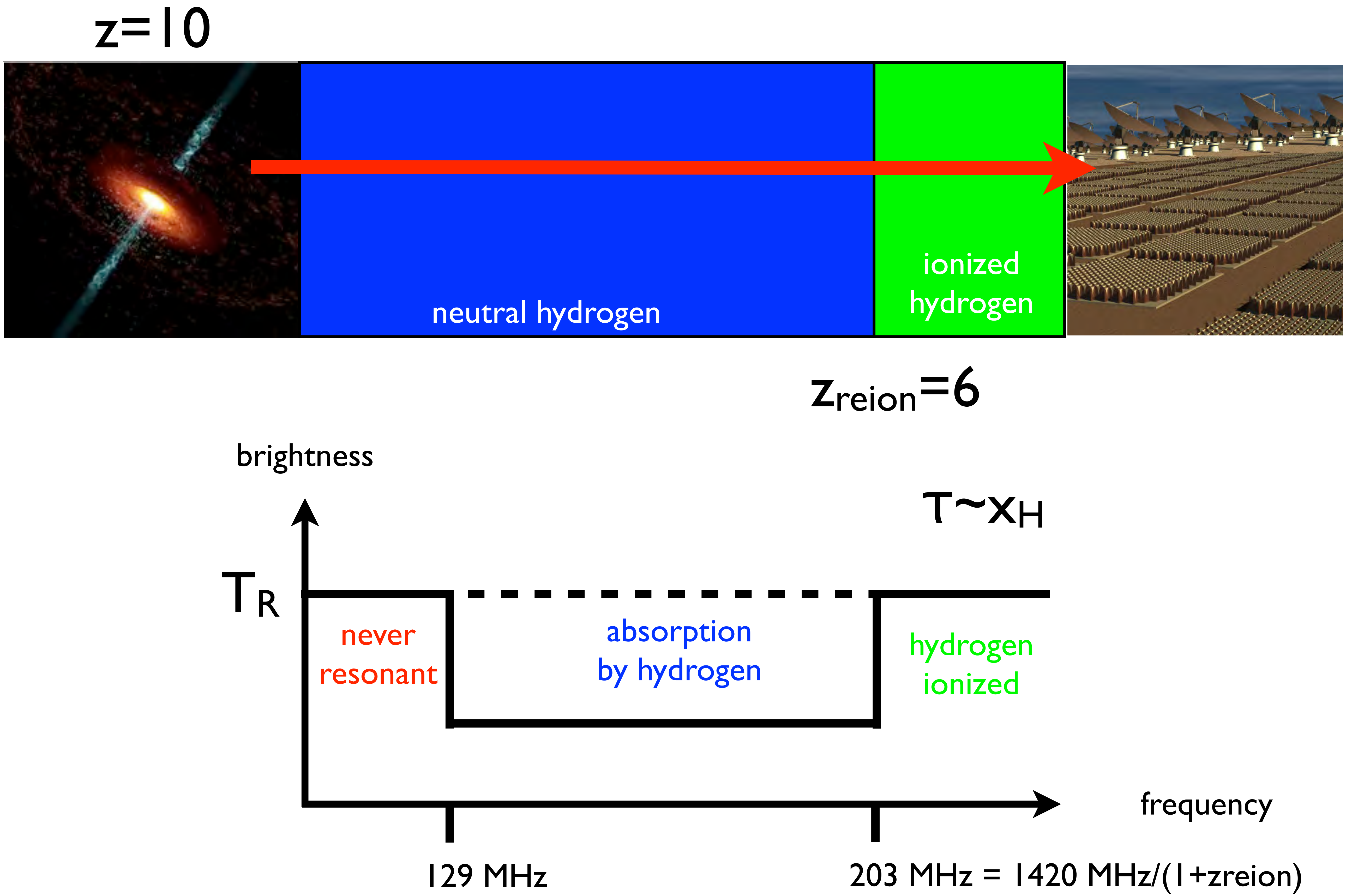


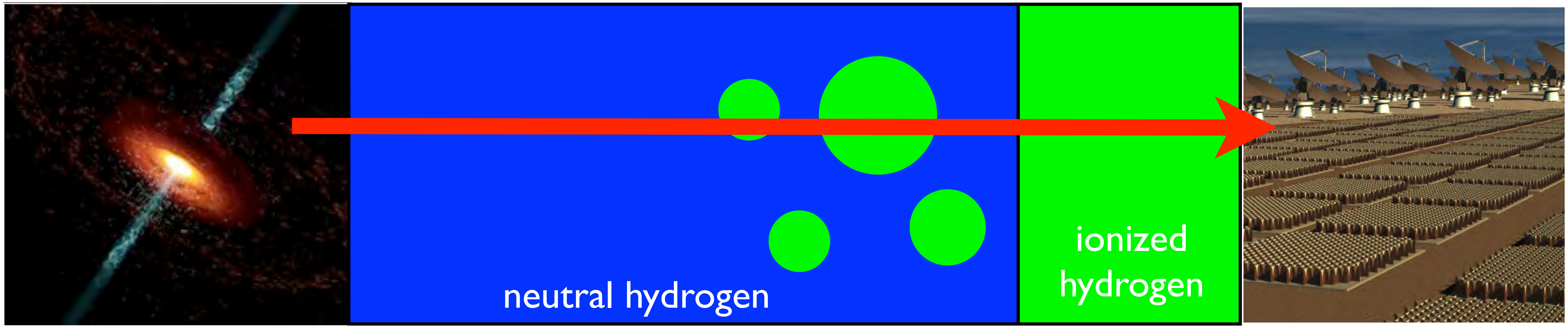
Tech requirement 3: A/T >1300 m^2/K

Reionization

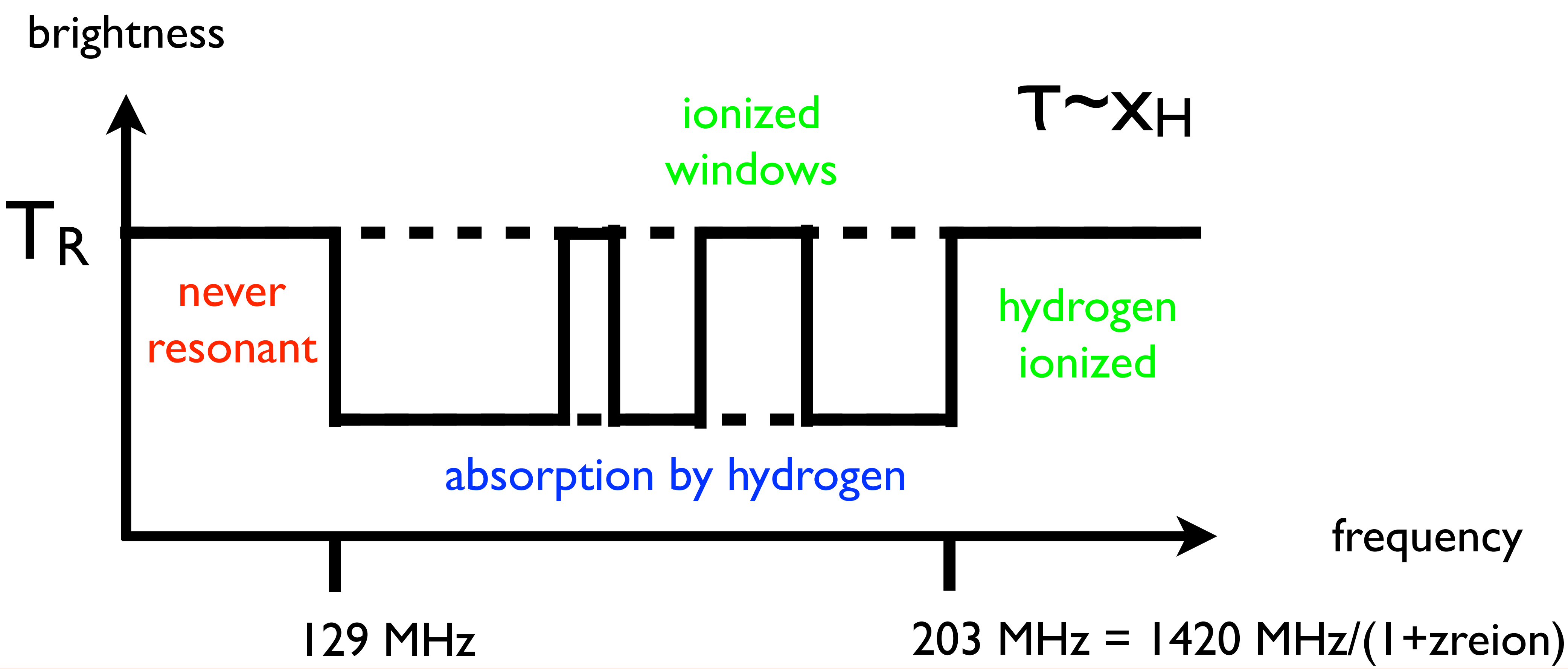


Patchy Reionization

$z=10$

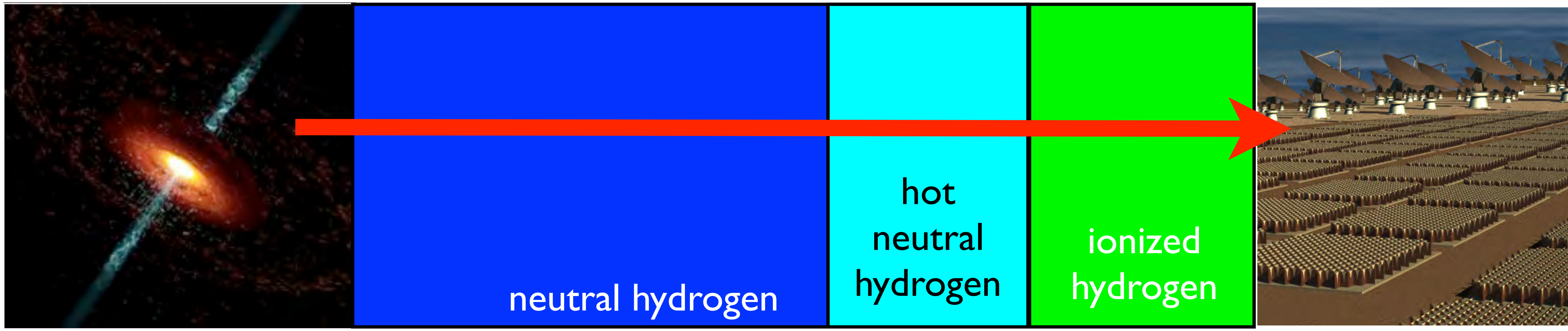


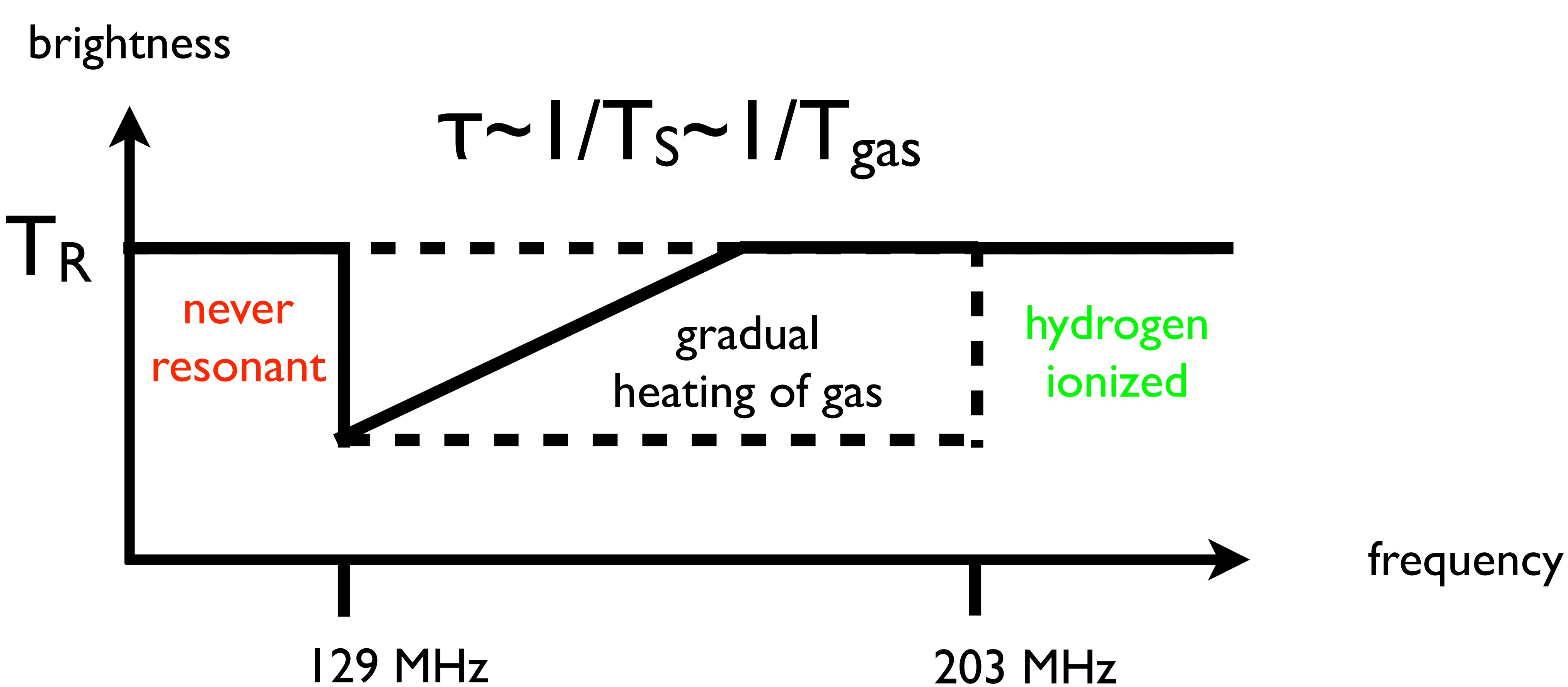
$z_{reion}=6$



Evolution of optical depth

z=10

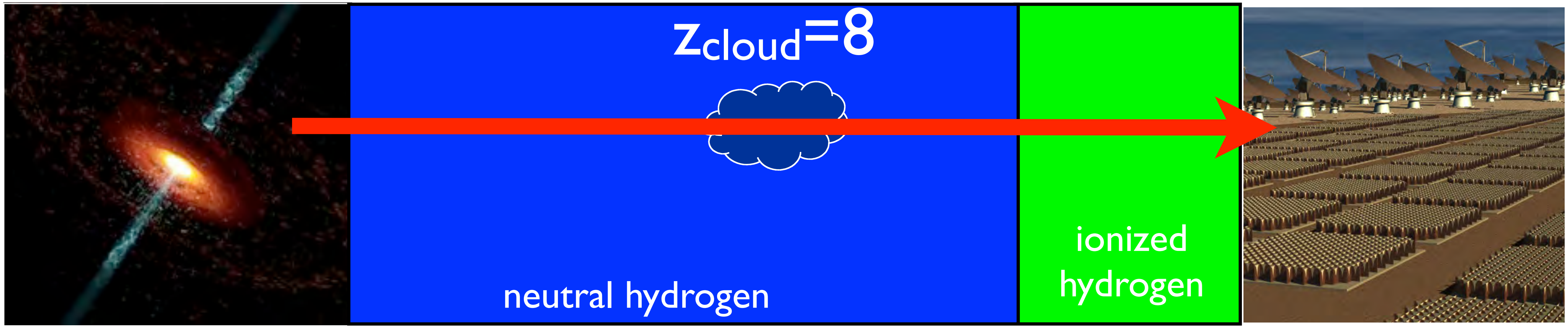




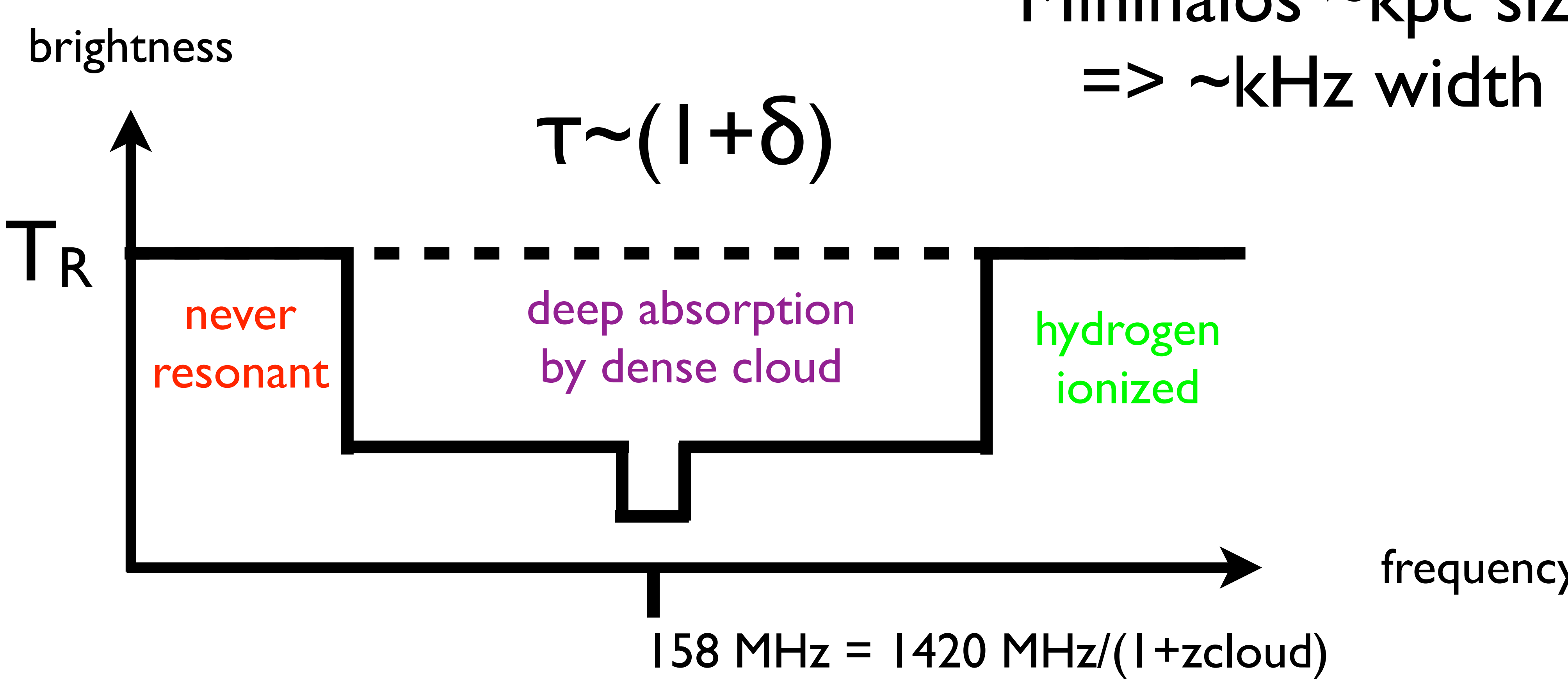
Jonathan Pritchard

Minihalos and structures

z=10

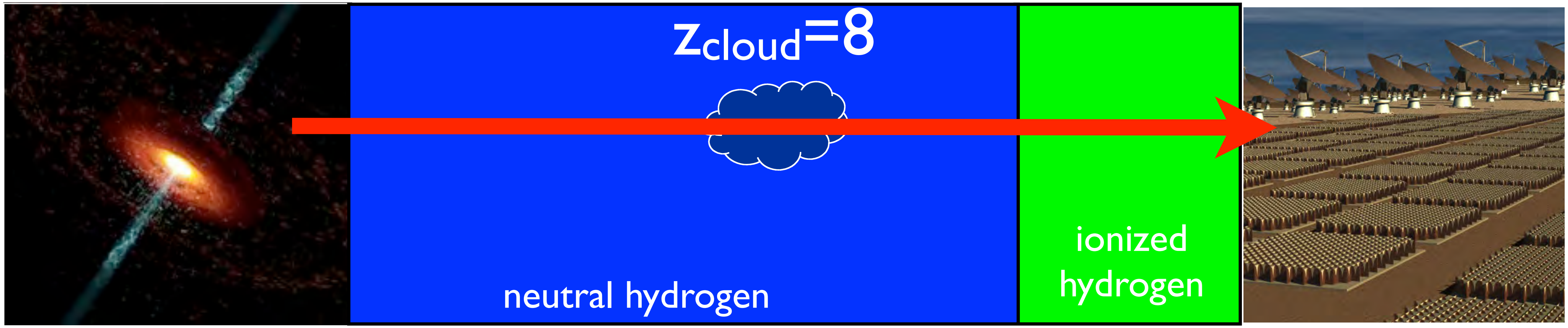


Minihalos ~kpc size
=> ~kHz width

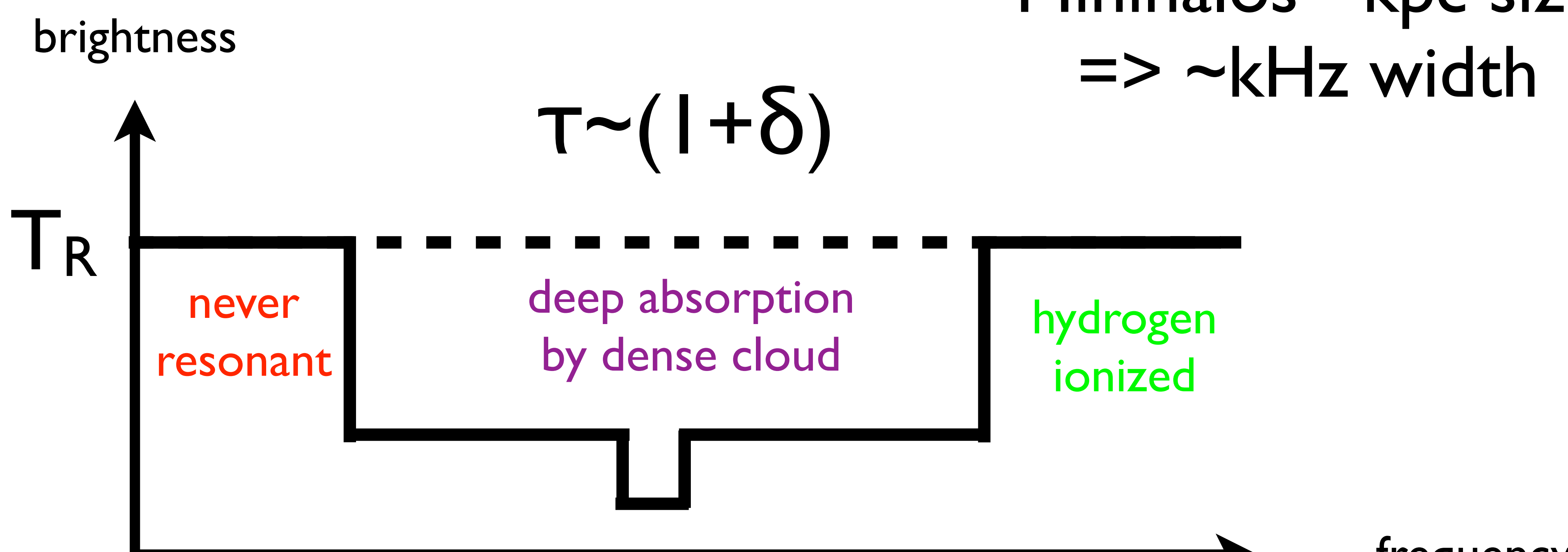


Minihalos and structures

z=10



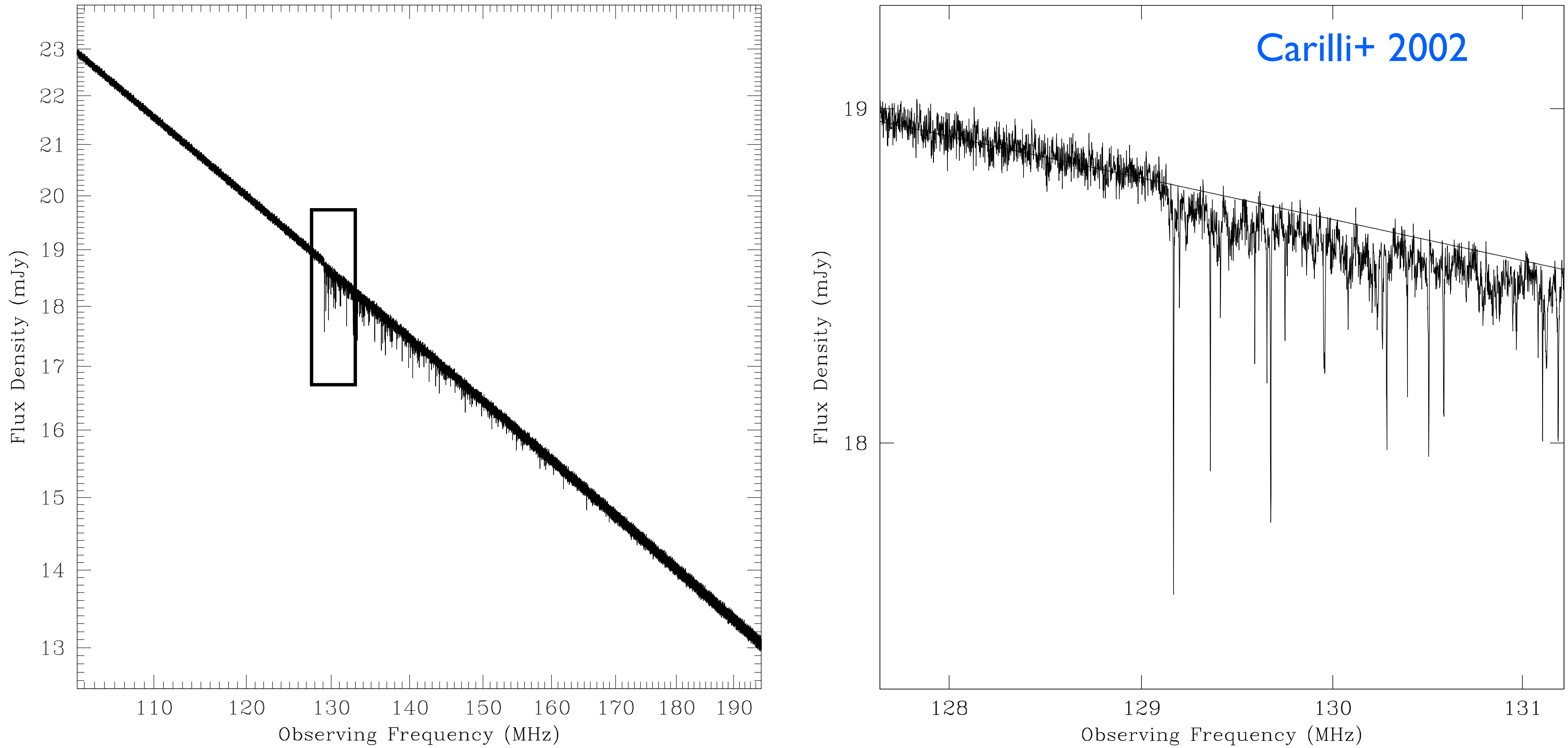
Minihalos ~kpc size
=> ~kHz width



Tech requirement 2: resolve 0.1 kHz

21cm forest simulations

Opportunity to study detailed structure of IGM



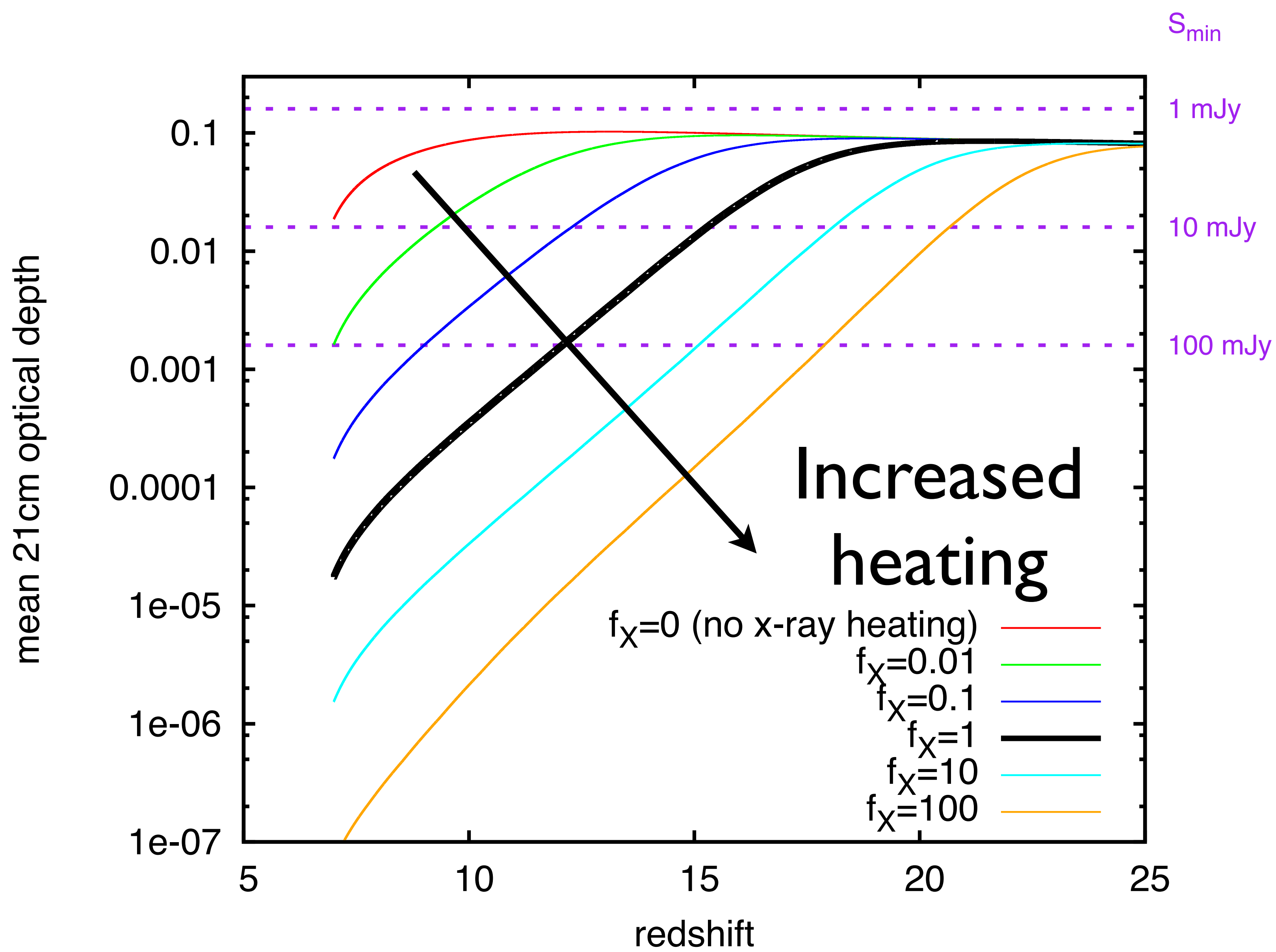
- When did reionization occur
- Statistics of ionized regions
- Properties of collapsed regions => dark matter

21 cm forest is a thermometer

Mack & Wyithe 2011

Optical depth tracks IGM temperature

Constrains early X-ray heating



High S/N, high resolution 21 cm forest observations require bright sources

Statistical techniques - e.g. variance - may make forest more accessible with fainter radio sources
Mack & Wyithe 2011

High redshift radio sources?

21 cm forest observations require existence of high redshift ($z>6.5$) radio loud sources ($S_{min}>1$ mJy)

Do they exist?

Radio loud quasars

Radio loud supernovae/GRB

(many >10 mJy sources in existing catalogues e.g. FIRST with no redshift)

Radio loud quasars?

NIR surveys are beginning to find z>7 quasars

UKIDSS
(3800 deg^2 total)
z~7.05

(~50% survey)

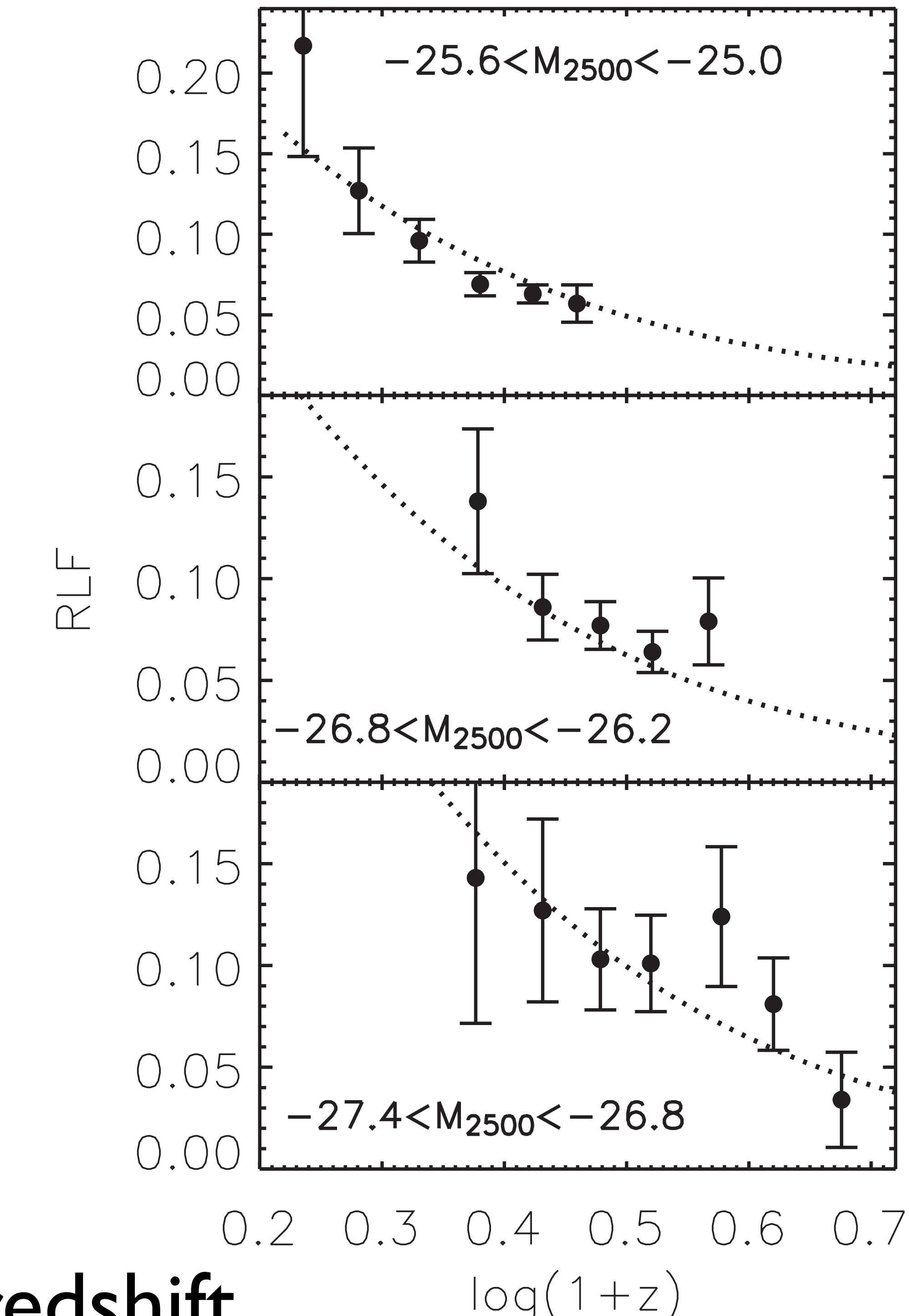
Mortlock+ 2011

VISTA-VIKING
(1500 deg^2 total)
z~6.8
z~6.9
(<20% survey)

Venemans+

2*10^9 Msol black hole can form
~700 million yrs after big bang

~10-20% quasars are radio loud



Evidence for RLF decreasing at higher redshift

Jiang+ 2007

Radio loud SN/GRB?

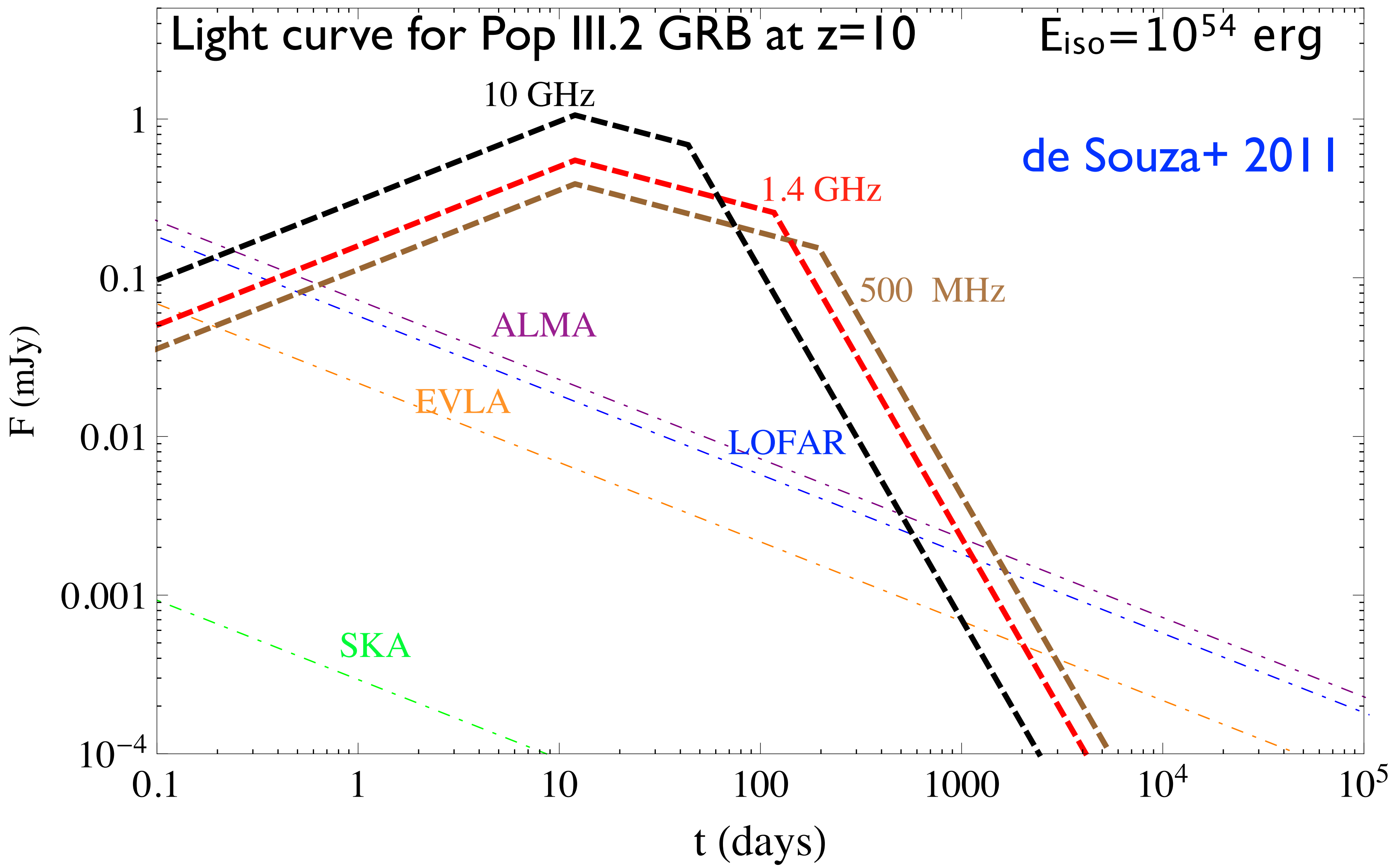
Advantage: GRB have been seen at desired redshifts

z=9.4 (Cucchiara+ 2011), z=8.6 (Lehnert+ 2010), z=8.26 (Greiner+ 2009), ...

Disadvantage:

1) Lower radio brightness temperature

2) Finite duration limits integration time.



Intrinsic event rate ~10-10^4 yr^{-1}

Transient surveys from LOFAR, MWA,... coming soon

Paradigm for first stars currently unclear e.g. Stacy+ 2011

Scientific requirements

Track evolution of IGM through reionization to first galaxies

SCI-S-REQ-0210: The SKA Phase 1 shall be able to access the H I line over at least the redshift range of 6 to 20.

Detect 21 cm forest for expected values of optical depth

SCI-S-REQ-0220: The SKA Phase 1 shall be able to detect H I absorption at optical depths of 0.001 or lower.

Resolve minihalos in forest

SCI-S-REQ-0230: The SKA Phase 1 shall be able to provide a velocity resolution of 0.2 km s^{-1} or better.

Ensure rare radio loud sources lie in survey

SCI-S-REQ-0235: The SKA Phase 1 shall be able to provide access as large a fraction of the sky as feasible, notionally at least 2π steradians.

Technical requirements

Frequency coverage to match redshift range

SCI-T-REQ-0210: The SKA Phase 1 shall provide a frequency range of at least 70 to 200 MHz.

Frequency resolution to resolve minihalos

SCI-T-REQ-0220: The SKA Phase 1 shall provide a frequency resolution commensurate with the velocity resolution, with a fiducial value of 0.1 kHz at an observation frequency of 150 MHz.

Sensitivity needed to see 21 cm forest in a bright (~20 mJy) source at z~8

SCI-T-REQ-0230 The SKA Phase 1 shall have a sensitivity of at least 1300 m^2 K^{-1}.

Summary of science progress

- 21 cm tomography and forest are key probes of reionization and first galaxies

- Related science, but different strategy and complementary

- New NIR surveys are finding z>7 quasars - hints of $x_H>0.1$ (also LAE-LBG fraction evolution at z~7)

- Global experiments taking baby steps - duration of reionization

- Pathfinders GMRT, MWA, LOFAR, PAPER making maps and measuring point sources

Summary DRM

- For 21 cm tomography
  - Match redshift range => z=6-30 => nu=250-50 MHz
  - Match size of bubbles ~Mpc => 1arcmin resolution & 0.1 MHz frequency resolution
  - High S/N => 1 mK thermal noise
  - Sample representative volume => large field of view
  - Ionosphere + calibration + point source removal may force longer baselines >5km for high angular resolution

- For 21 cm forest
  - Match redshift range => z=6-30 => nu=250-50 MHz
  - Match size of minihalos ~kpc => 0.1 kHz frequency res.
  - High S/N => >1300 m^2/K
  - Find rare radio loud sources => large field of view ~2pi steradians.