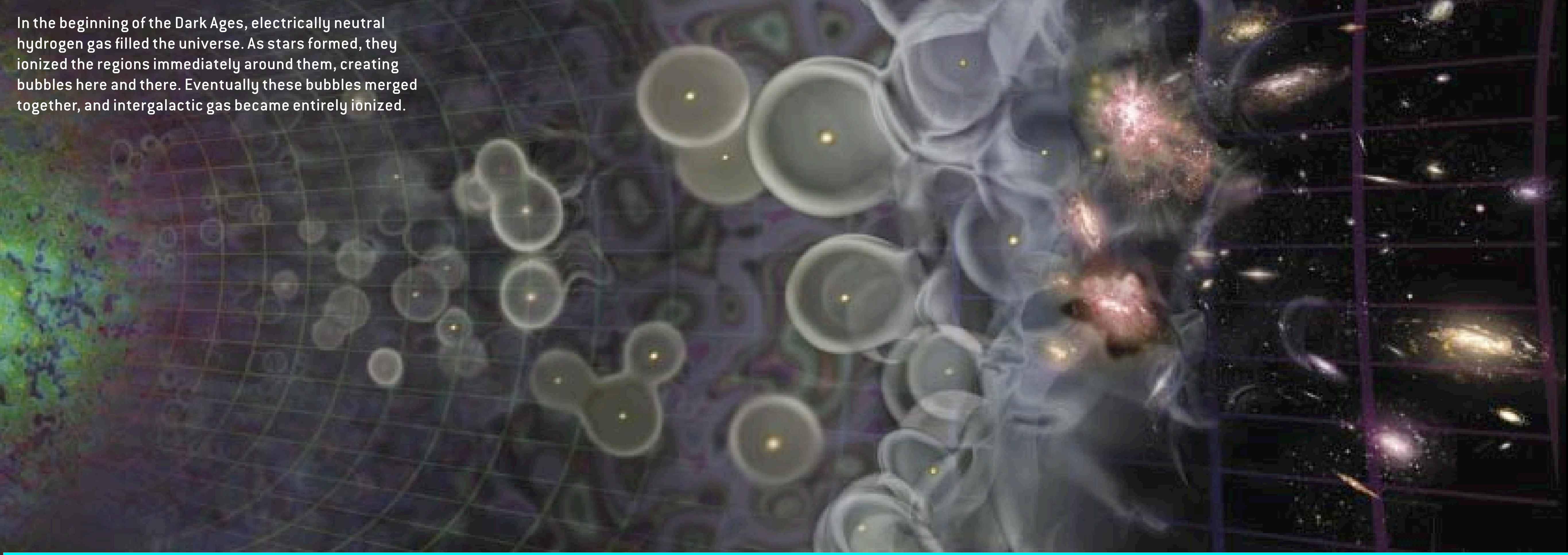
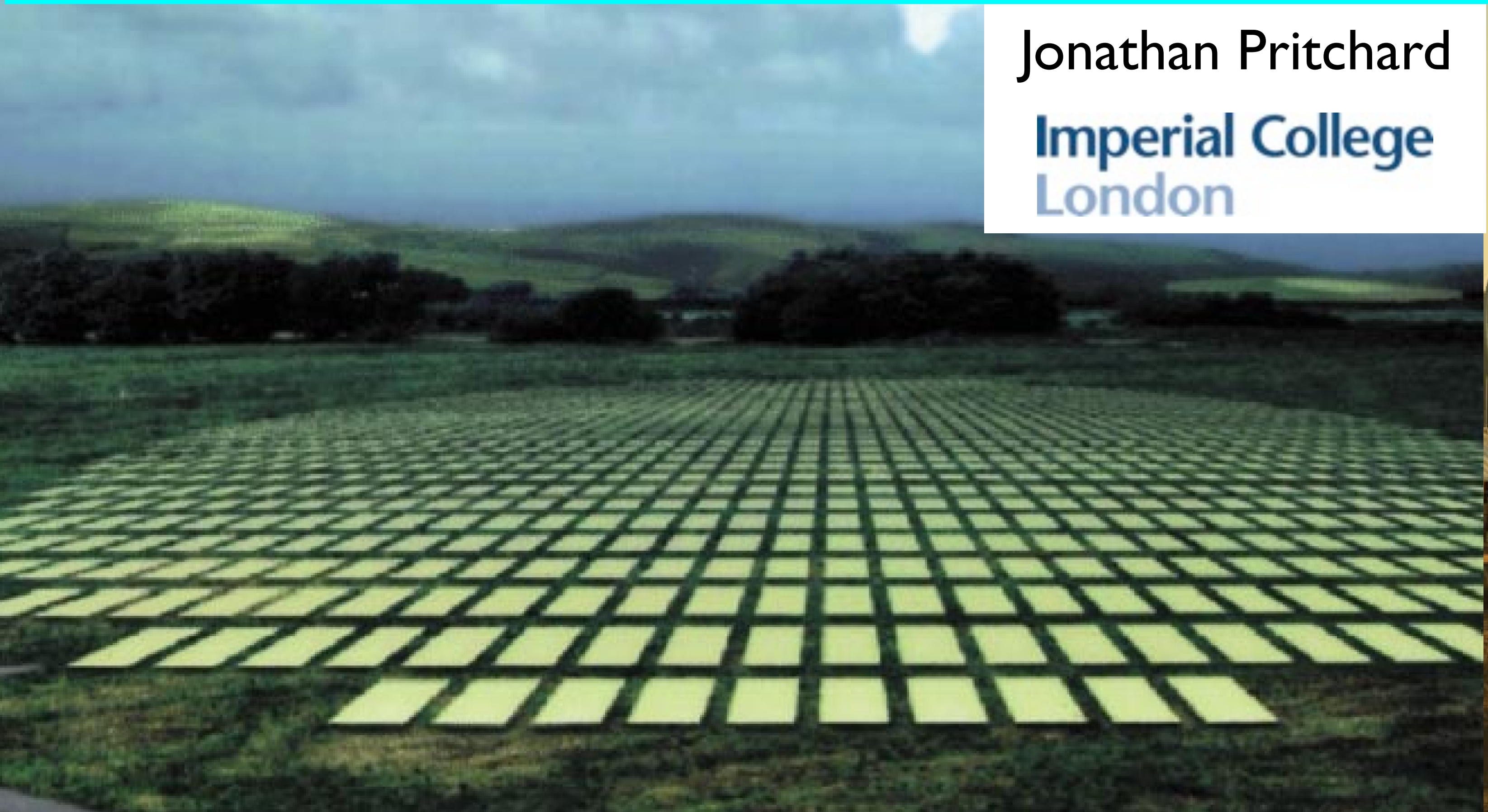


In the beginning of the Dark Ages, electrically neutral hydrogen gas filled the universe. As stars formed, they ionized the regions immediately around them, creating bubbles here and there. Eventually these bubbles merged together, and intergalactic gas became entirely ionized.

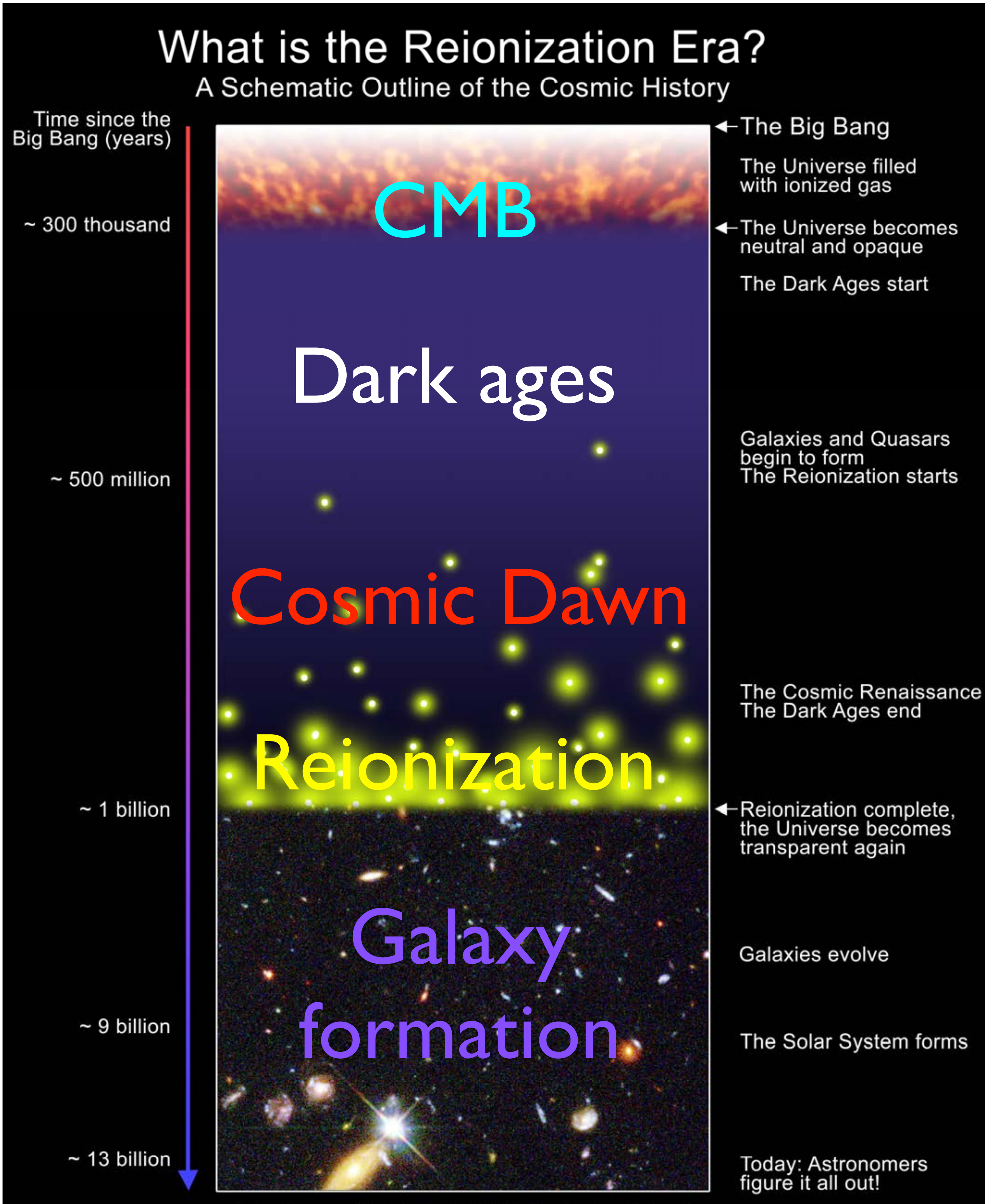
21 cm global signal and tomography

Jonathan Pritchard

Imperial College
London



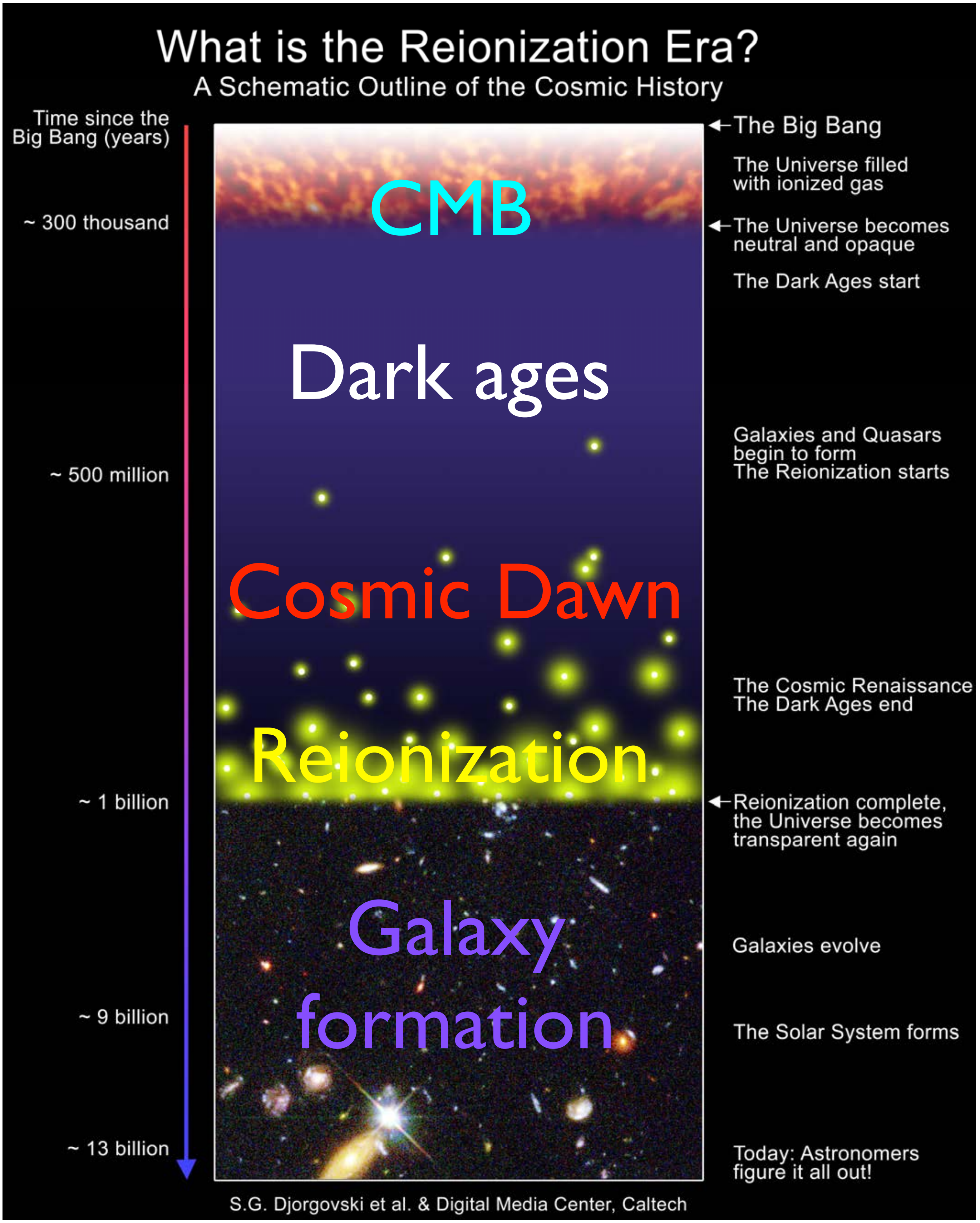
The first billion years



S.G. Djorgovski et al. & Digital Media Center, Caltech

Reionization marks the limits of current observations

The first billion years



S.G. Djorgovski et al. & Digital Media Center, Caltech

Reionization marks the limits of current observations

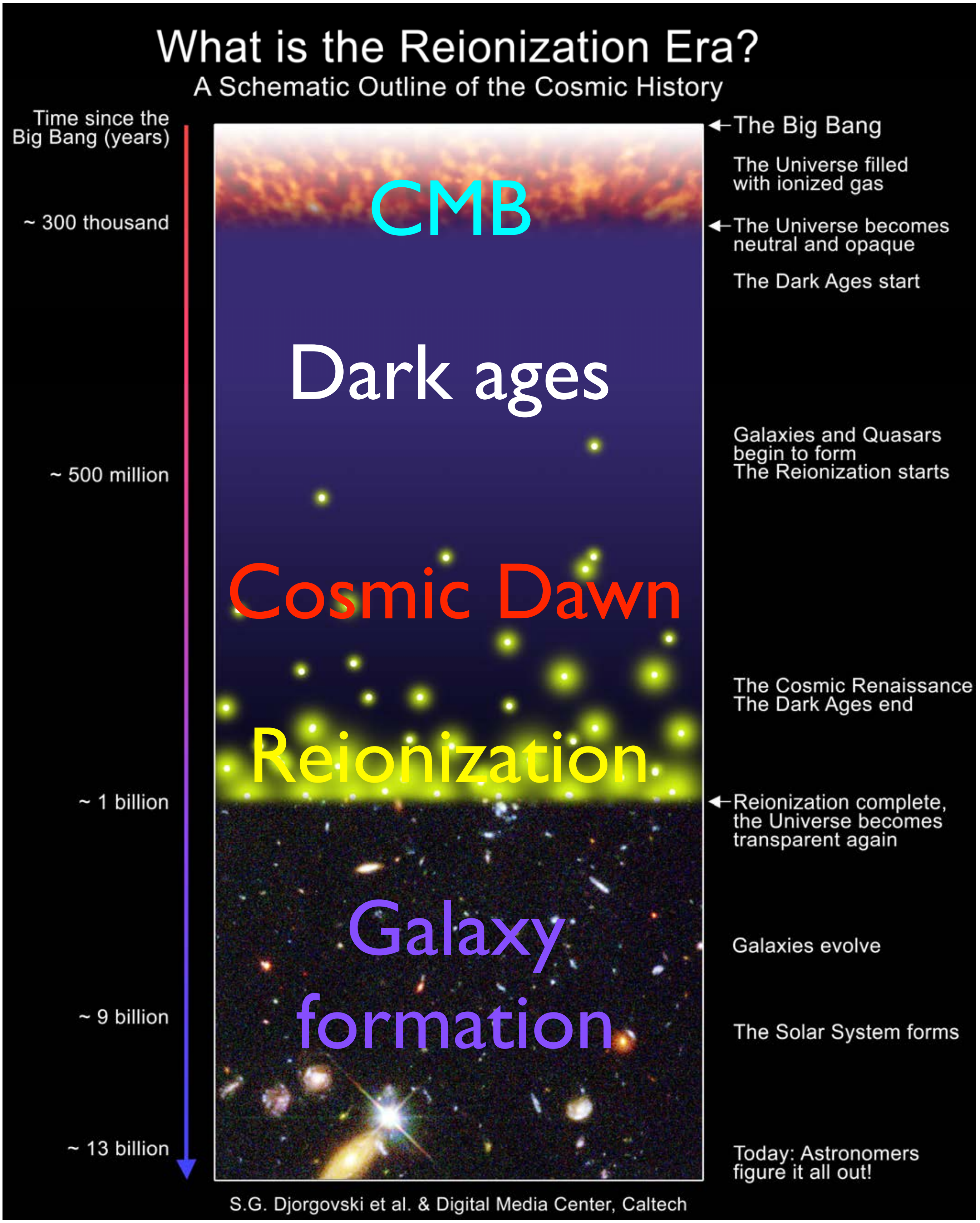
When did the first galaxies form?

When did the first black holes form?

How did reionization proceed?

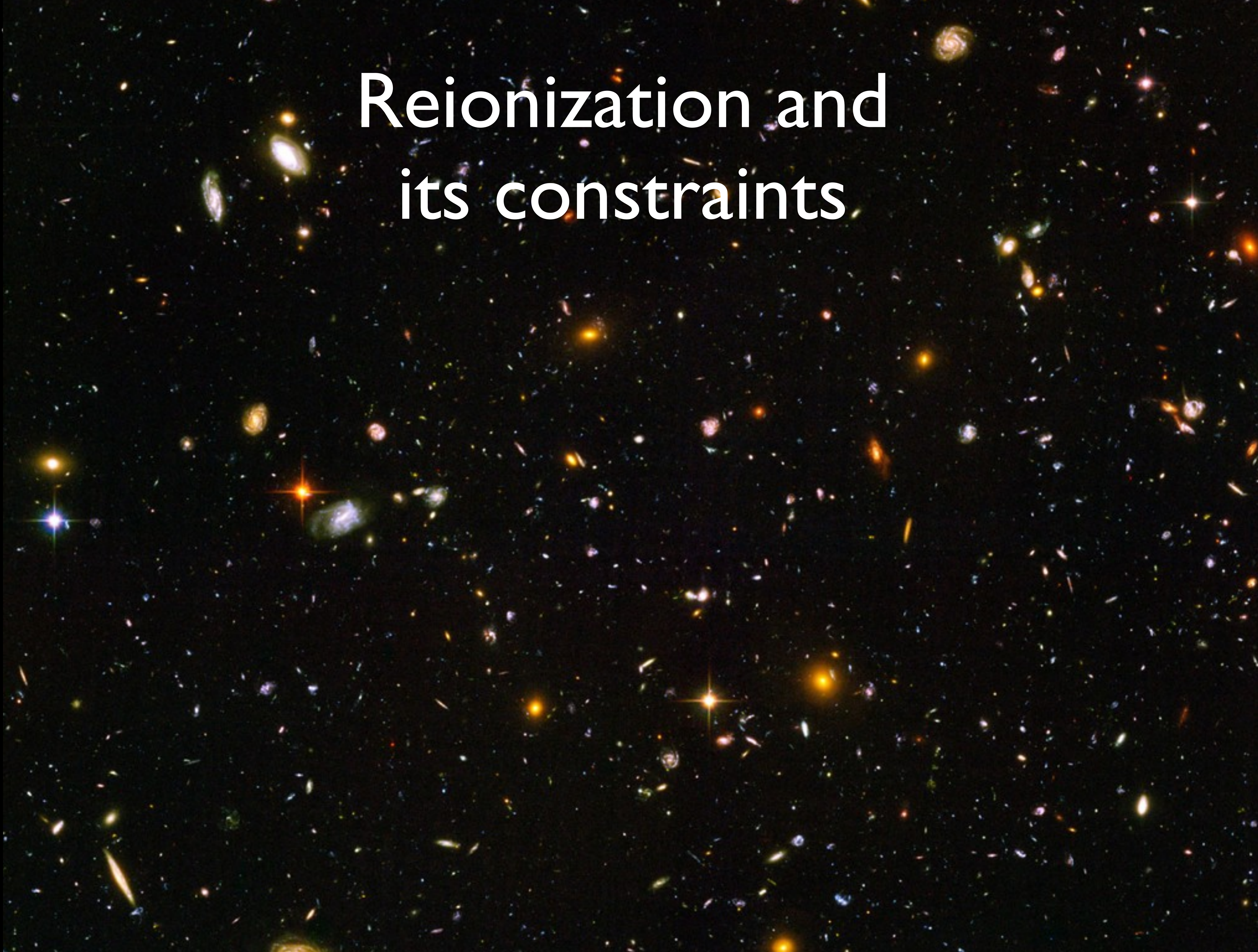
How do galaxies form and evolve?

Overview



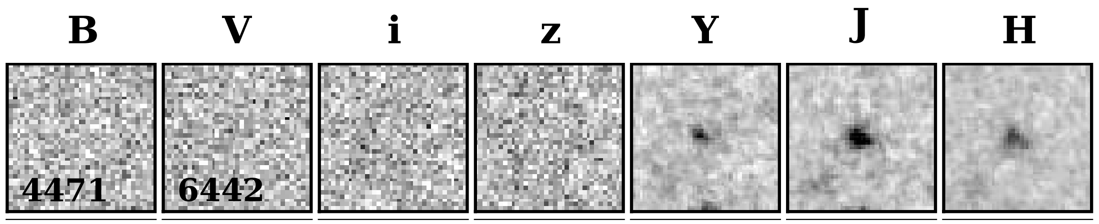
- Recap of reionization
- 21 cm global signal
- 21 cm fluctuations
- CO intensity mapping

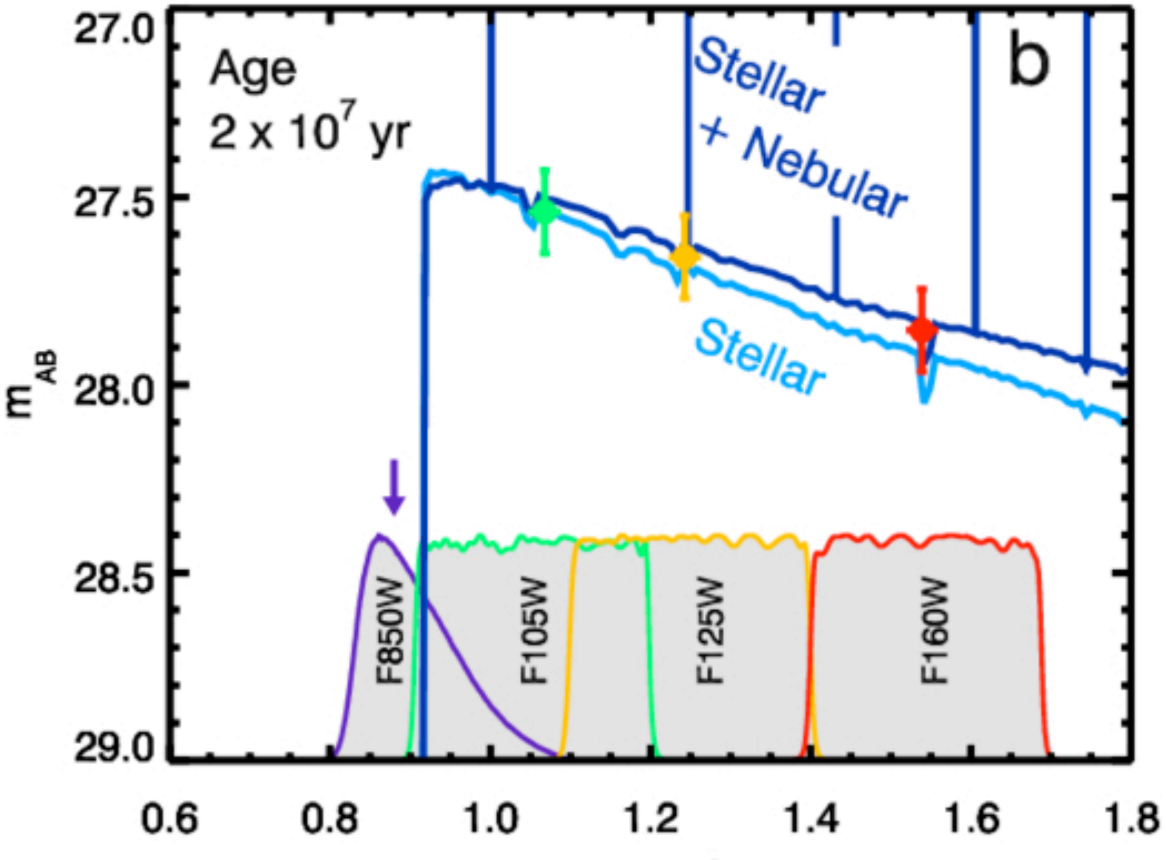
Reionization and its constraints



Tip of the iceberg

Hubble identify high redshift galaxies as “drop outs”
- identifications ok to z~8.5; z>8.5 mirky
- “J-band drop outs”, so appear in only one filter
- line contamination?

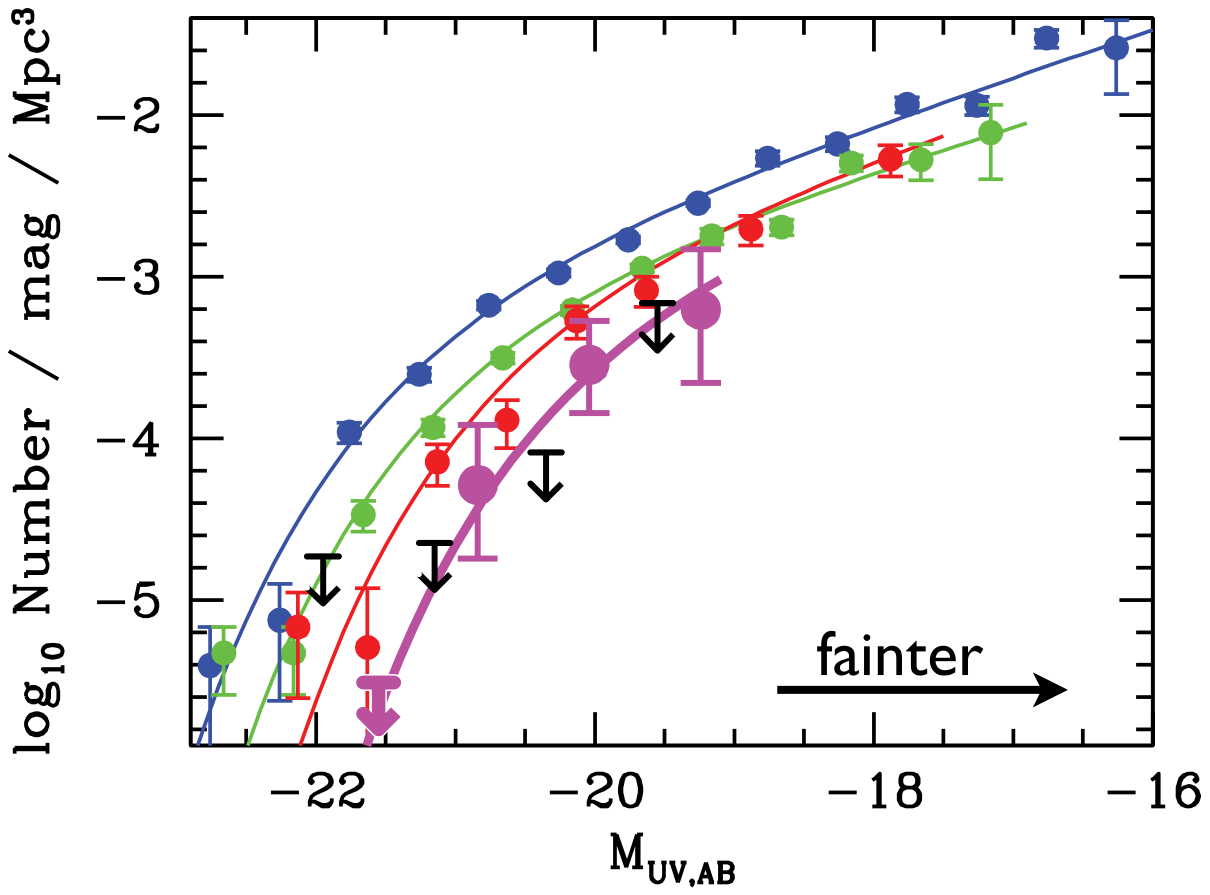




Robertson+ 2010

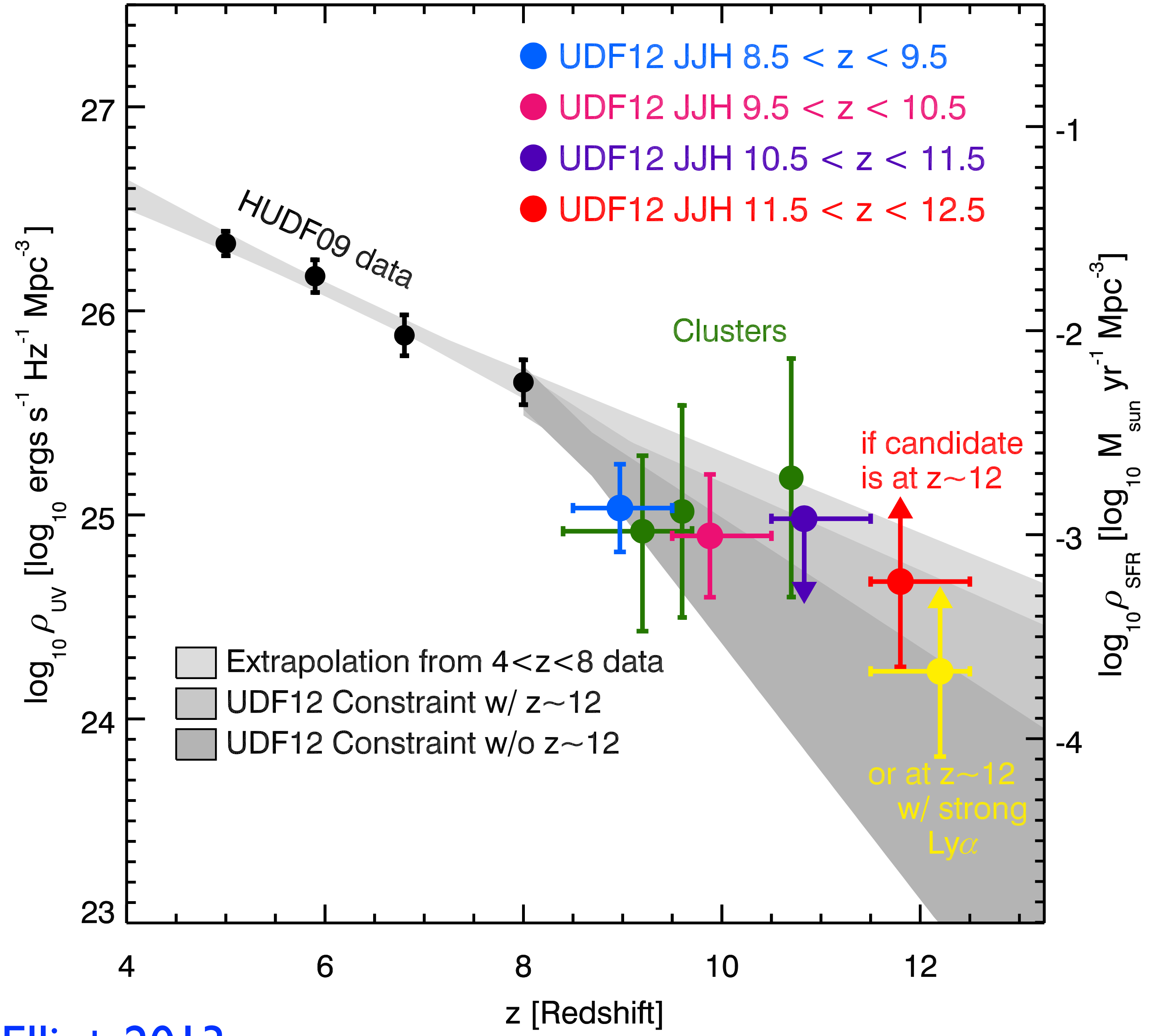
Counting galaxies out to z~10 constrains sources of ionization

Bunker+ 2009, Bouwens+2009



GRBs probe star formation in faint galaxies   Tanvir+ 2012

The z=8.5 ceiling



Ellis+ 2013

Mapping star formation to ionization is difficult

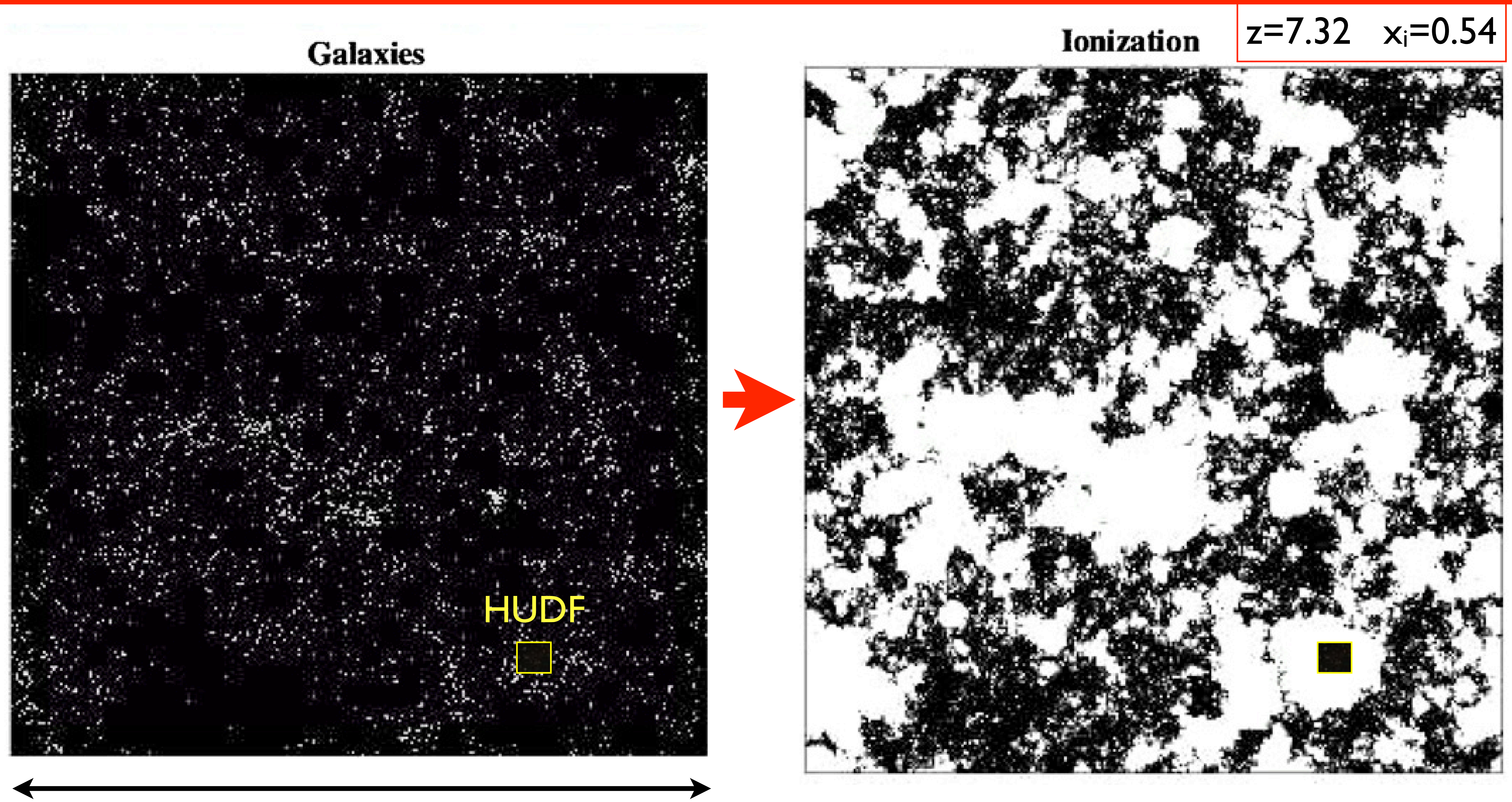
- ionizing photon escape fraction
- stellar IMF

- recombinations (clumping)

Ionization rate vs total amount of stellar mass

JWST needed to extend galaxy luminosity function to z~12 (currently 2018)

Hard to probe wide and deep

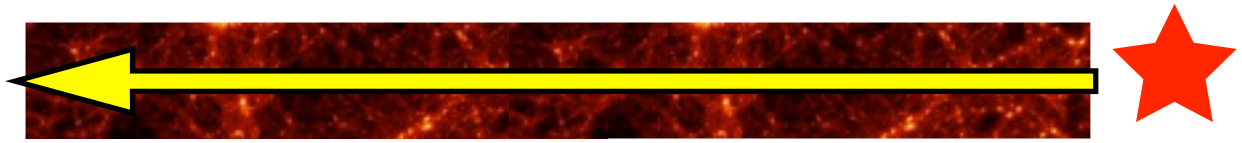


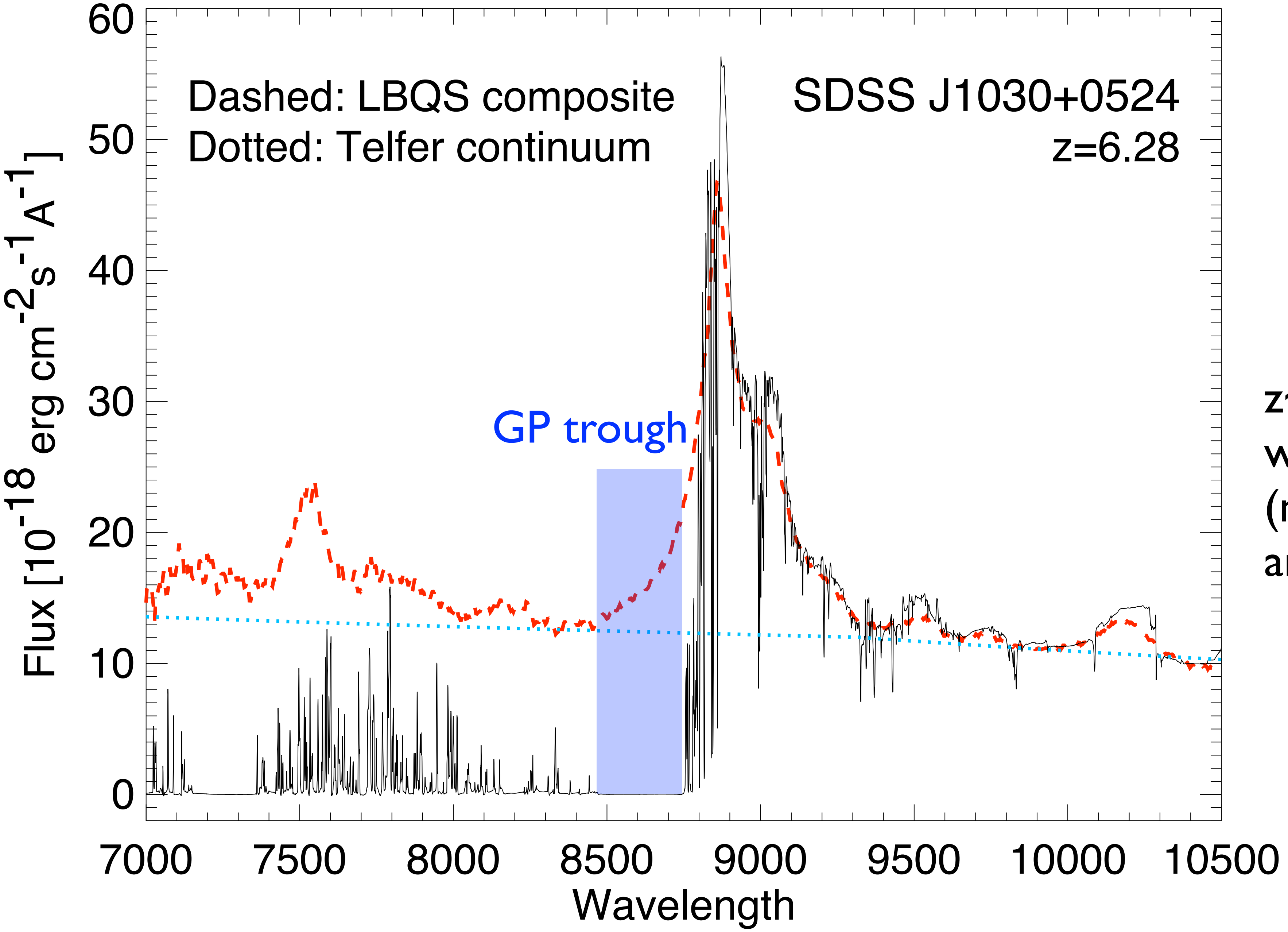
Lidz+ 2009 130/h Mpc=1.2 deg HUDF= 11‘x11’

Galaxy surveys give details of small patch*

*LAE may allow wide surveys

Gunn-Peterson trough





z~7 quasars being found now

Mortlock+ 2011

z~8 quasars only with Euclid (need redder bands and large area)

absence of GP trough tells us that the Universe is ~fully ionized at z<6.5

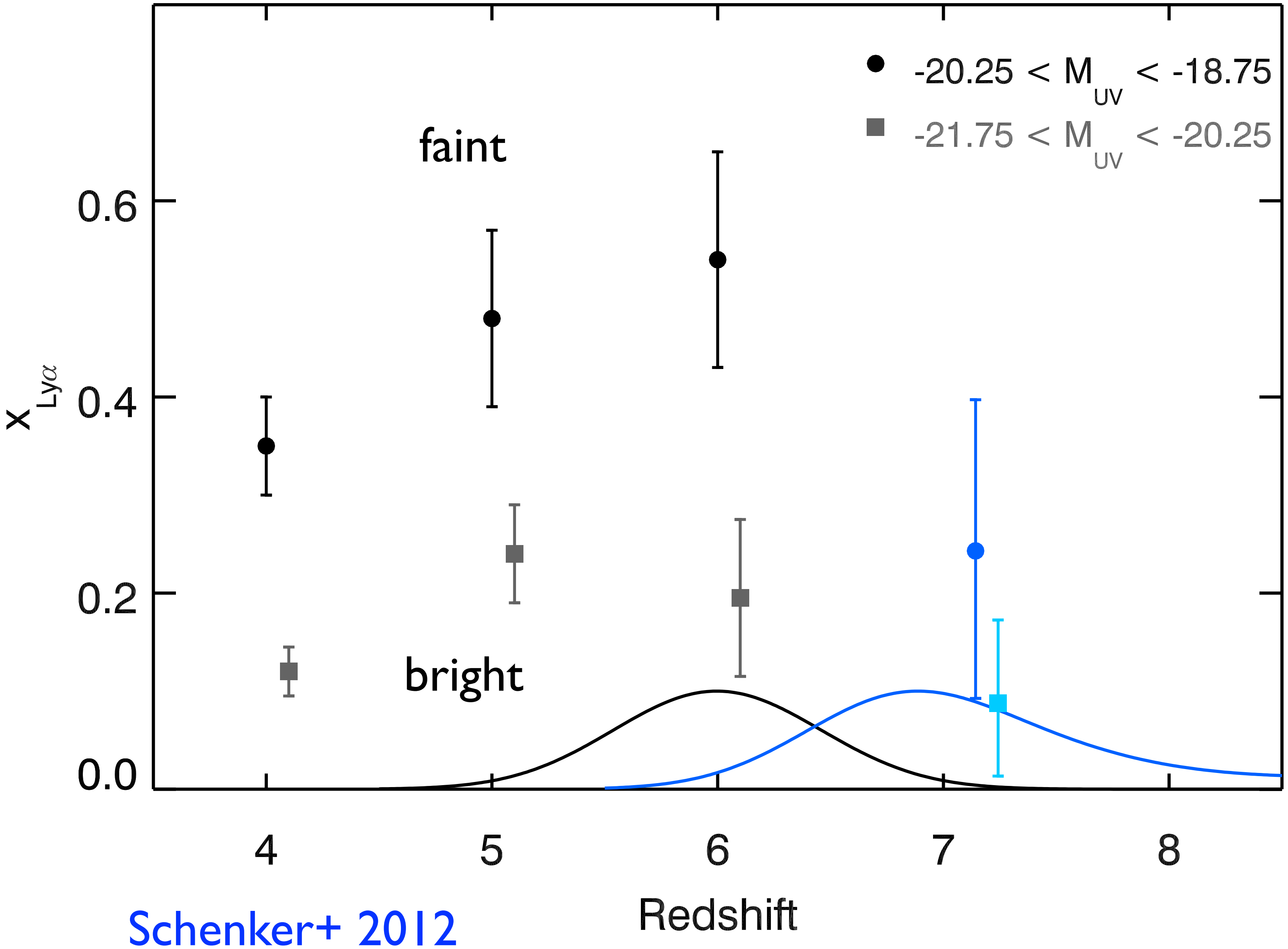
LAE/LBG fraction

Taking LAE/LBG fraction helps normalise out evolution of intrinsic galaxy properties

Fraction of LAE/LBG declines at z~7 => evidence for partially neutral IGM?

More pronounced in faint galaxies - would ionize smaller region around host, so right trend

Estimates of xH~0.5 at z~7, but no systematic analysis as of yet



Schenker+ 2012

CMB tau + patchy kSZ

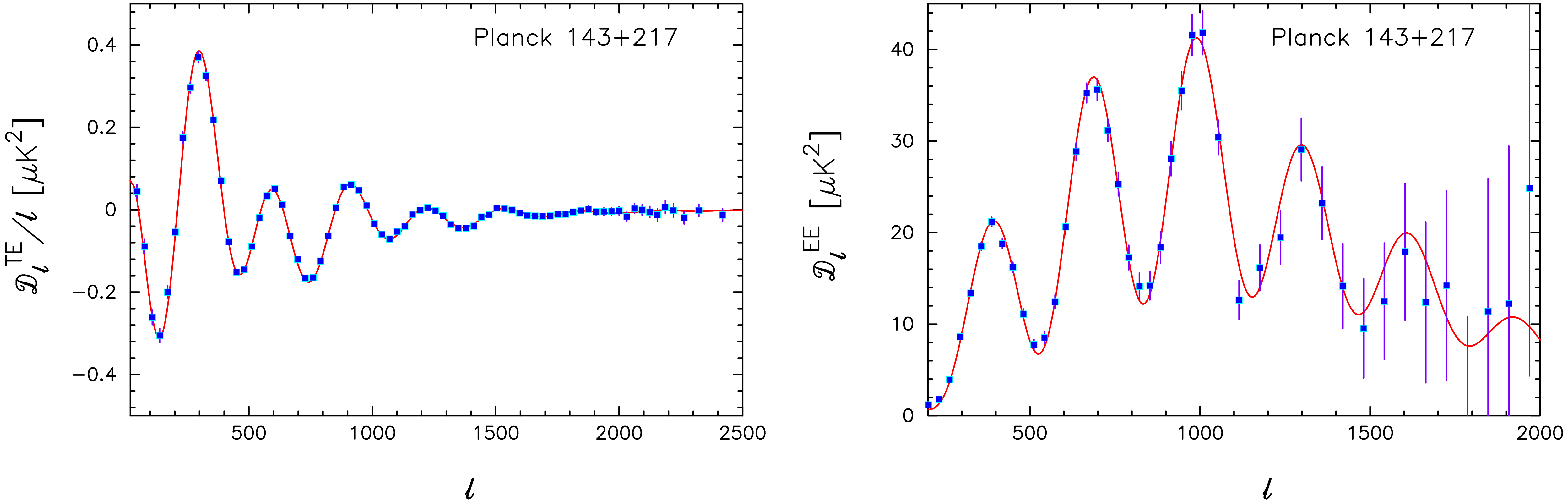
Optical depth ~constrains midpoint of reionization

Planck 0.097 ± 0.038 Planck+WMAP pol $0.089^{+0.012}_{-0.014}$

Planck polarisation ~2014 constraints ~2-3 PCA of history

$$\sigma_\tau^{\rm Planck} = 0.005$$

Planck teaser for polarisation quality...



Planck XVI 2013

red curve=prediction from TT maps; blue points=Planck polarisation data

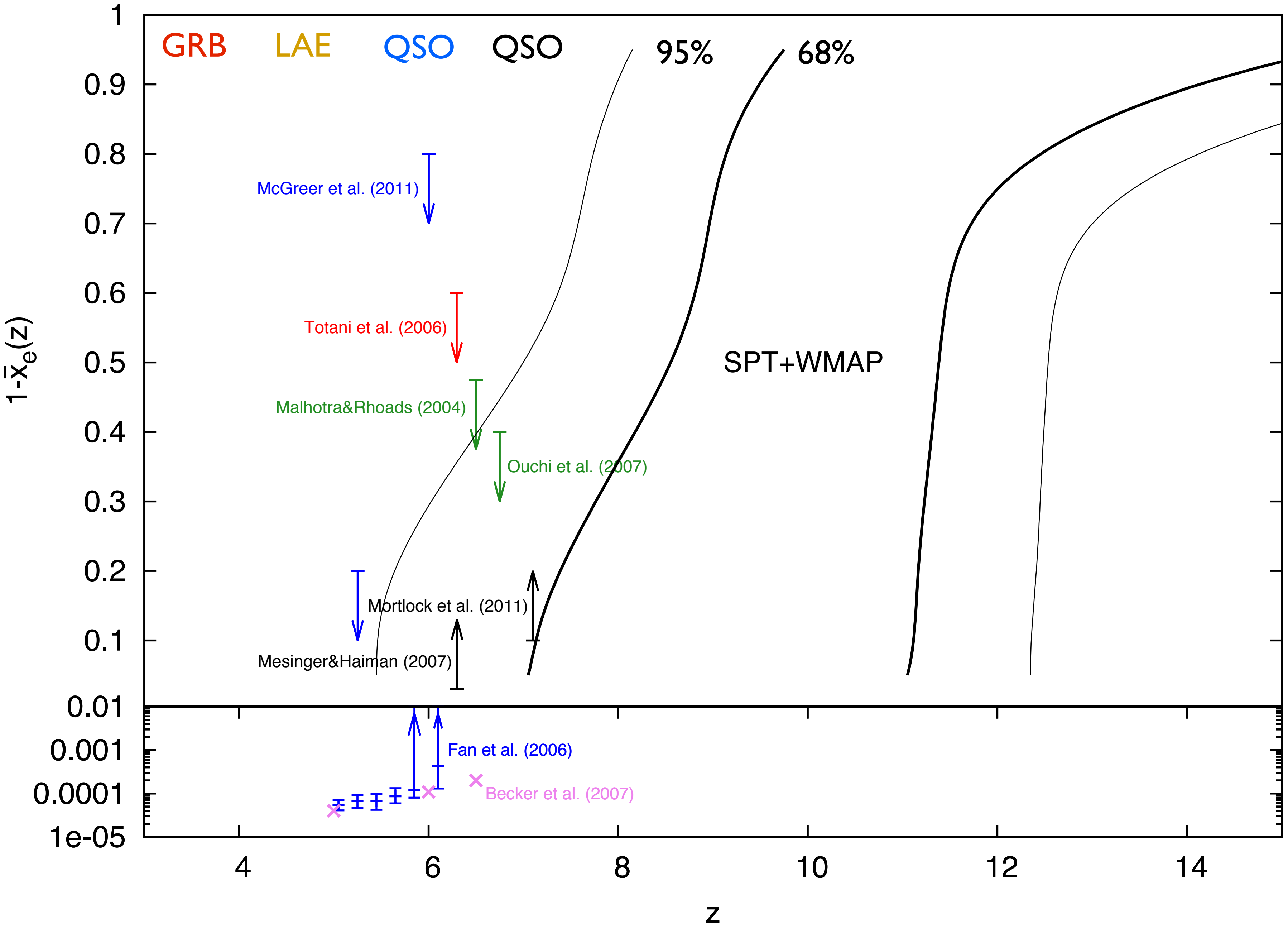
CMB tau + patchy kSZ

Imperial College London

Optical depth from WMAP constrains midpoint of reionization

Planck 0.097 ± 0.038 Planck+WMAP pol $0.089^{+0.012}_{-0.014}$

SPT uses patchy kSZ signal to constrain duration of reionization

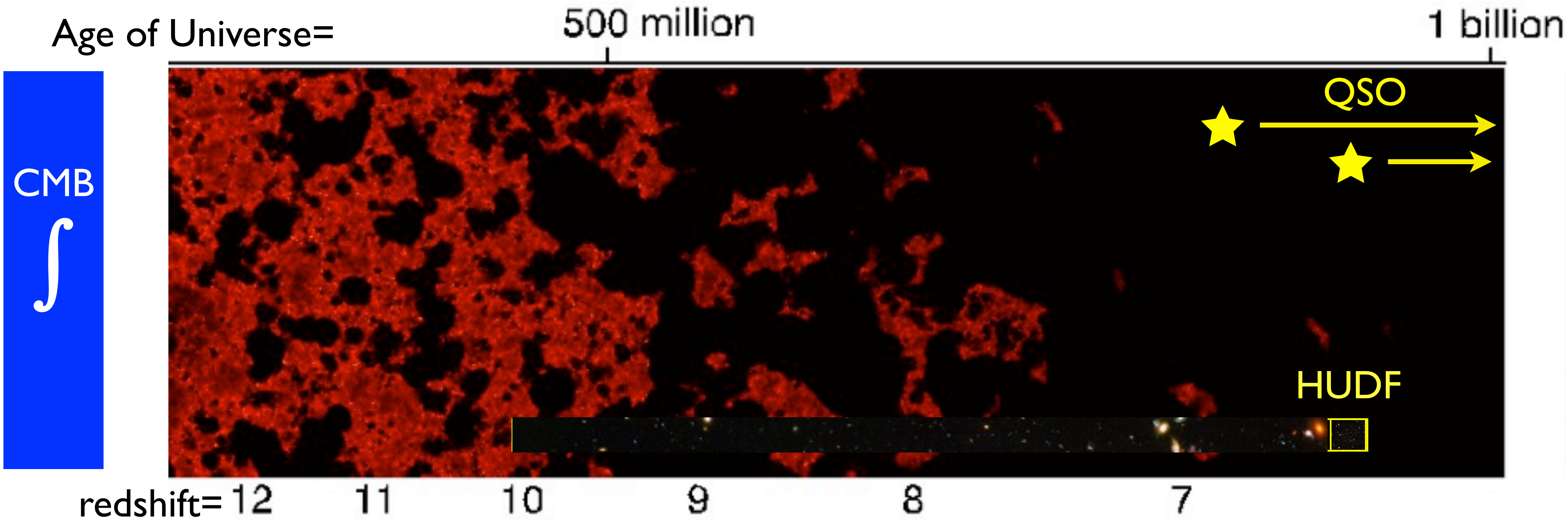


Zahn+ 2011

Lots of caveats on interpretation: a one parameter model is not enough

Mesinger+2012
Park+ 2013

More needed...



Existing observations leaves much unanswered

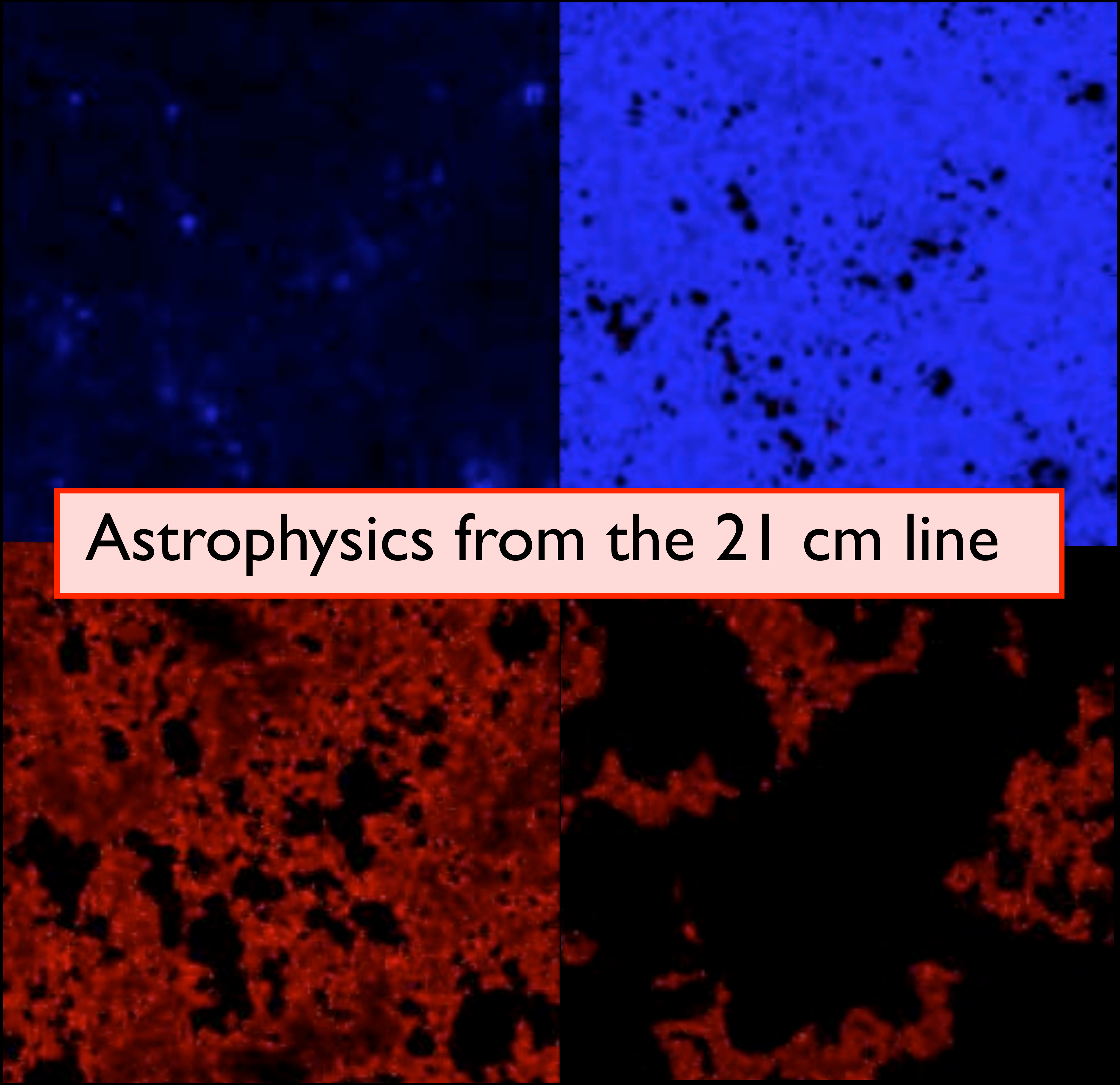
Possible hints of neutral hydrogen at z~7, e.g. z=7 QSO, LAE/LBG ratio

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 z~12
   (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?

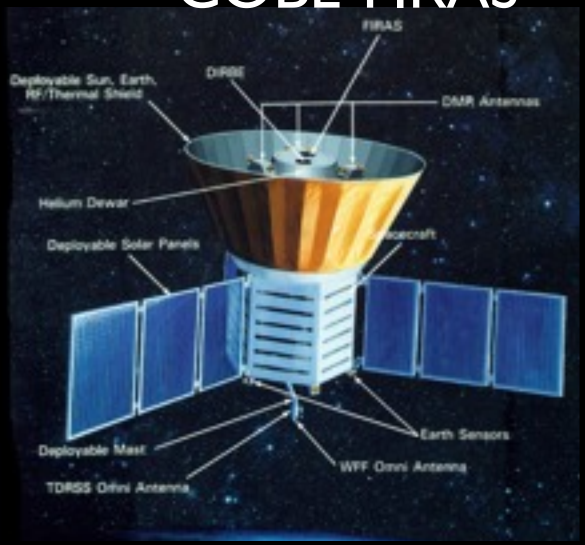
SKA will map out details of reionization

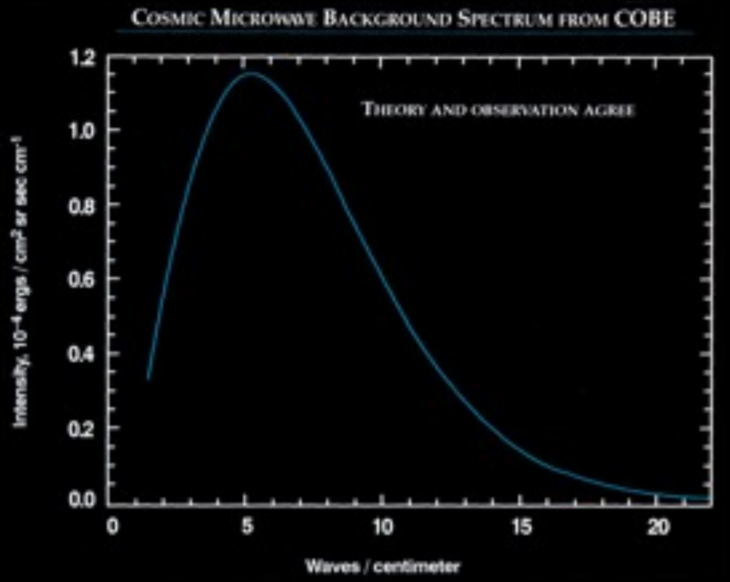
Astrophysics from the 21 cm line



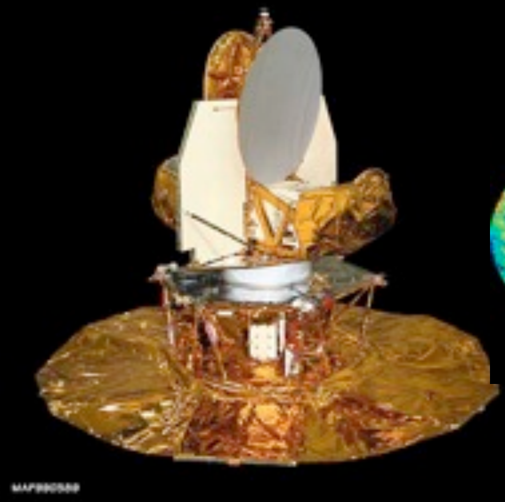
Global vs Fluctuations

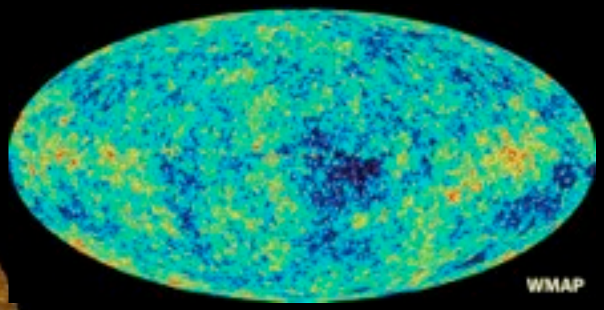
COBE-FIRAS



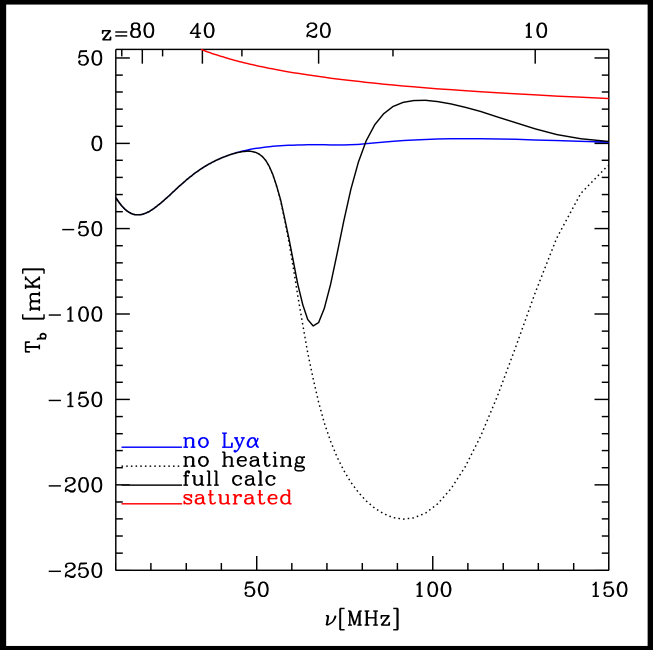


WMAP

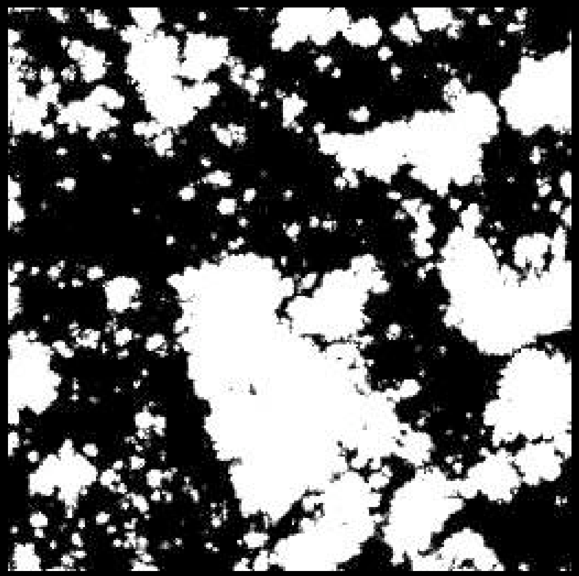




EDGES

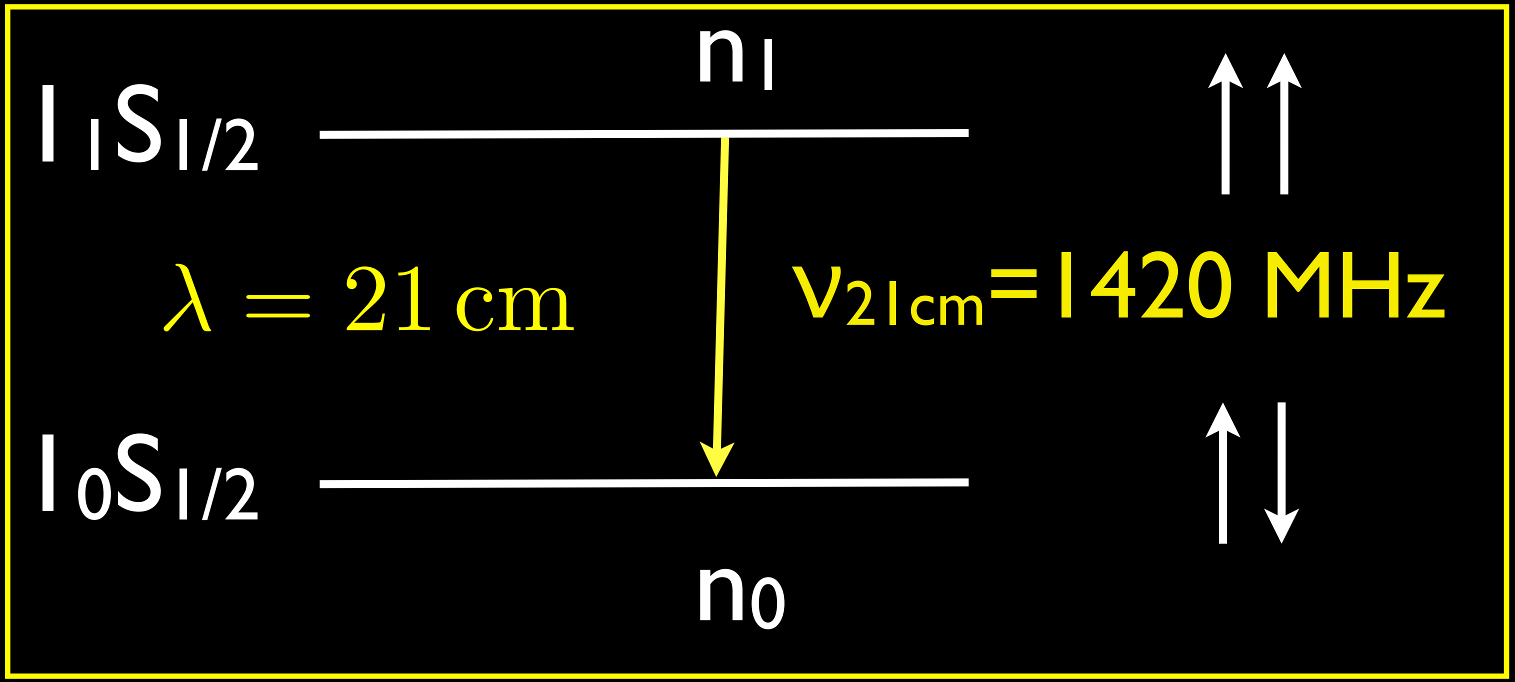


LOFAR



21 cm basics

Hyperfine transition of neutral hydrogen



Useful numbers:

$200\,\mathrm{MHz} \longrightarrow z = 6$
$100\,\mathrm{MHz} \longrightarrow z = 13$
$70\,\mathrm{MHz} \longrightarrow z \approx 20$
50 MHz => z~27

$t_{\mathrm{Age}}(z = 6) \approx 1\,\mathrm{Gyr}$

$t_{\mathrm{Age}}(z = 10) \approx 500\,\mathrm{Myr}$

$t_{\mathrm{Age}}(z = 20) \approx 150\,\mathrm{Myr}$

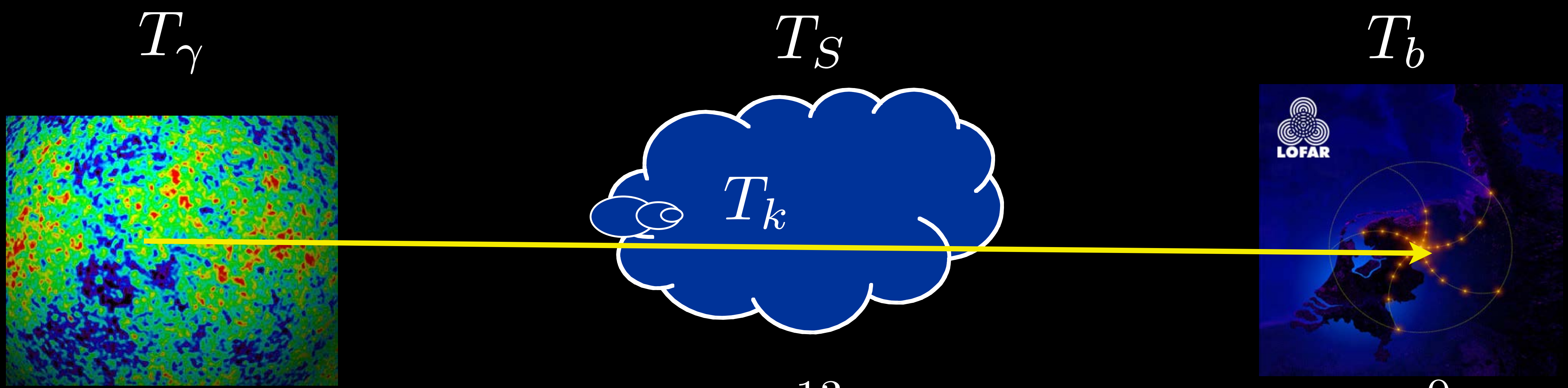
t_{Age}(z=27) ~100 Myr

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

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



$z = 13$

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

$z = 0$

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

CMB acts as back light

Neutral gas imprints signal

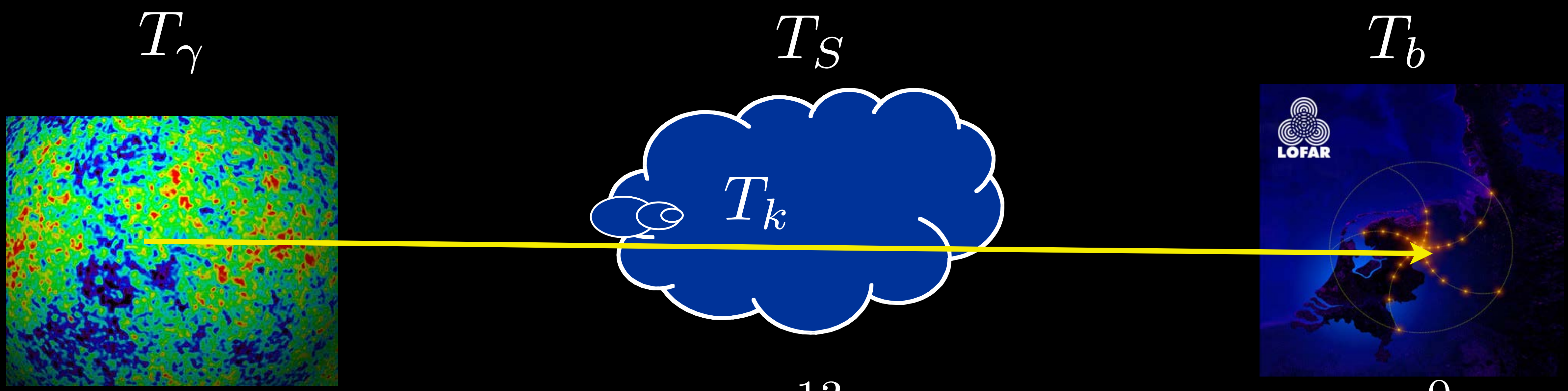
Redshifted signal detected

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



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

CMB acts as
back light

Neutral gas
imprints signal

Redshifted signal
detected

brightness temperature

$$T_b = 27\overset{\substack{\text{neutral}\\\text{fraction}\\\downarrow}}{x}_{\mathrm{HI}}(1+\delta_b)\left(\frac{T_S - T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\right)^{1/2}\left[\frac{\partial_r v_r}{(1+z)H(z)}\right]^{-1}\,\mathrm{mK}$$

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T_γ T_S T_b

$z = 13$ $\nu = 1.4\,\mathrm{GHz}$

$z = 0$ $\nu = 100\,\mathrm{MHz}$

CMB acts as back light

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Redshifted signal detected

neutral fraction

baryon density

brightness temperature

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

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T_γ T_S T_b

$z = 13$ $z = 0$

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Redshifted signal detected

neutral fraction

baryon density

spin temperature

brightness temperature

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Radiative transitions (CMB)
Collisions
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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

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

spin temperature set by different mechanisms:
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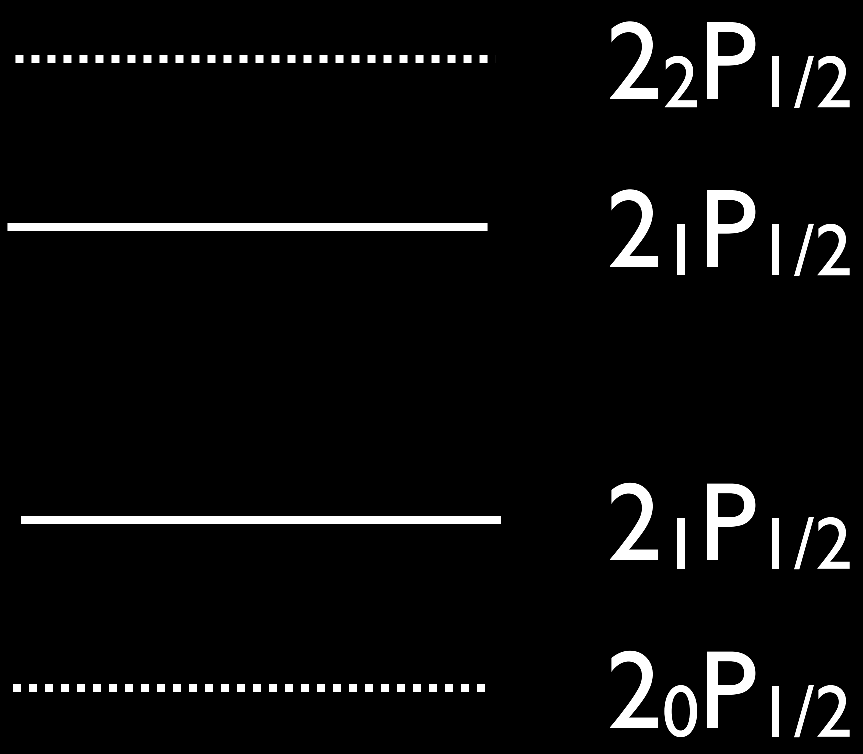
Wouthuysen-Field Effect

Hyperfine structure of HI

Resonant Lyman α scattering couples ground state hyperfine levels

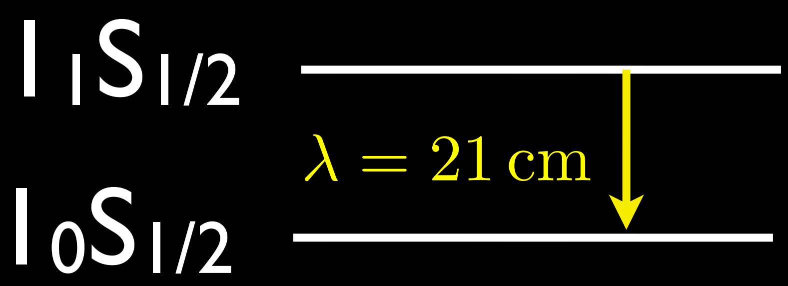
Coupling ∝ Lyα flux

$$\overset{\text{spin}}{T_S} \underset{\overset{\uparrow}{\text{W-F}}}{\sim} \overset{\text{colour}}{T_\alpha} \underset{\overset{\uparrow}{\text{recoils}}}{\sim} \overset{\text{gas}}{T_K}$$



Wouthuysen 1959

Field 1959



Wouthuysen-Field Effect

Hyperfine structure of HI

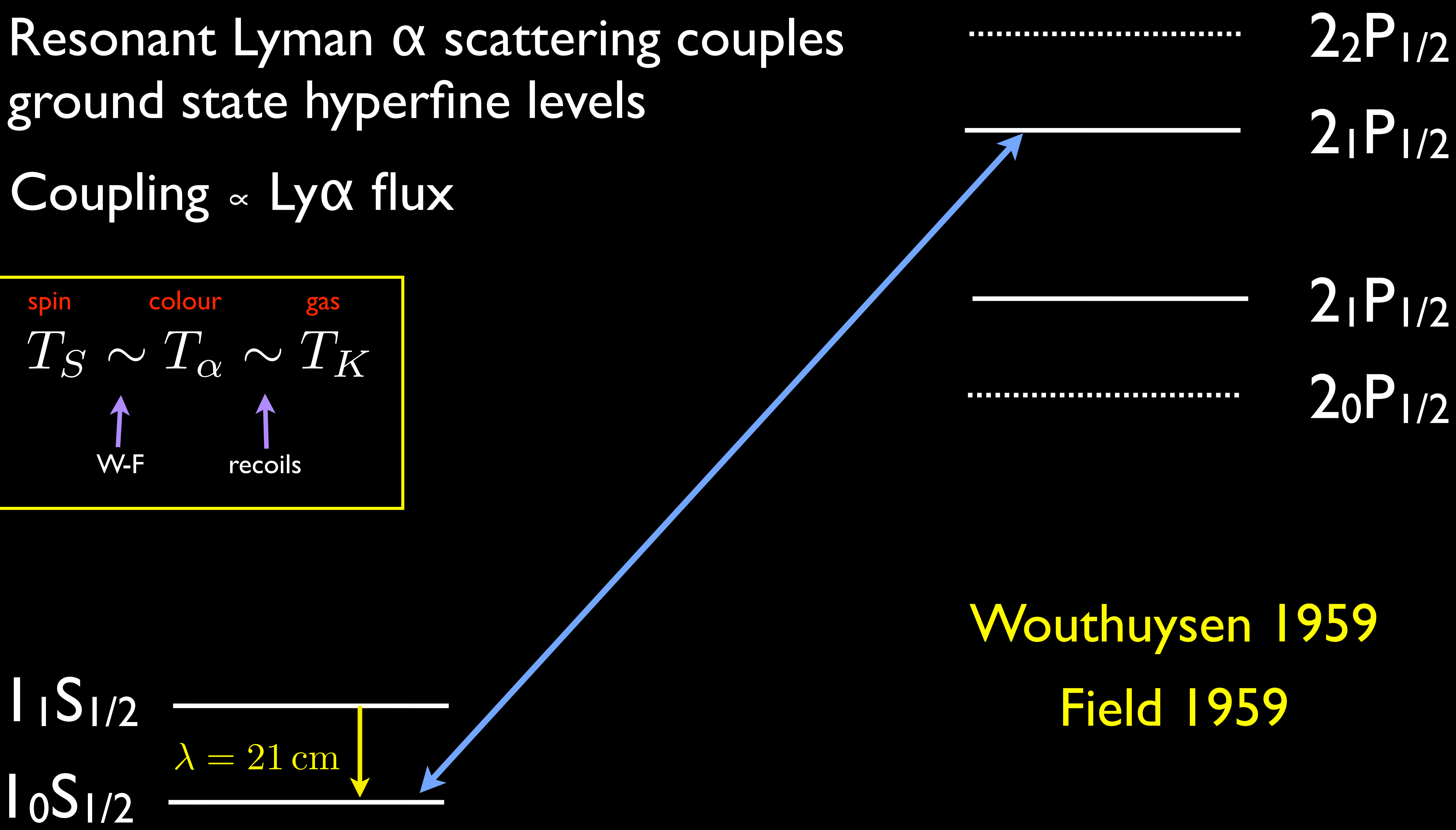
Resonant Lyman α scattering couples ground state hyperfine levels

Coupling ∝ Lyα flux

spin colour gas

$$T_S \sim T_\alpha \sim T_K$$

W-F recoils



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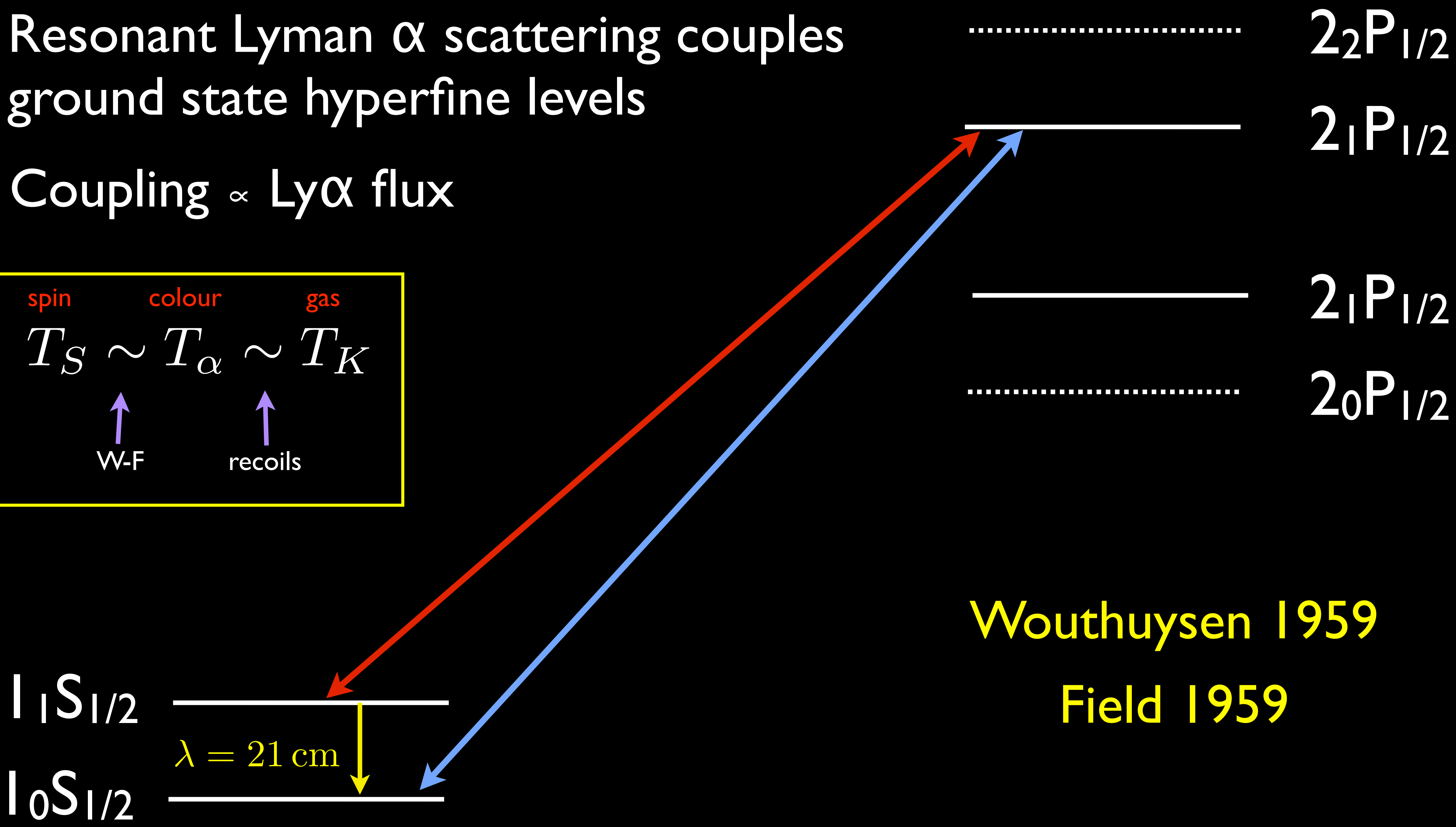

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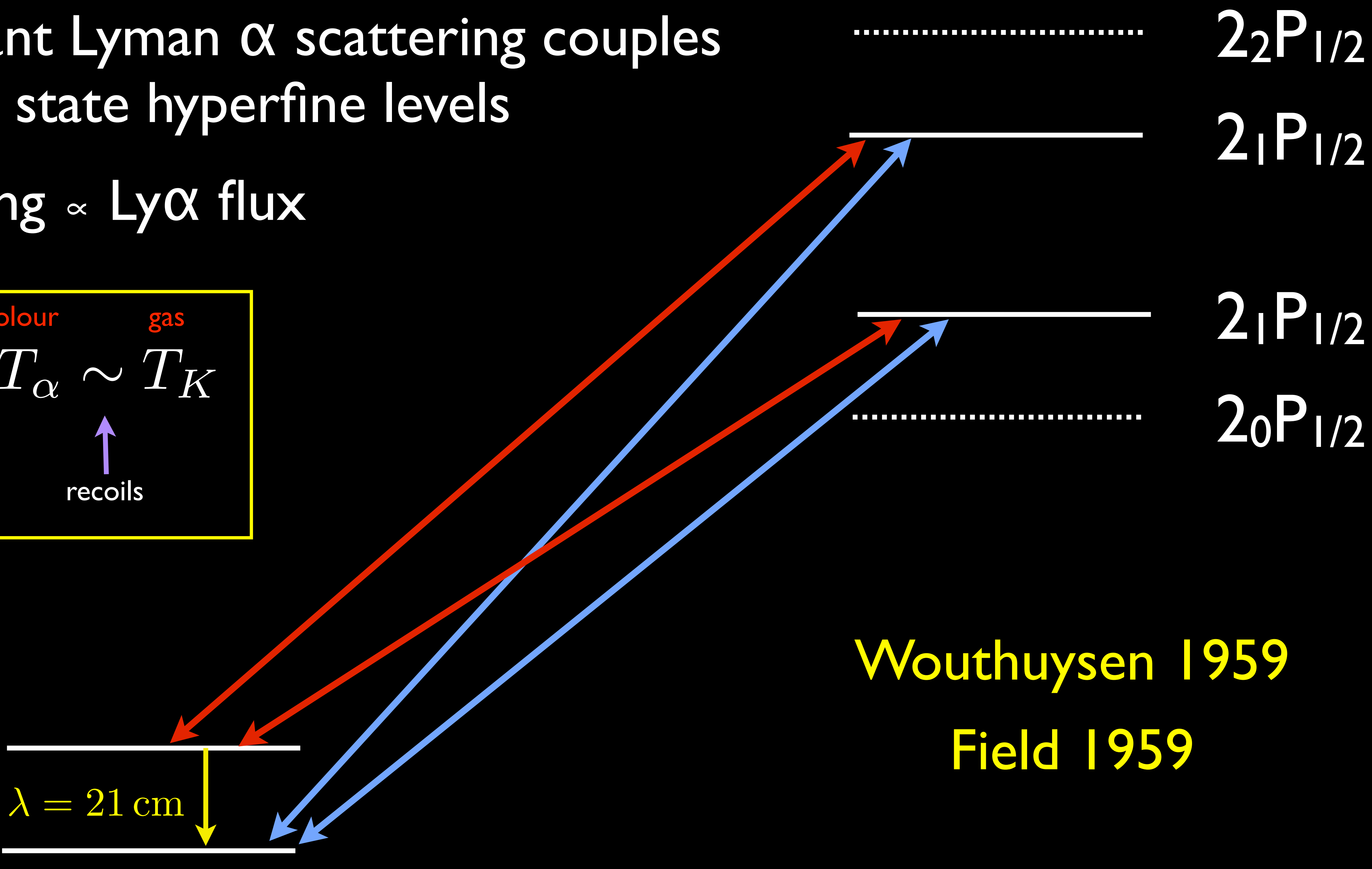


Wouthuysen 1959

Field 1959

Nature of first galaxies?

Lyman alpha photons originate from stars

Star formation rate?

Population II or III?

When did galaxies form?

Thermal history

- X-rays likely dominant heating source in the early universe
  - (also Lya heating, shocks but inefficient)

Madau+1997, Chen+ 2004
McQuinn & O'Leary 2012

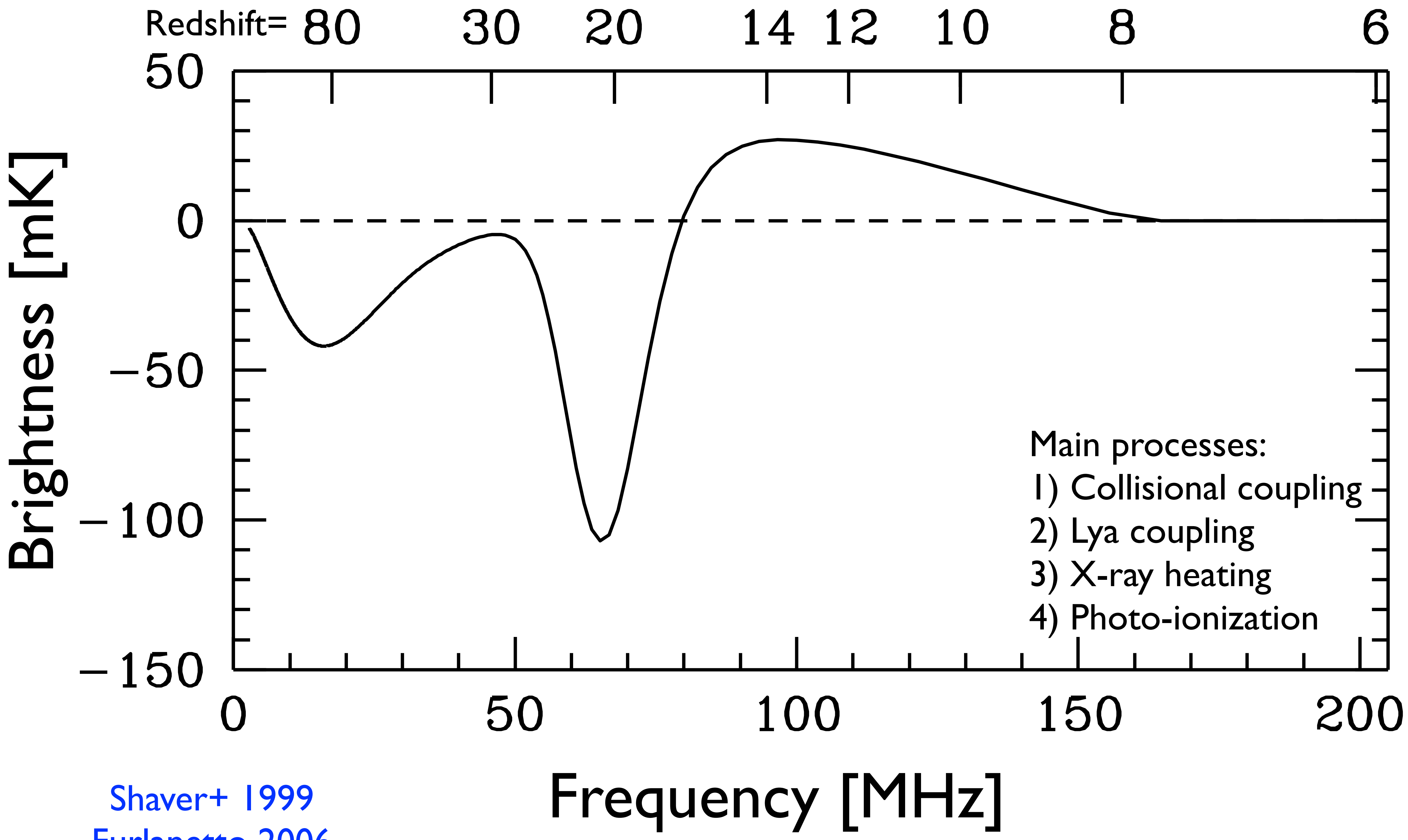
- Only weak constraints from diffuse soft X-ray background

Dijkstra, Haiman, Loeb 2004

- Fiducial model extrapolates local X-ray-FIR correlation to connect X-ray emission to star formation rate

  ~1 keV per baryon in stars

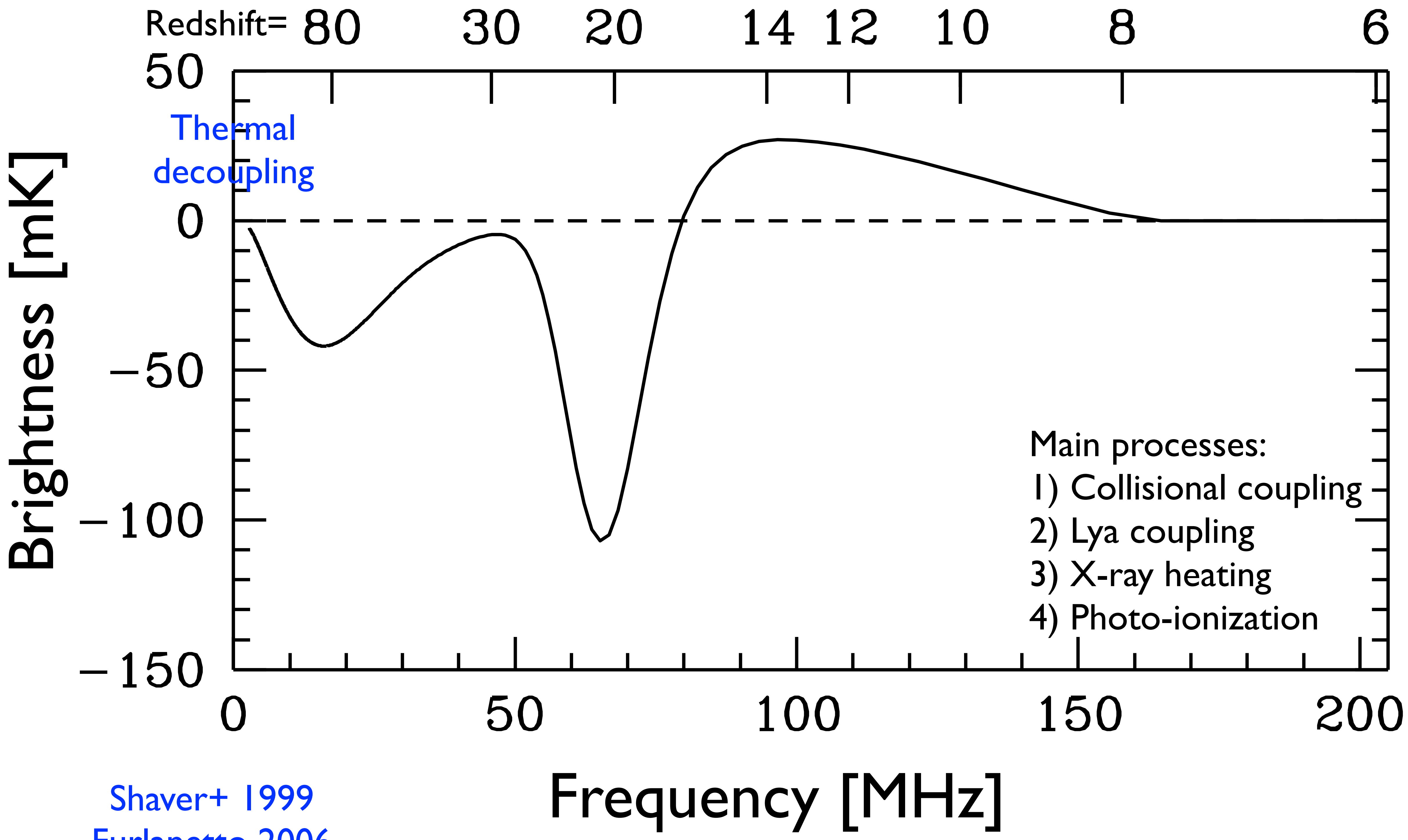
21 cm global signal



Main processes:
1) Collisional coupling
2) Lya coupling
3) X-ray heating
4) Photo-ionization

Shaver+ 1999
Furlanetto 2006
Pritchard & Loeb 2010

21 cm global signal



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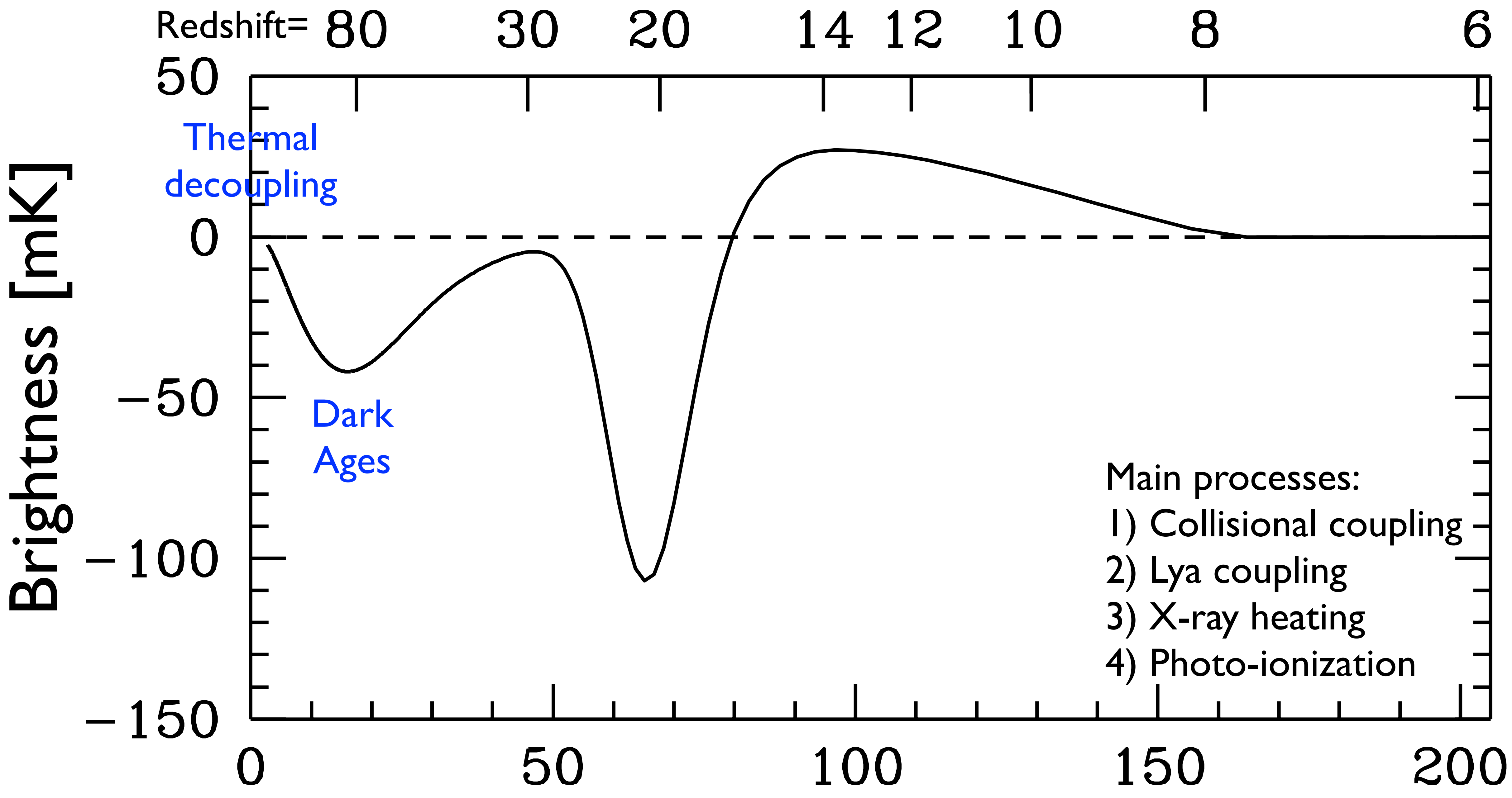

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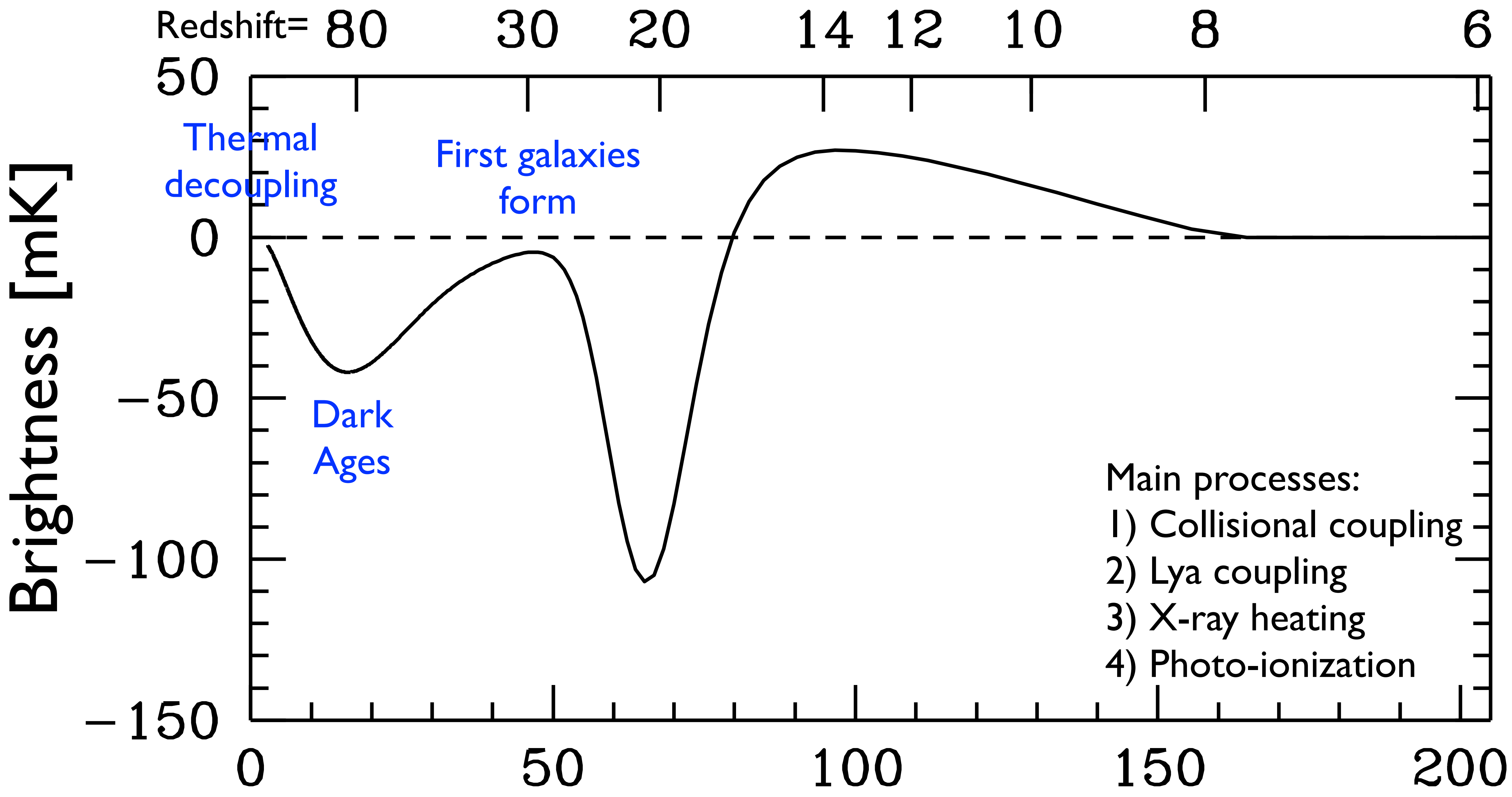

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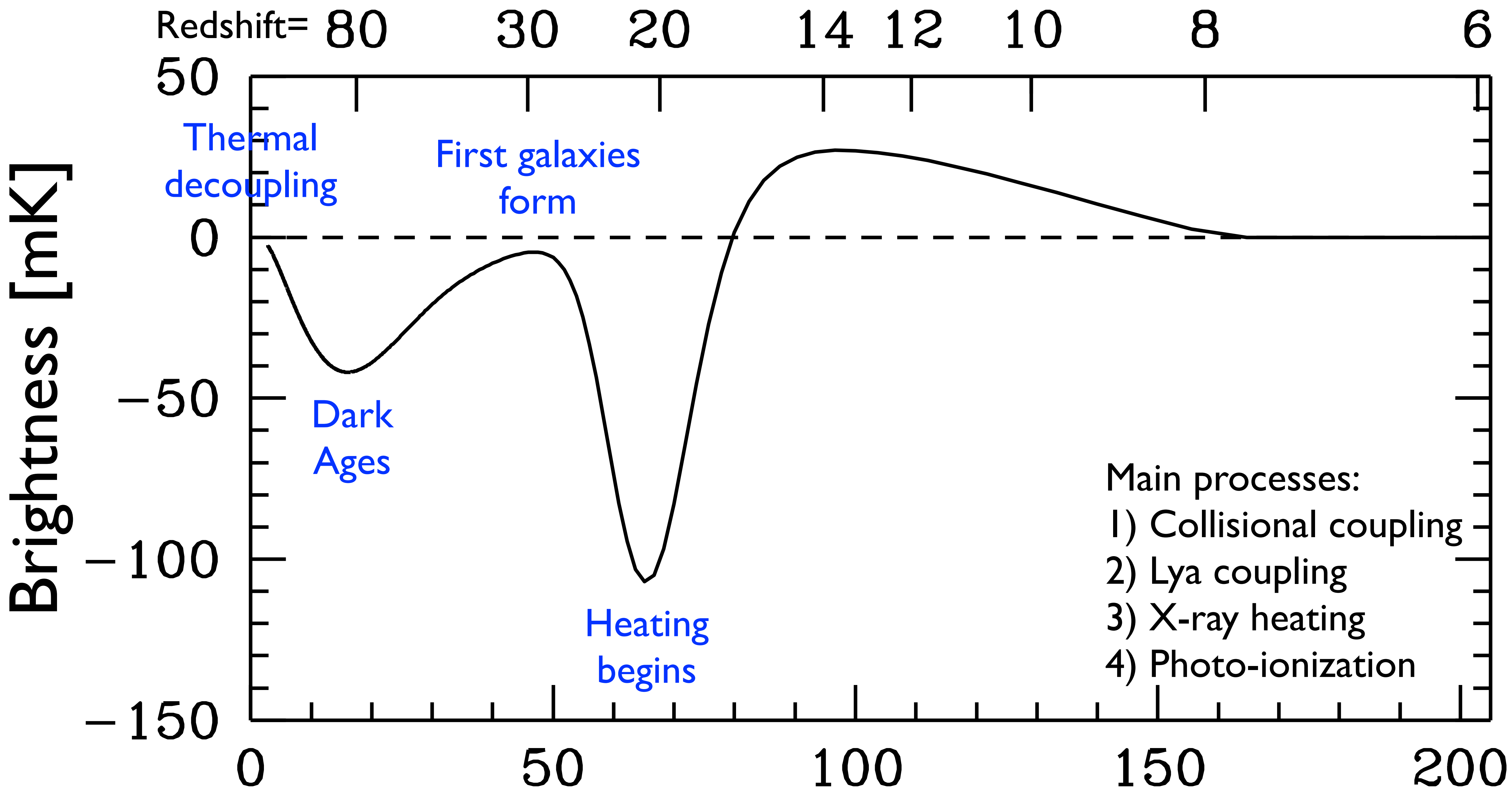

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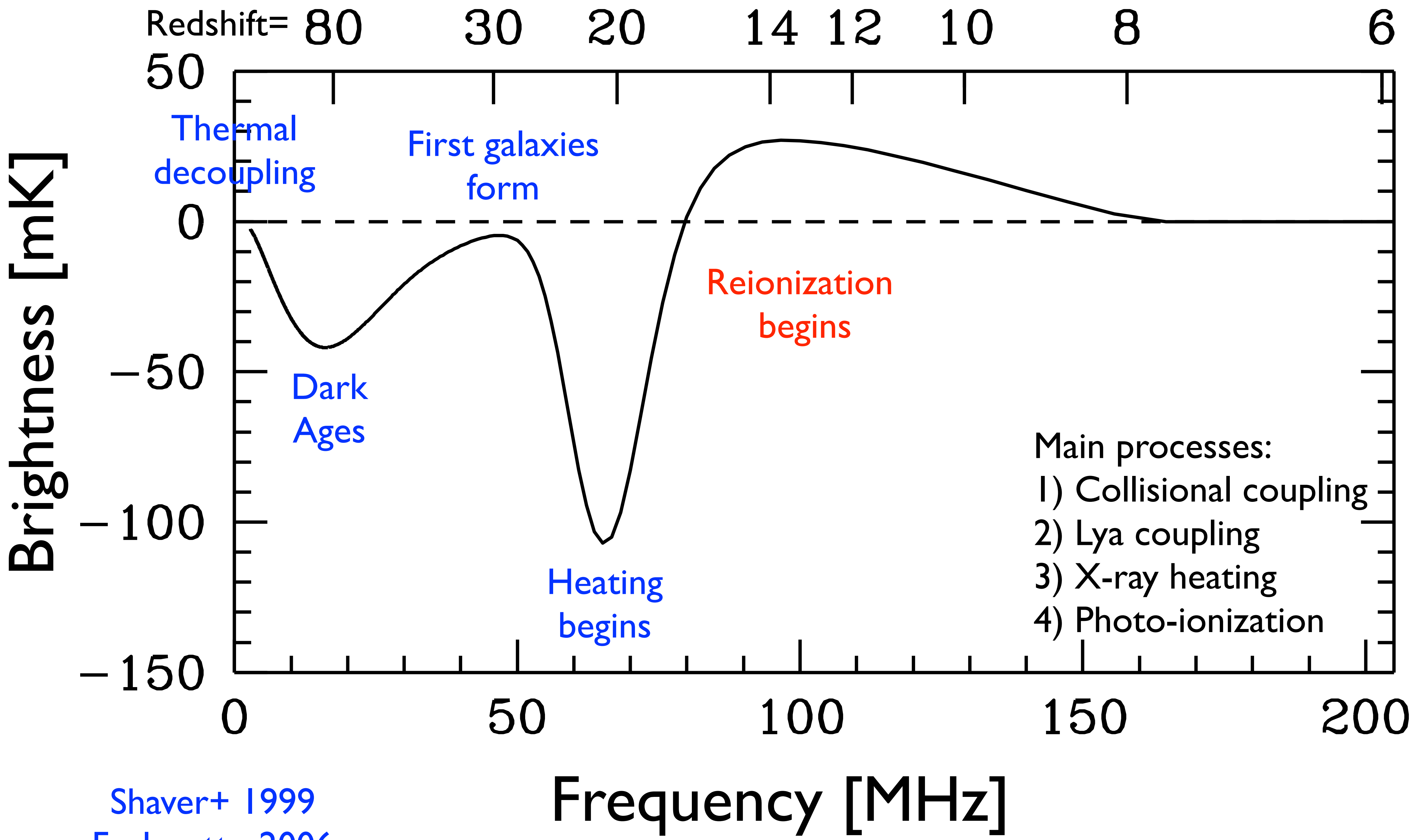

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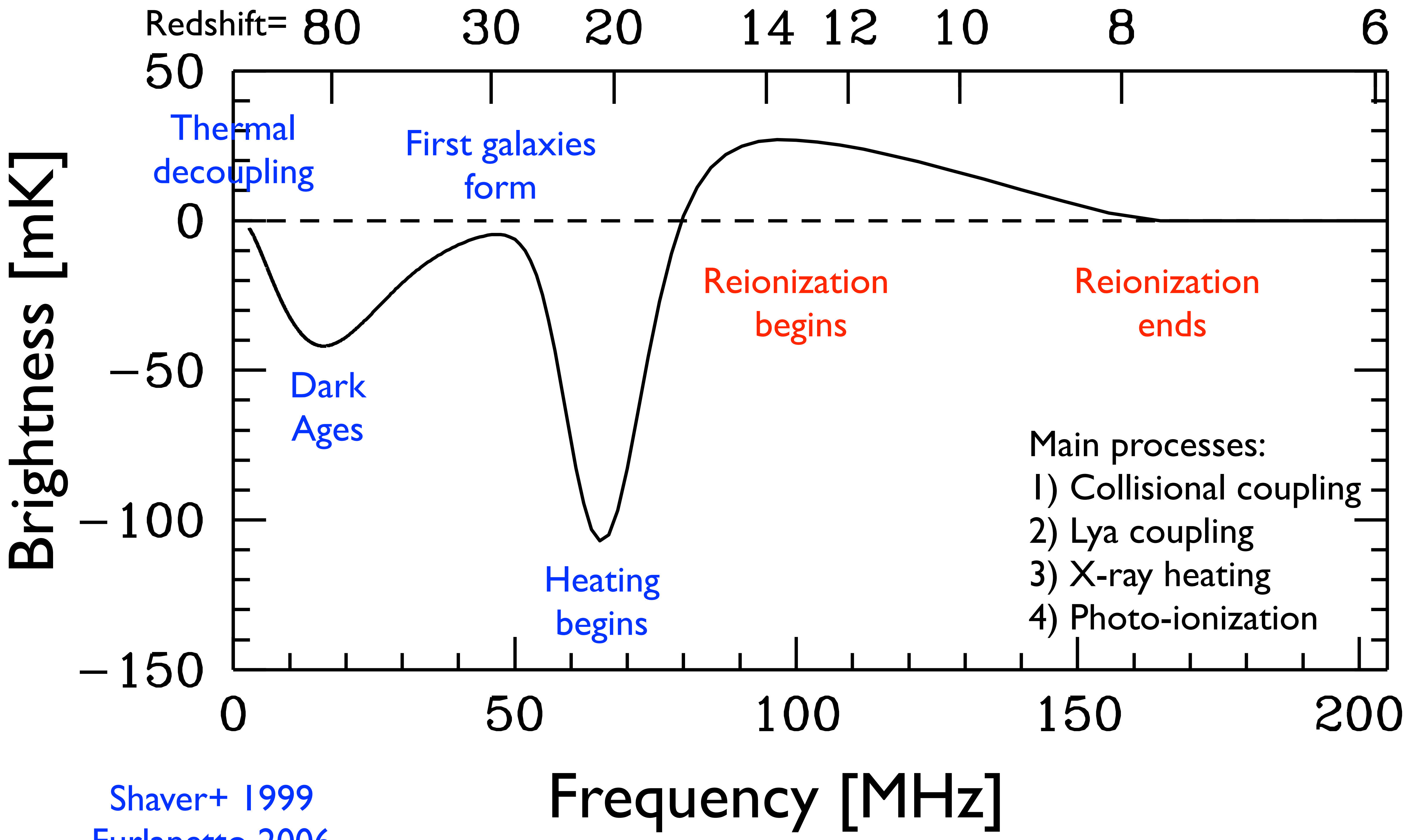

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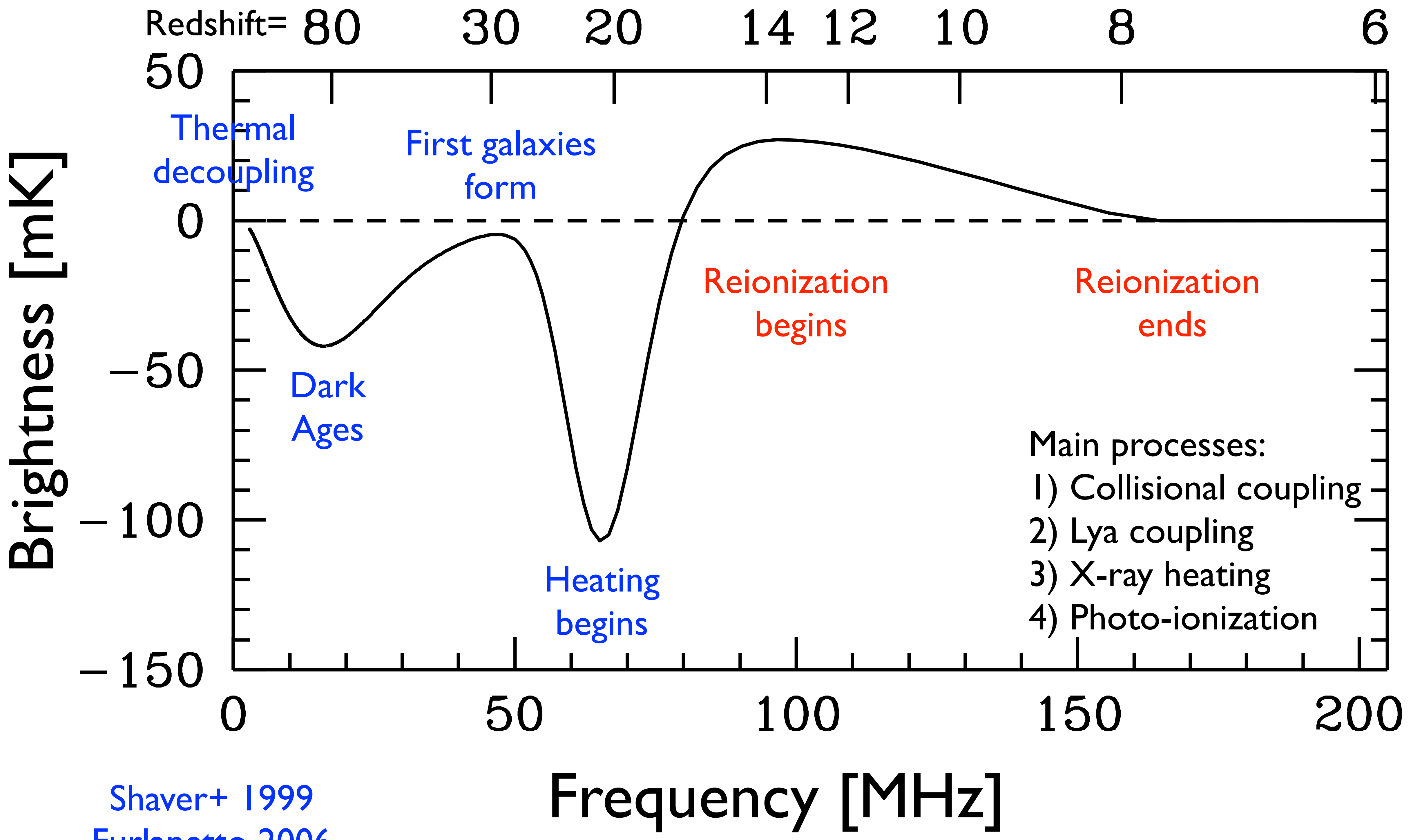

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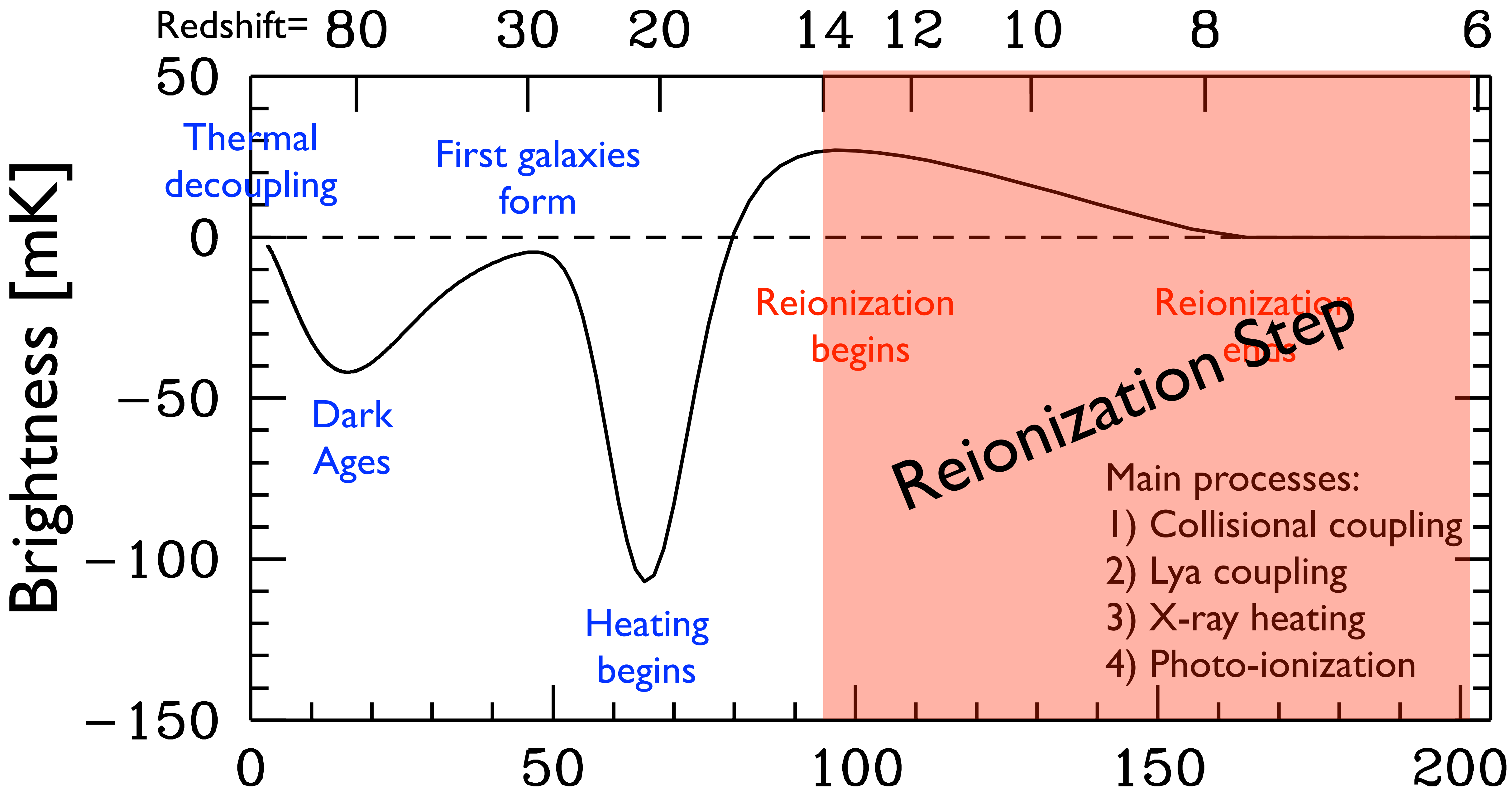
measurement would constrain basic features of first galaxies

21 cm global signal



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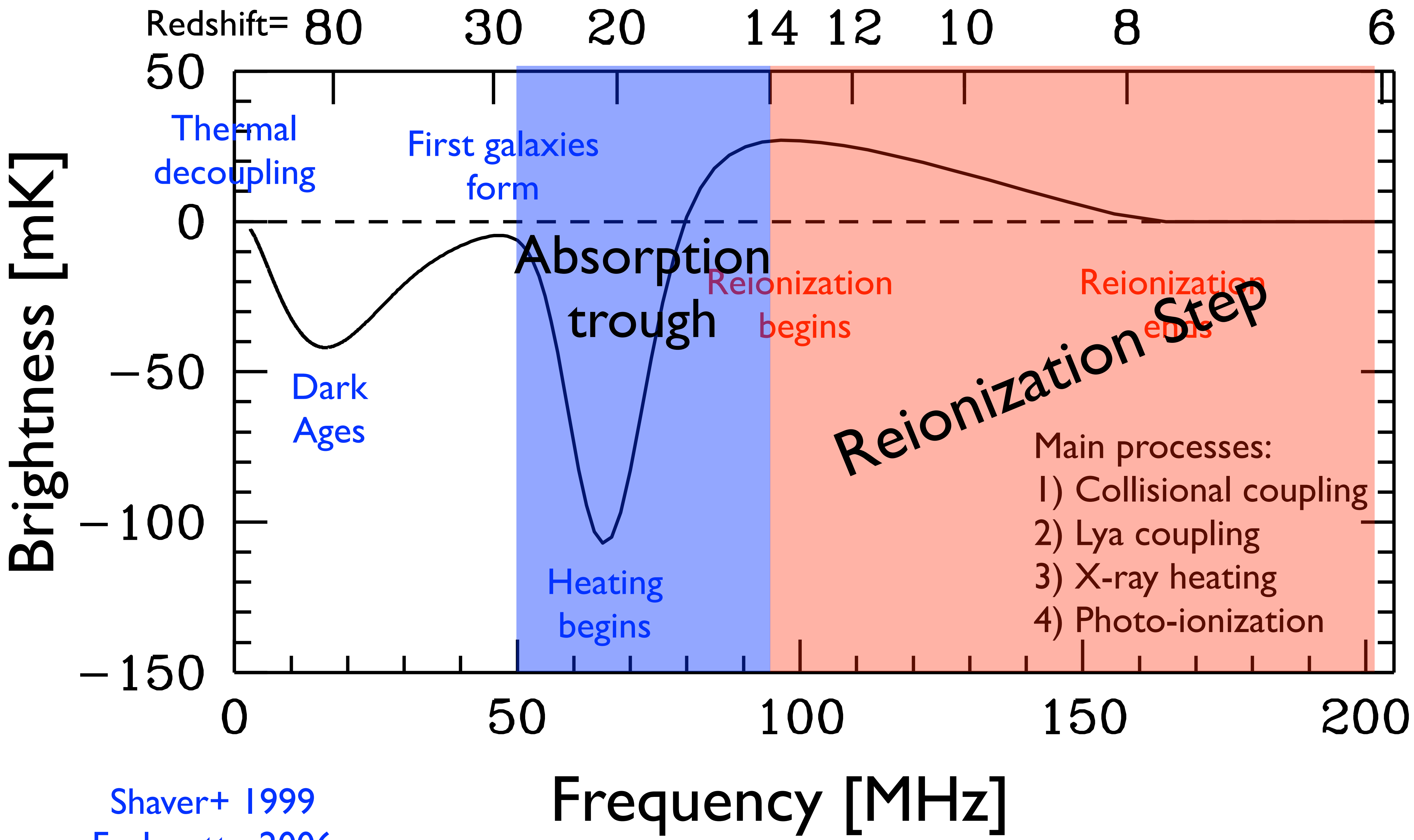

Shaver+ 1999
Furlanetto 2006
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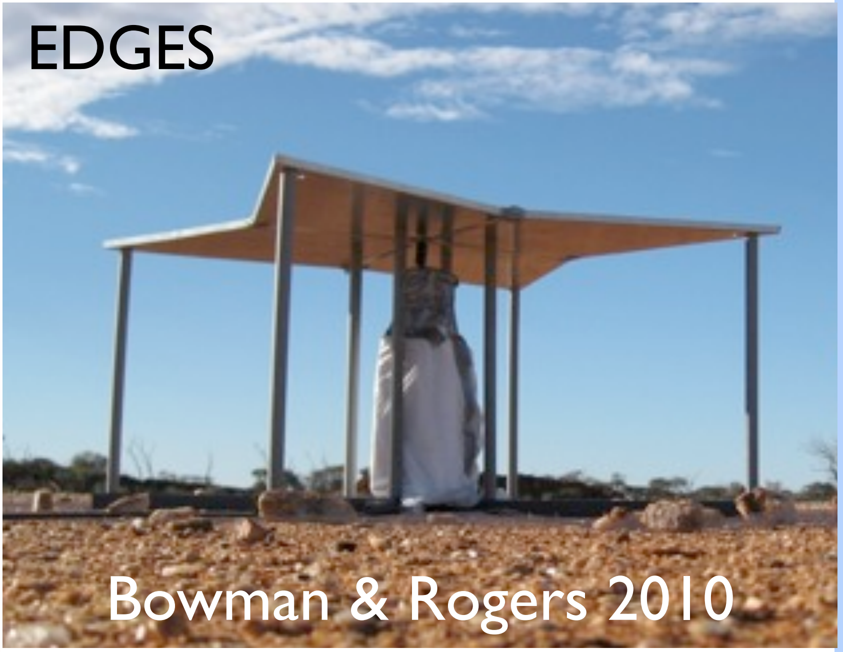
measurement would constrain basic features of first galaxies

Absolute temperature measurements


EDGES

Bowman & Rogers 2010


BIGHORNS - Tingay+

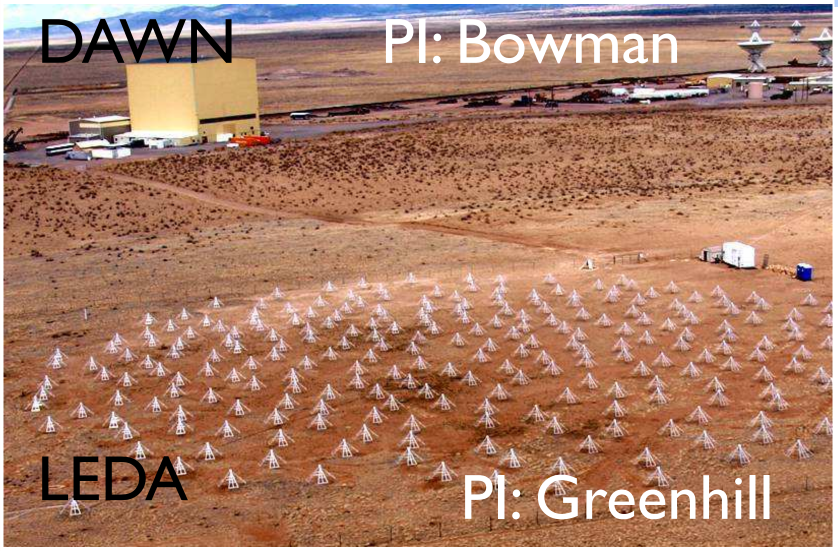

ZEBRA - PI: Subrahmanyan

also CoRE - Ekers+

DARK AGES RADIO EXPLORER

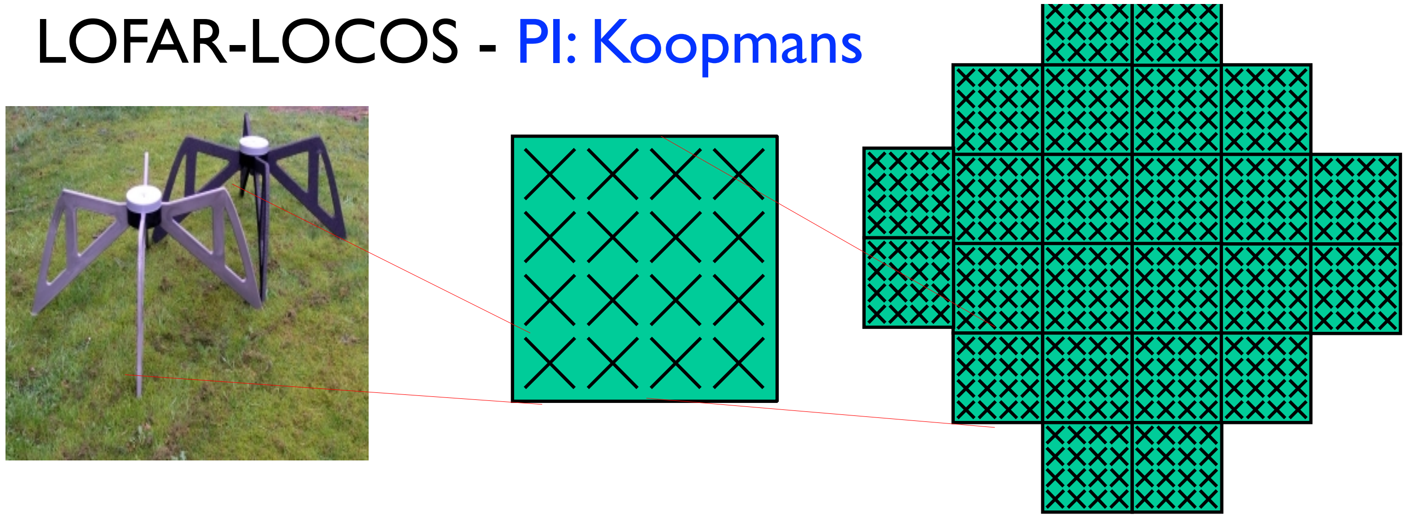
DARE

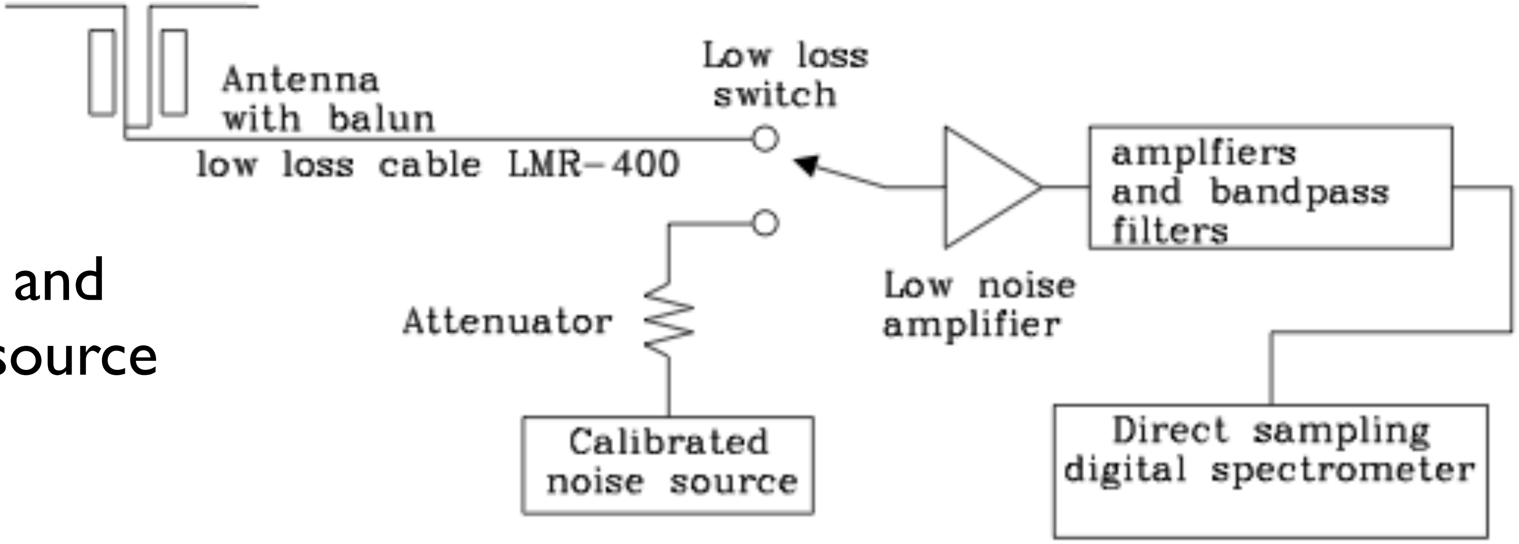
Burns+


DAWN PI: Bowman

LEDA PI: Greenhill

LOFAR-LOCOS - PI: Koopmans




Antenna with balun

low loss cable LMR-400

Low loss switch

Attenuator

Calibrated noise source

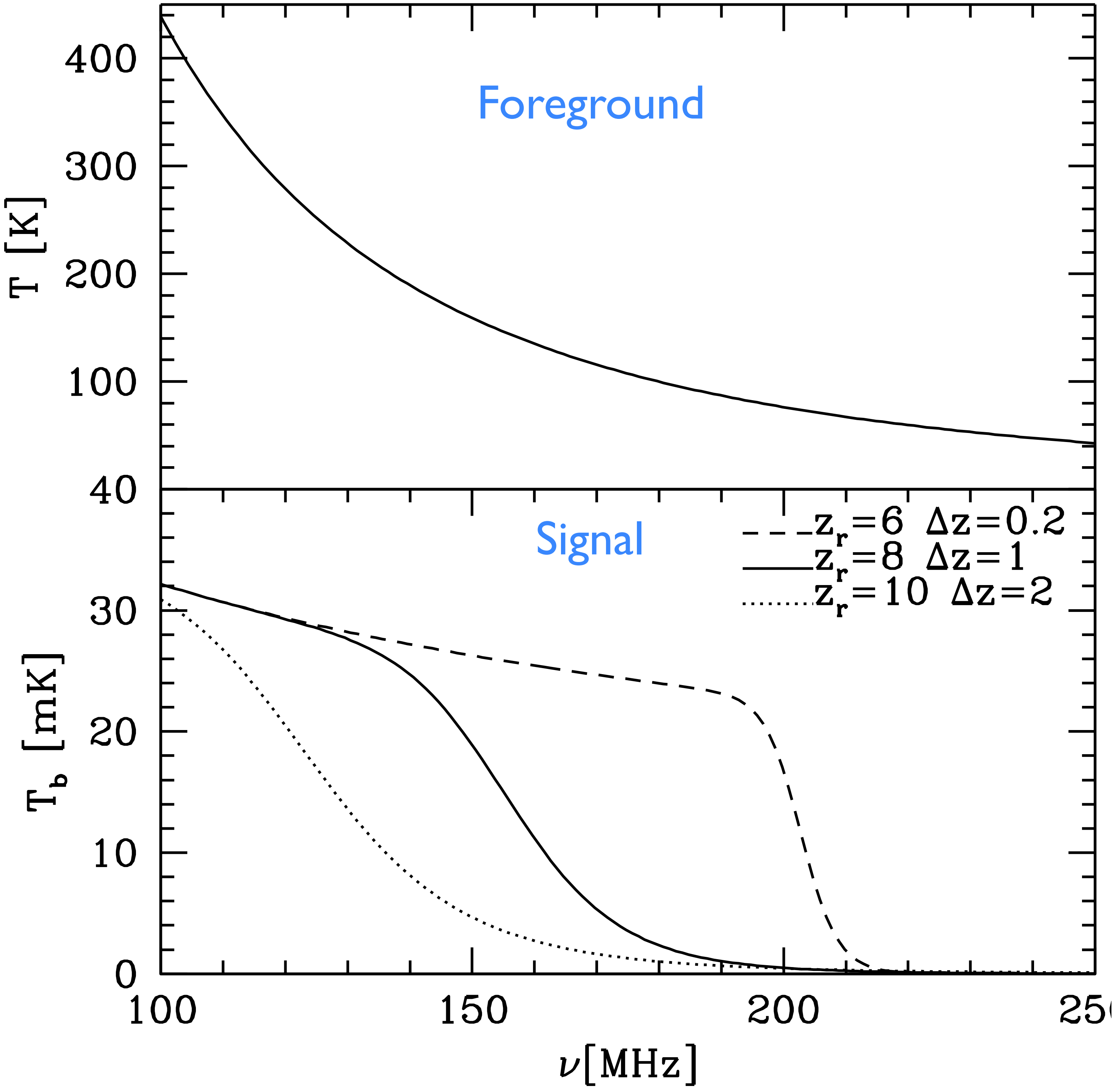
Low noise amplifier

amplfiers and bandpass filters

Direct sampling digital spectrometer

Switch between sky and calibrated reference source

Foreground removal



$$T_b(z) = \frac{T_{21}}{2}\left(\frac{1+z}{10}\right)^{1/2}\left[\tanh\left(\frac{z-z_r}{\Delta z}\right)+1\right]$$

Look for sharp 21 cm features against smooth foregrounds
Shaver+ 1999

$$\log T_{\rm fit} = \sum_{i=0}^{N_{\rm poly}} a_i \log(\nu/\nu_0)^i.$$

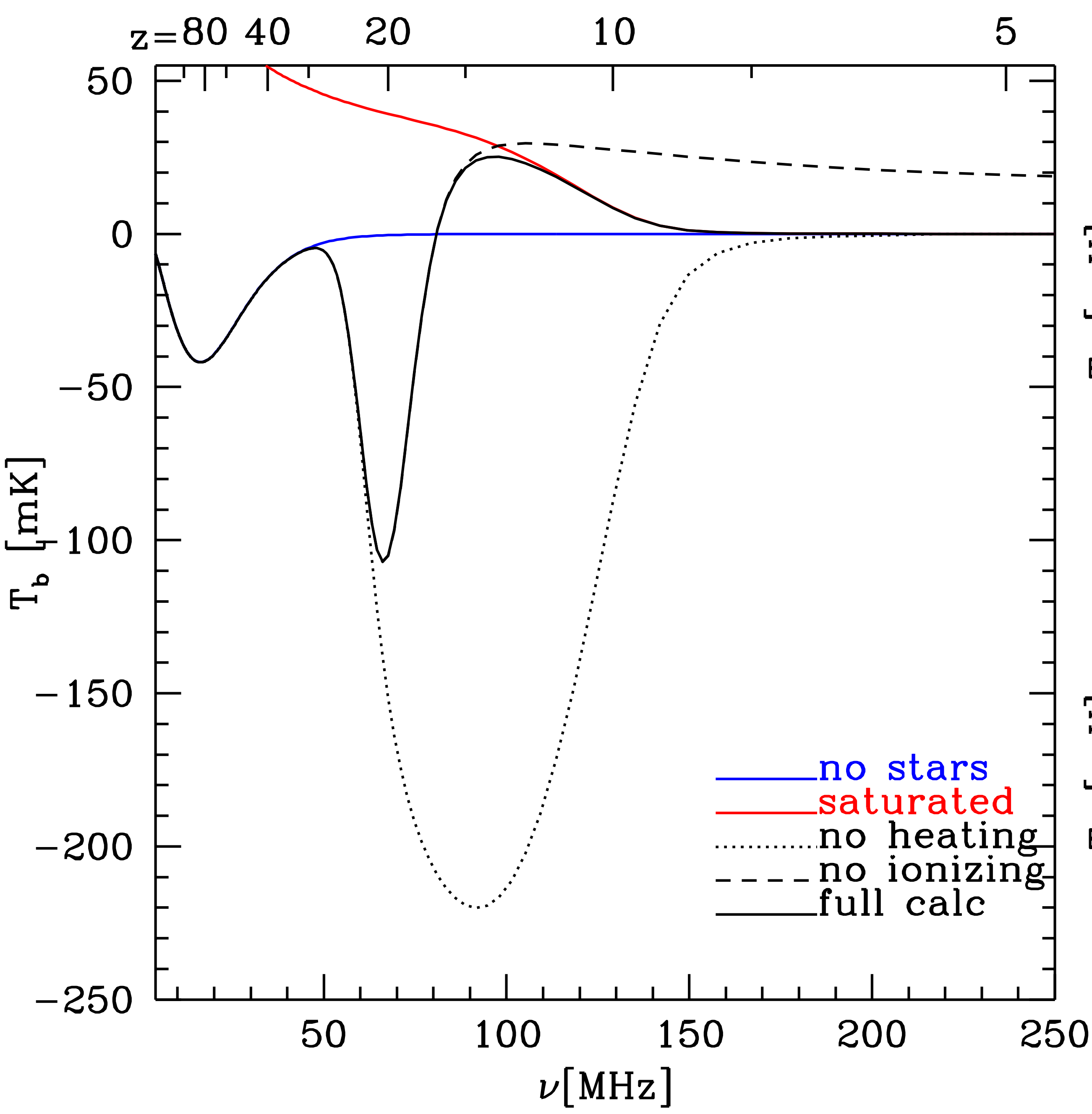
Extended reionization histories closer to foregrounds

Can also exploit spatial information
- dipole with gain e.g. DARE
- array e.g. LWA as LEDA, LOFAR tile as LOCOS

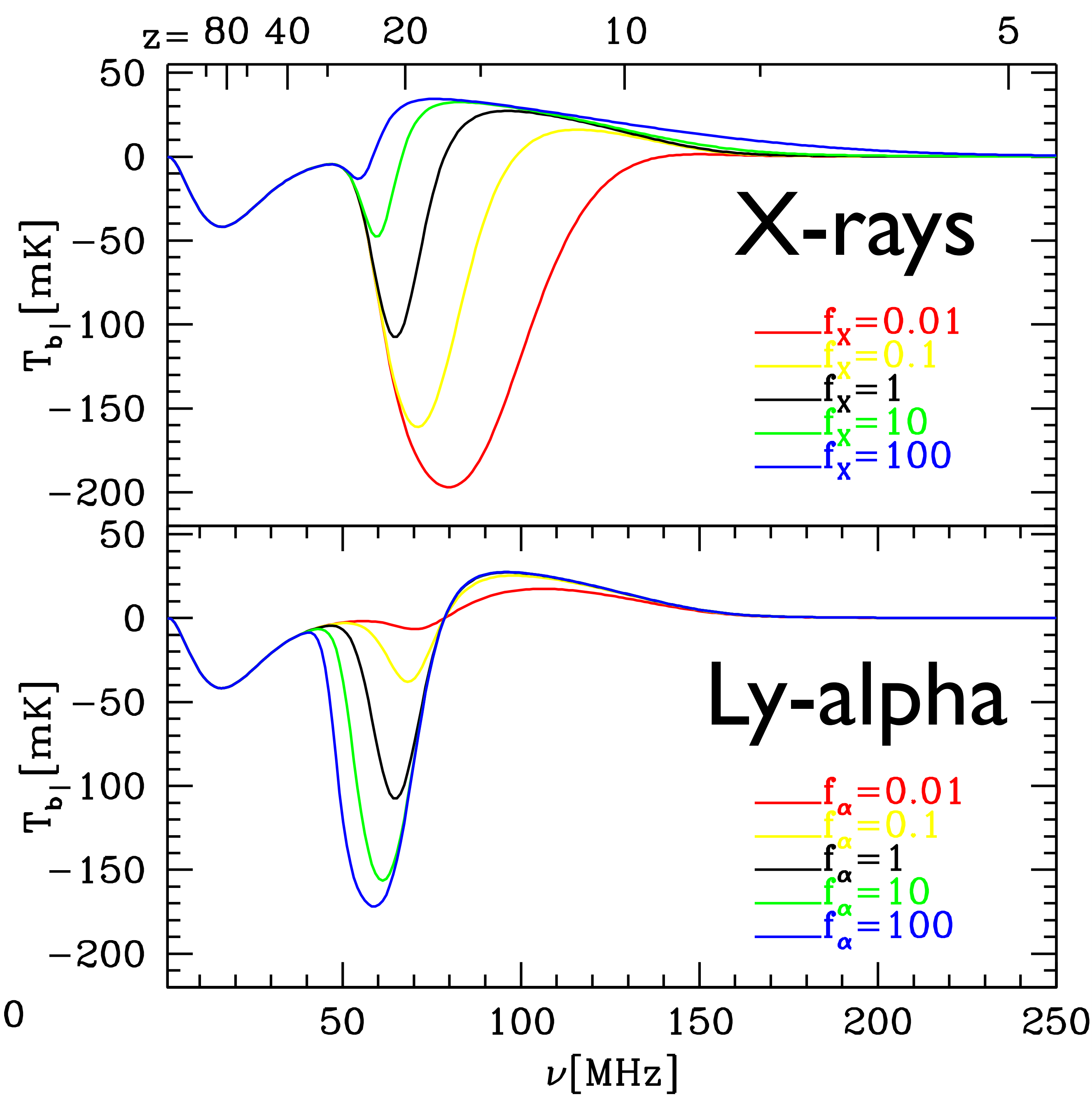
Liu, Pritchard, Tegmark, Loeb 2012

Stories and myths

Do we have all the physics?



What do galaxies look like?



absorption trough
probes properties
of first galaxies

reionization step
constrains duration
and when of reionization

Pritchard & Loeb 2010

21 cm global signal

- 21 cm global signal accessible with few-N dipole experiments

- Instrumental calibration and foreground removal are key to extracting astrophysics

Harker, Pritchard, Burns, Bowman 2011
Liu, Pritchard, Tegmark, Loeb 2012

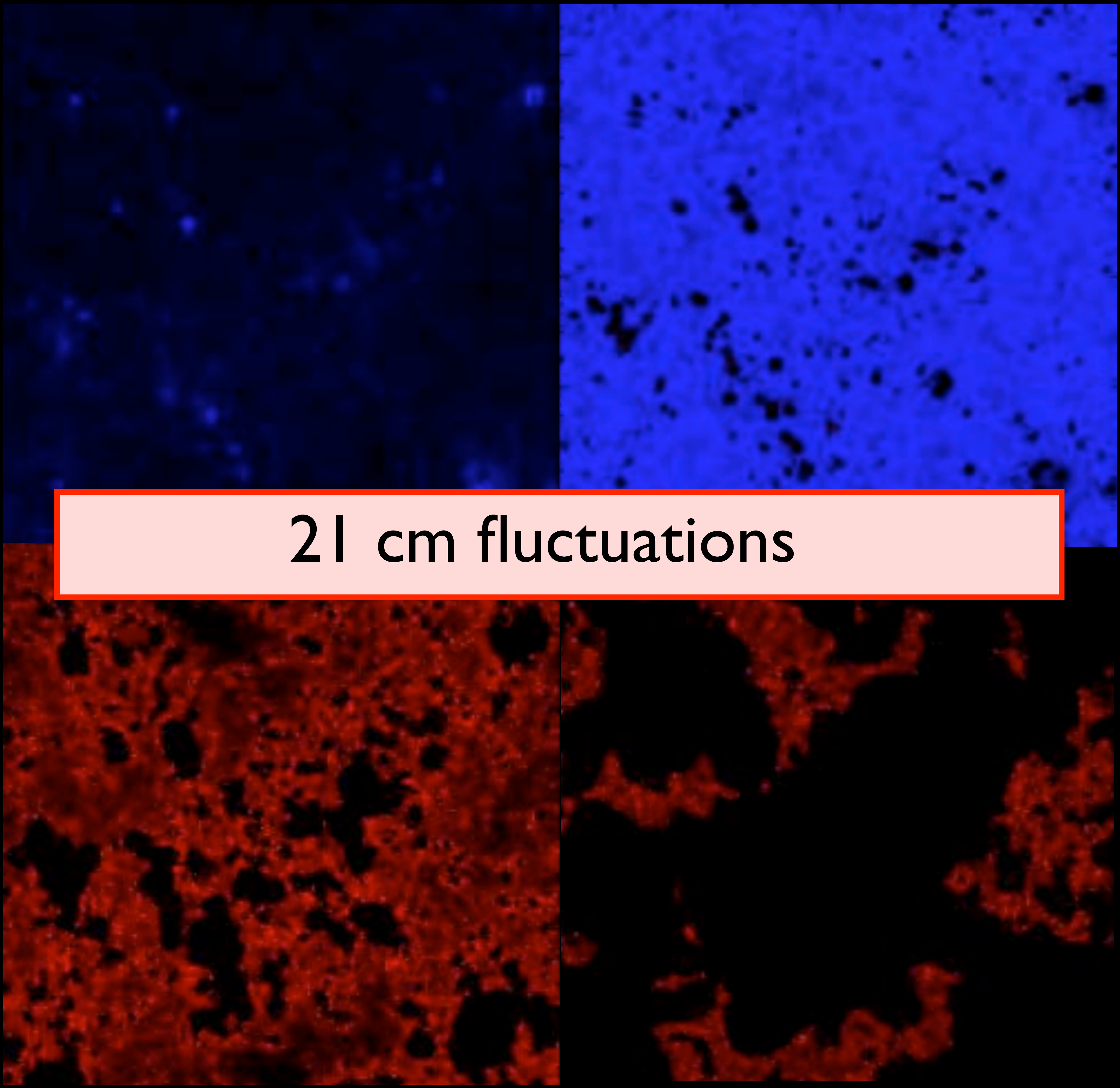
- Sensitive to major transitions in the thermal and ionization history

- Constrains basic properties of the first galaxies (and exotic energy injection)

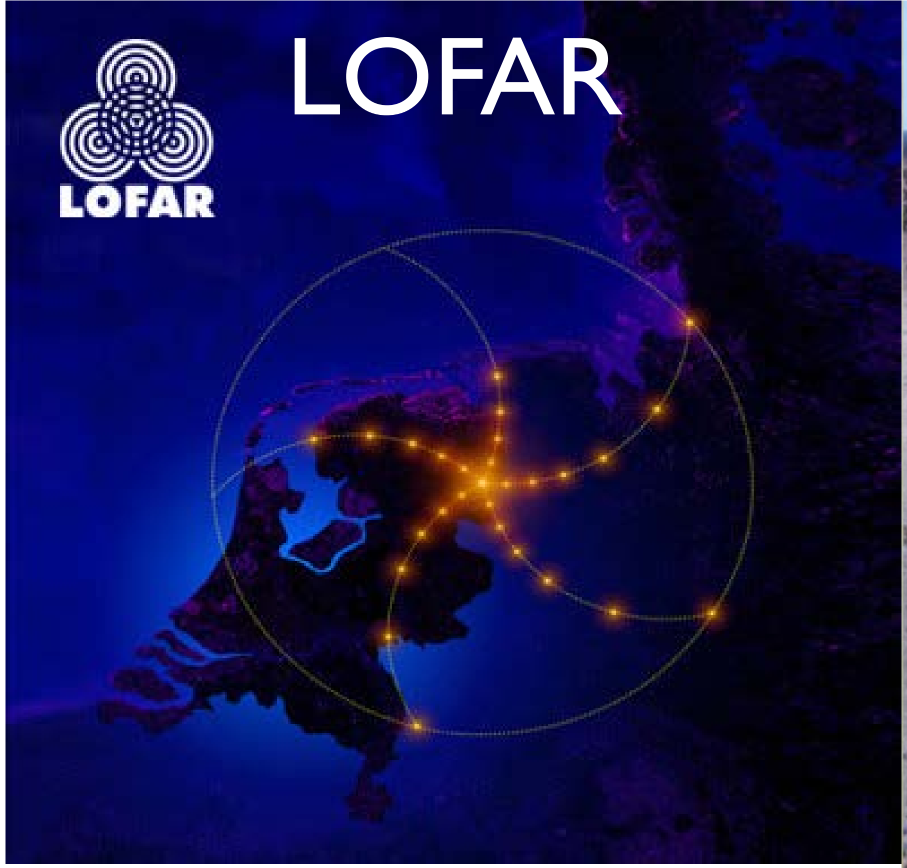
- Experiments in their infancy and lots of room for progress

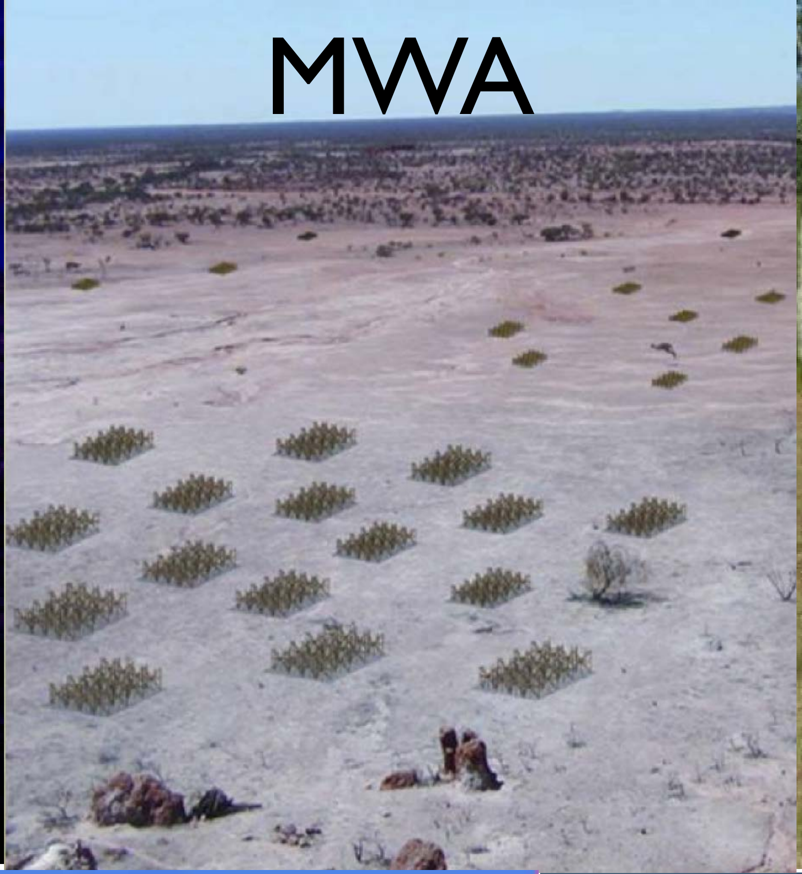
- Complementary to 21cm tomography.

21 cm fluctuations



21 cm experiments


LOFAR


MWA


PAPER


GMRT

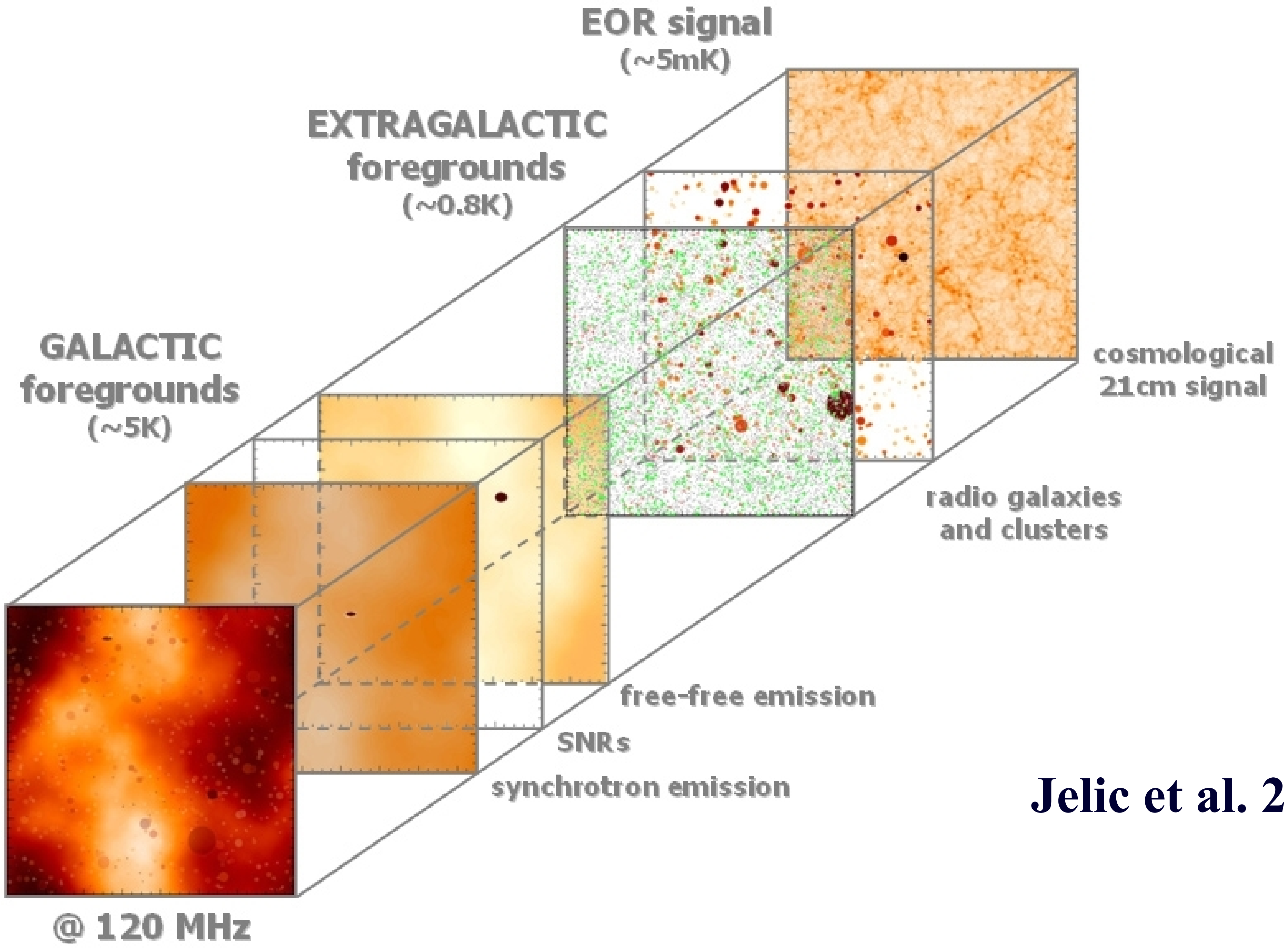

SKA

Several interferometers under construction
data expected in the next few years
probe reionization (z<12)

Next generation required for probing fluctuations
from the first galaxies (z>12)
e.g. Square Kilometer Array (~2017-22)

Foreground removal

Foregrounds ~ 10^3-10^5 signal



Jelic et al. 2008

More on foregrounds in other talks: drives longer baselines for point source removal

Brightness Fluctuations

brightness temperature	density	neutral fraction	gas temperature	Lyman alpha flux	peculiar velocities
	cosmology	reionization	X-ray heating	Lya sources	cosmology

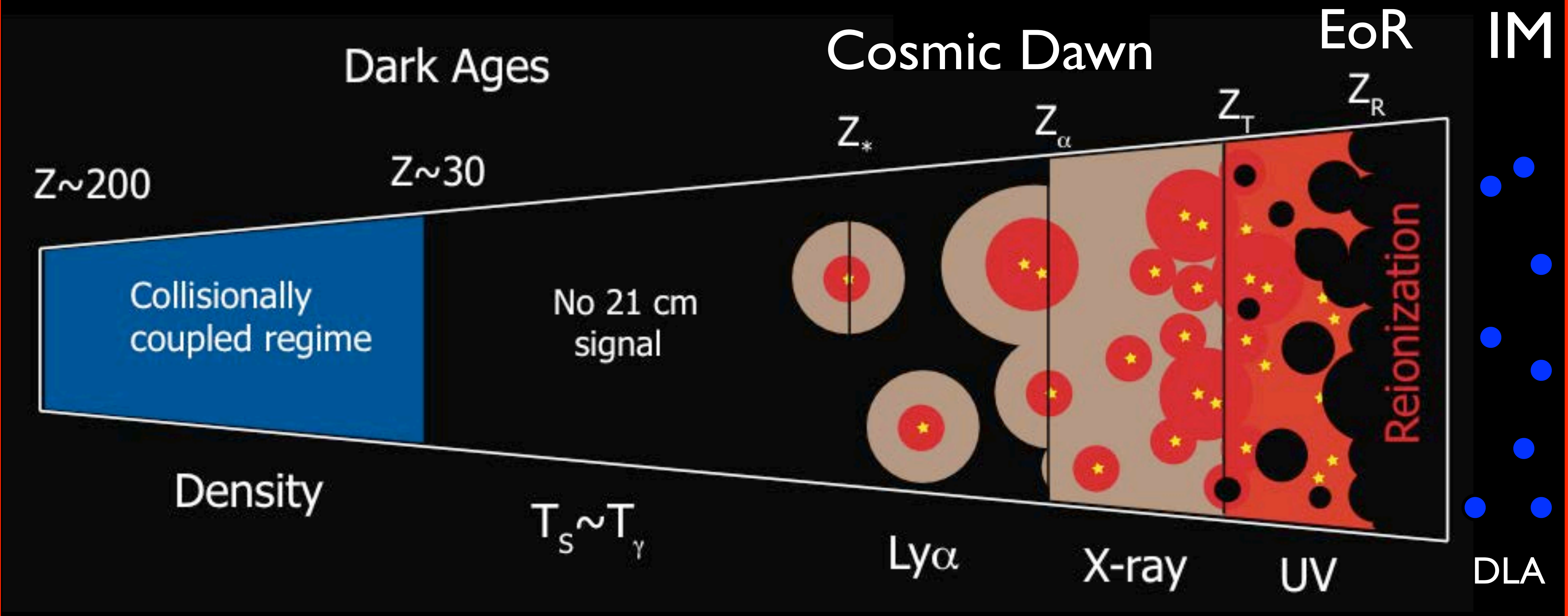
$$\delta_{T_b} = \underbrace{\beta\delta_b + \beta_x\delta_{x_{HI}}}_{\text{Neutral hydrogen}} + \underbrace{\beta_T\delta_{T_k} + \beta_\alpha\delta_\alpha}_{\text{spin temperature}} - \delta_{\partial v}$$

Brightness Fluctuations

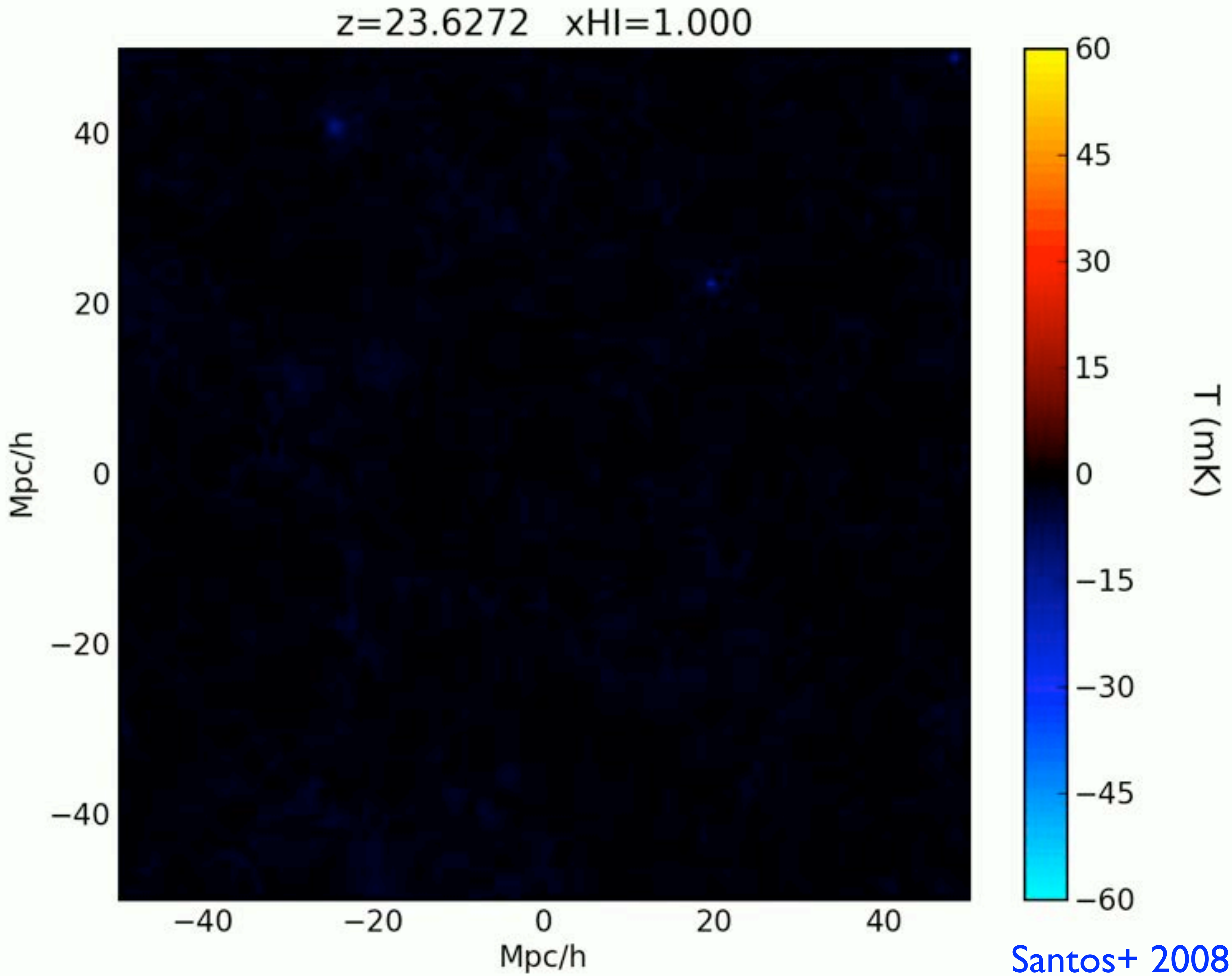
brightness temperature
density
neutral fraction
gas temperature
Lyman alpha flux
peculiar velocities

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

cosmology
reionization
X-ray heating
Lya sources
cosmology

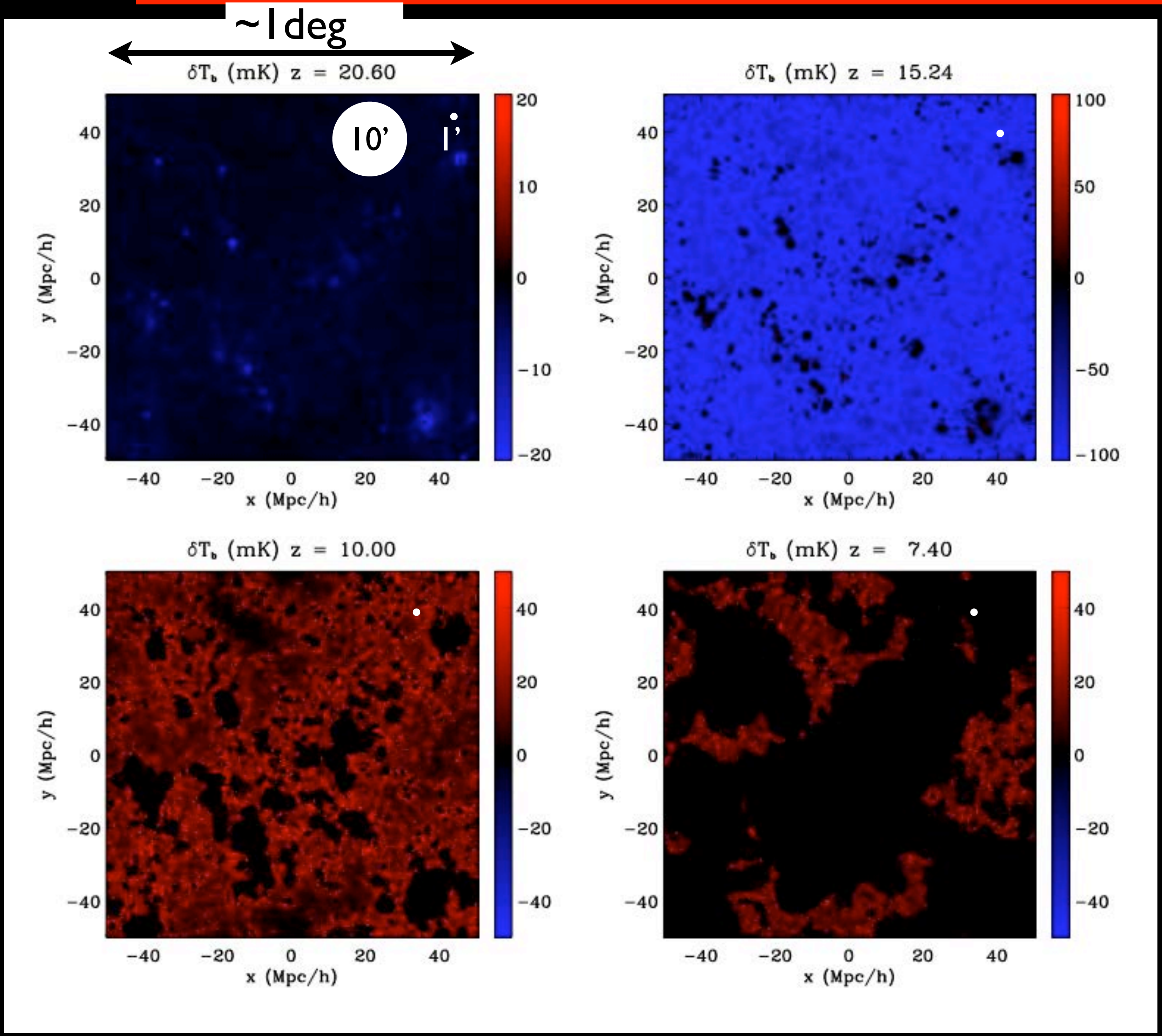


Numerical simulation



Santos+ 2008

Imaging brightness fluctuations



At z=8 (150 MHz)

1 arcmin~0.3 pMpc
~2 cMpc

0.1 MHz~0.3 pMpc
~2 cMpc

1degree~ 100cMpc

Want to resolve bubbles in 3D
and cover large structures towards end of reionization

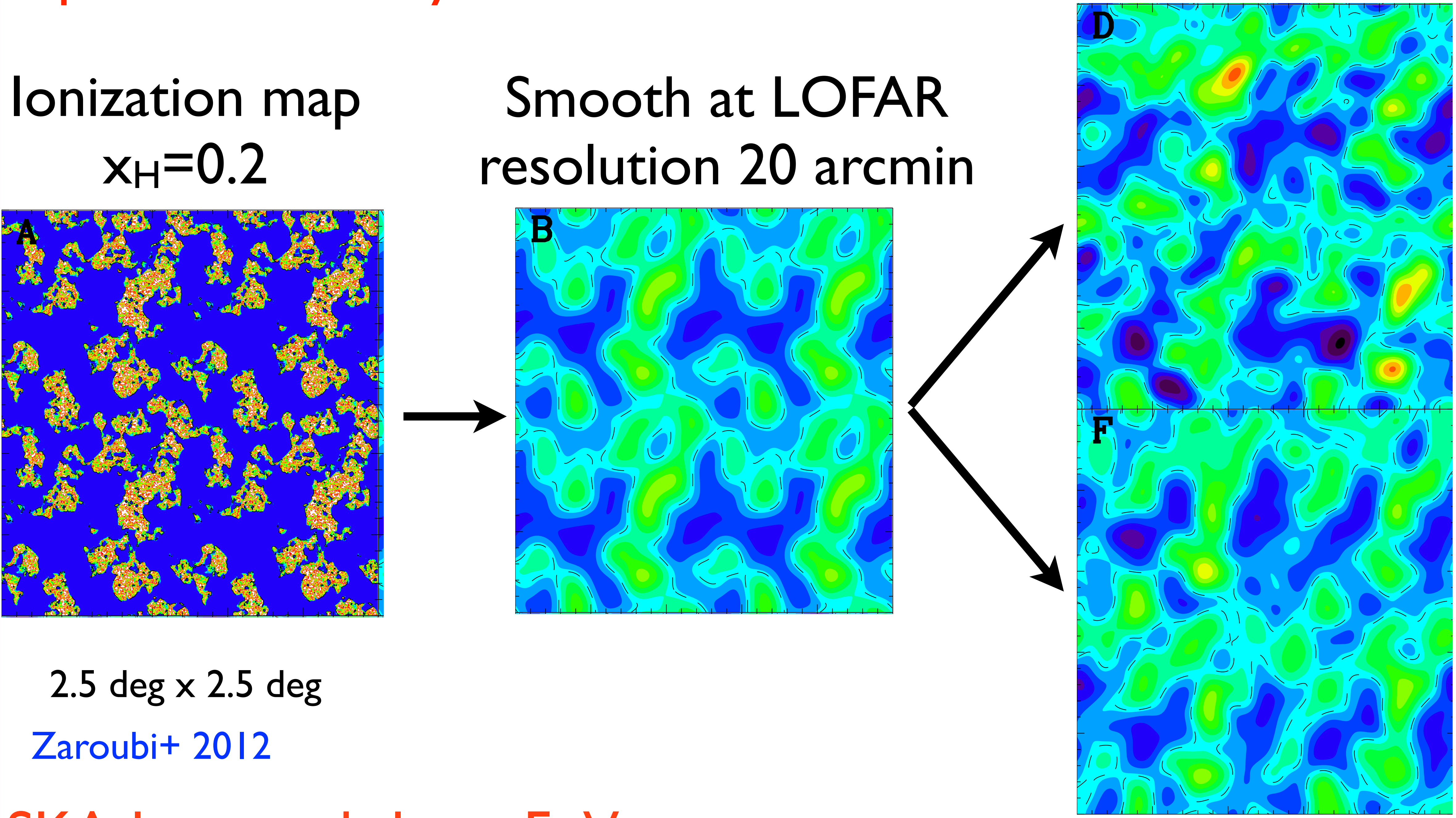
Imaging large scale structures

Correlations in structure on ~120h^{-1} Mpc from LSS may be visible in LOFAR

After noise & foreground removal

Ionization map x_H=0.2

Smooth at LOFAR resolution 20 arcmin



600 hr

2400 hr

2.5 deg x 2.5 deg

Zaroubi+ 2012

SKA-low needs large FoV to image ionized structures from EoR

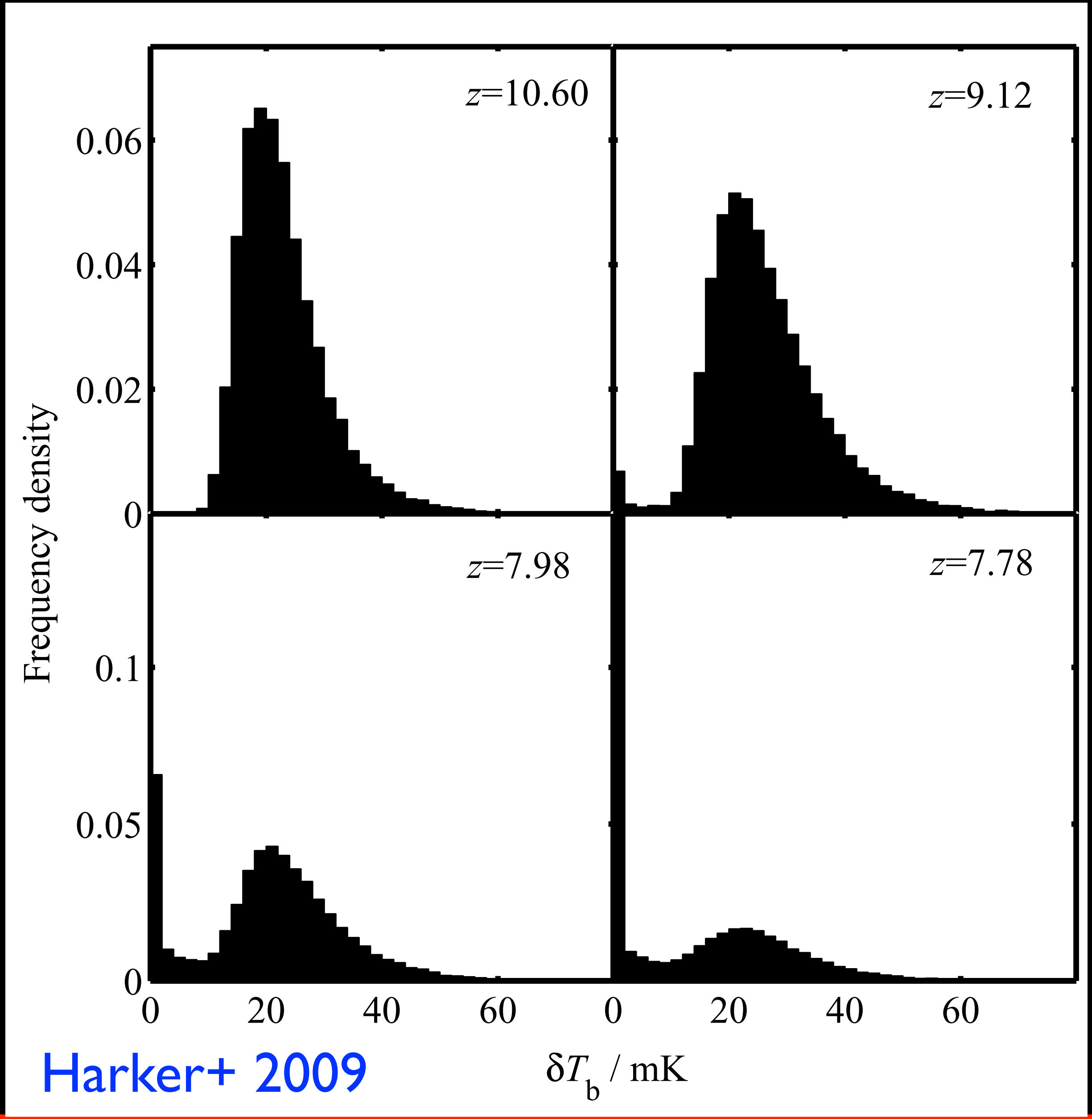
$$V_{\rm survey} \approx 0.1\,{\rm Gpc}^3 \left(\frac{\theta}{5^\circ}\right)^2 \left(\frac{B}{12\,{\rm MHz}}\right) [(1+z)^{1/2}-2]$$

Statistical probes

Power spectrum will be dominant statistical signature

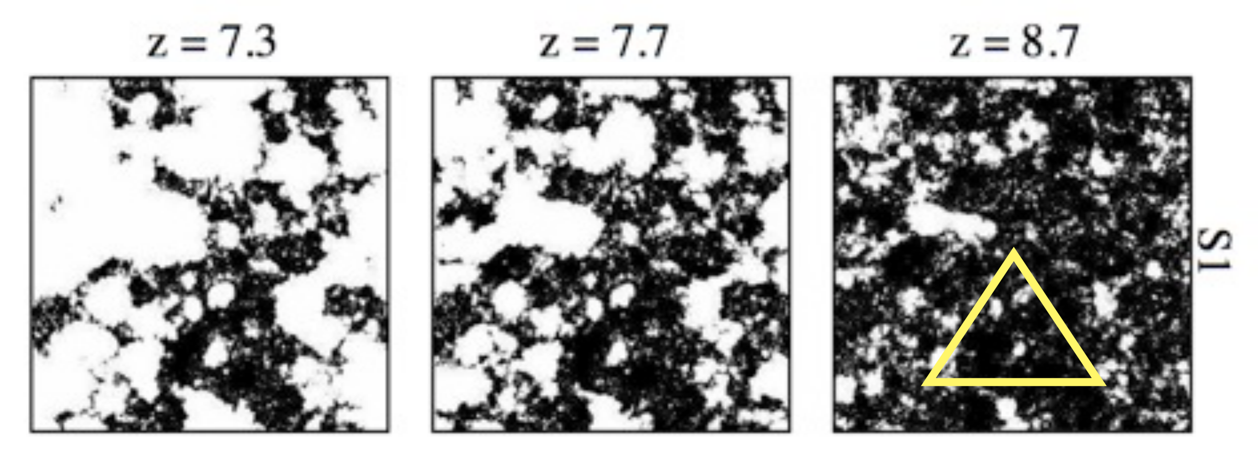
Ionization field is highly non-Gaussian => statistics beyond power spectrum are important

1-point function



Harker+ 2009

3-point correlations



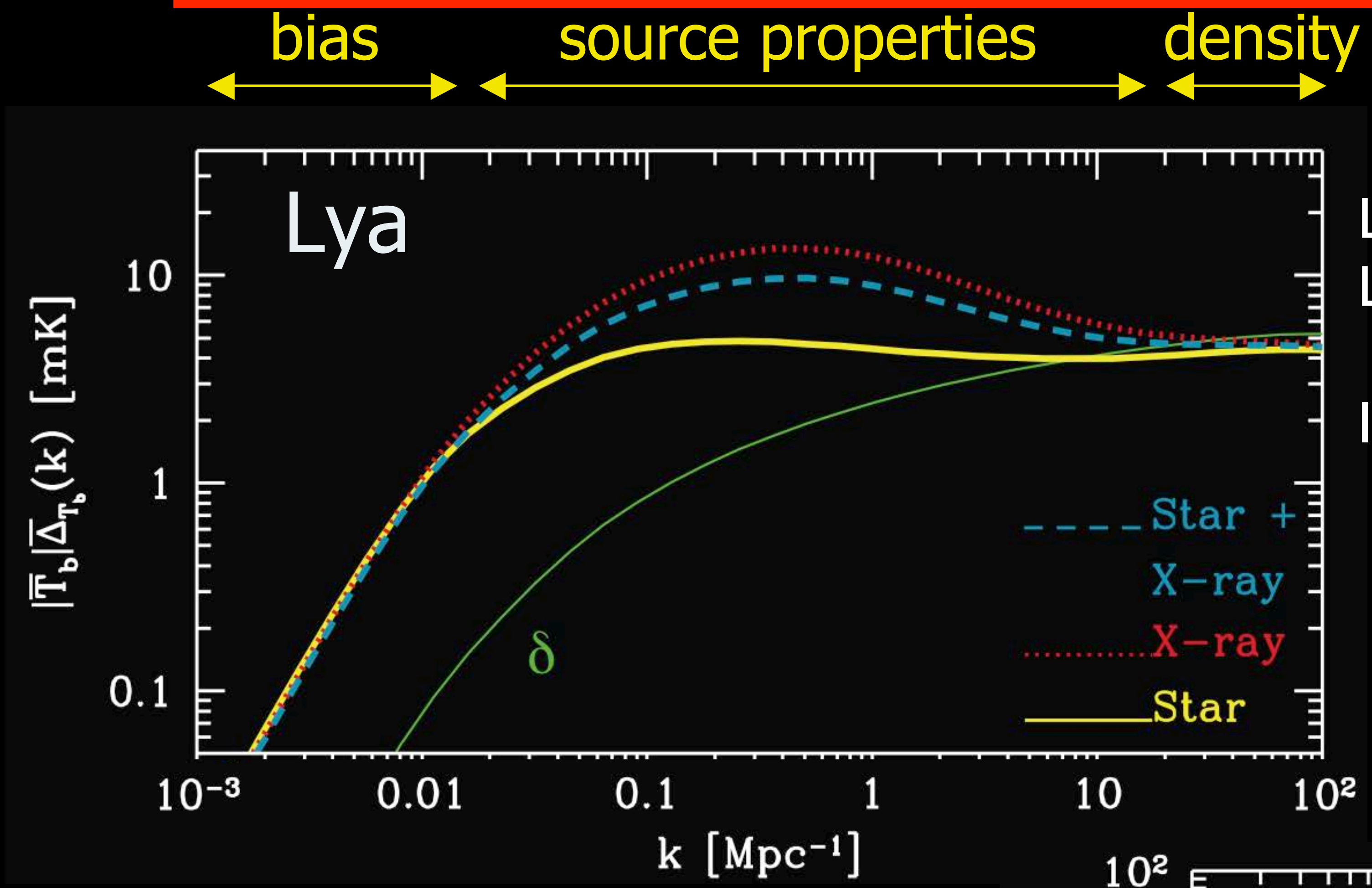
Important to explore new statistics that might be useful:

- skewness, bispectrum, wavelets, threshold statistics, ...?

Friedrich+ 2010, ...

Good for identifying astrophysics & foreground residuals

Power spectrum



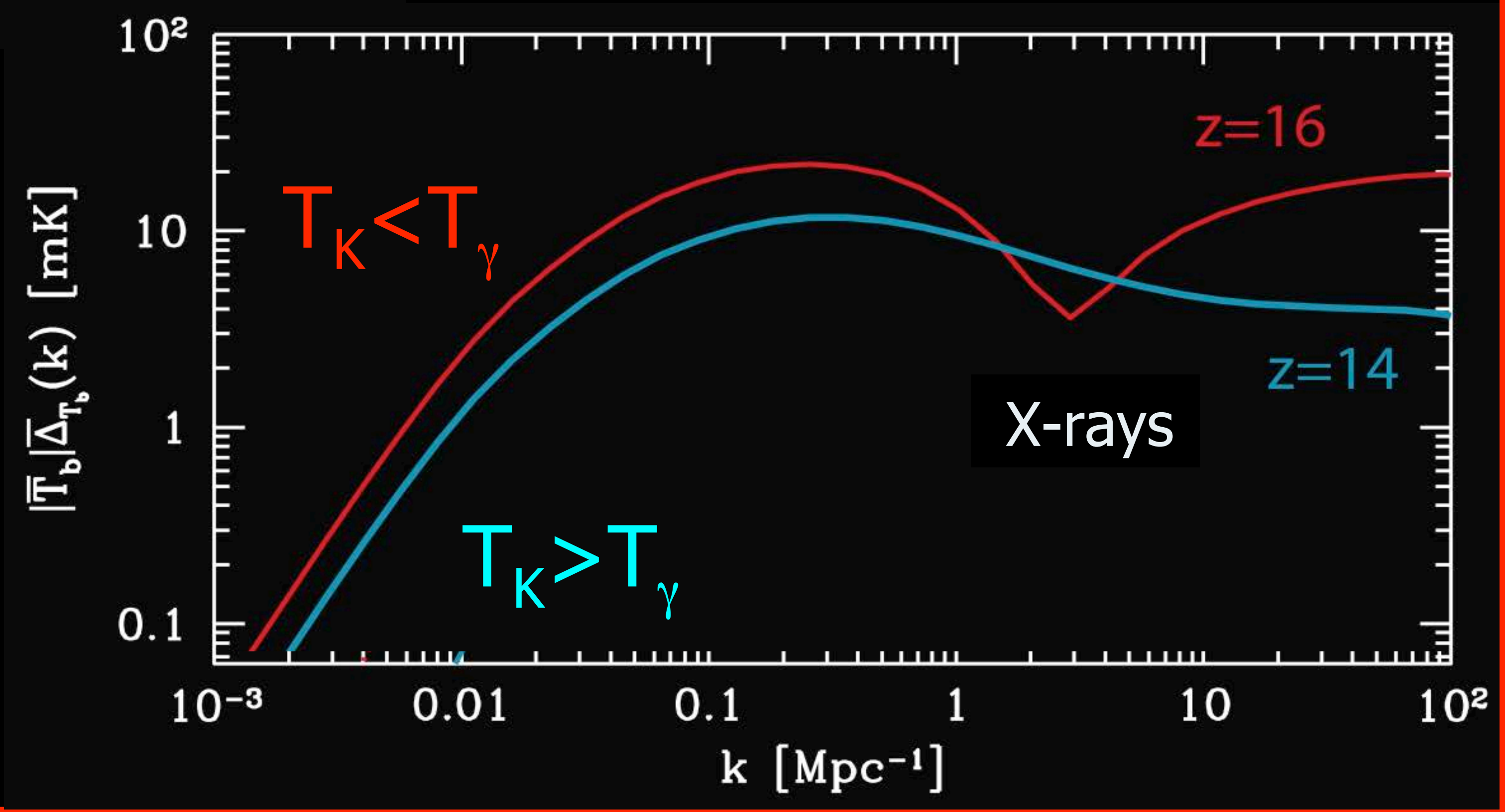
Lya fluctuations add power on large scales
Largest scales give information on source bias
Intermediate scales on source spectrum

Barkana & Loeb 2004
Chuzhoy, Alverez & Shapiro 2006
Pritchard & Furlanetto 2006

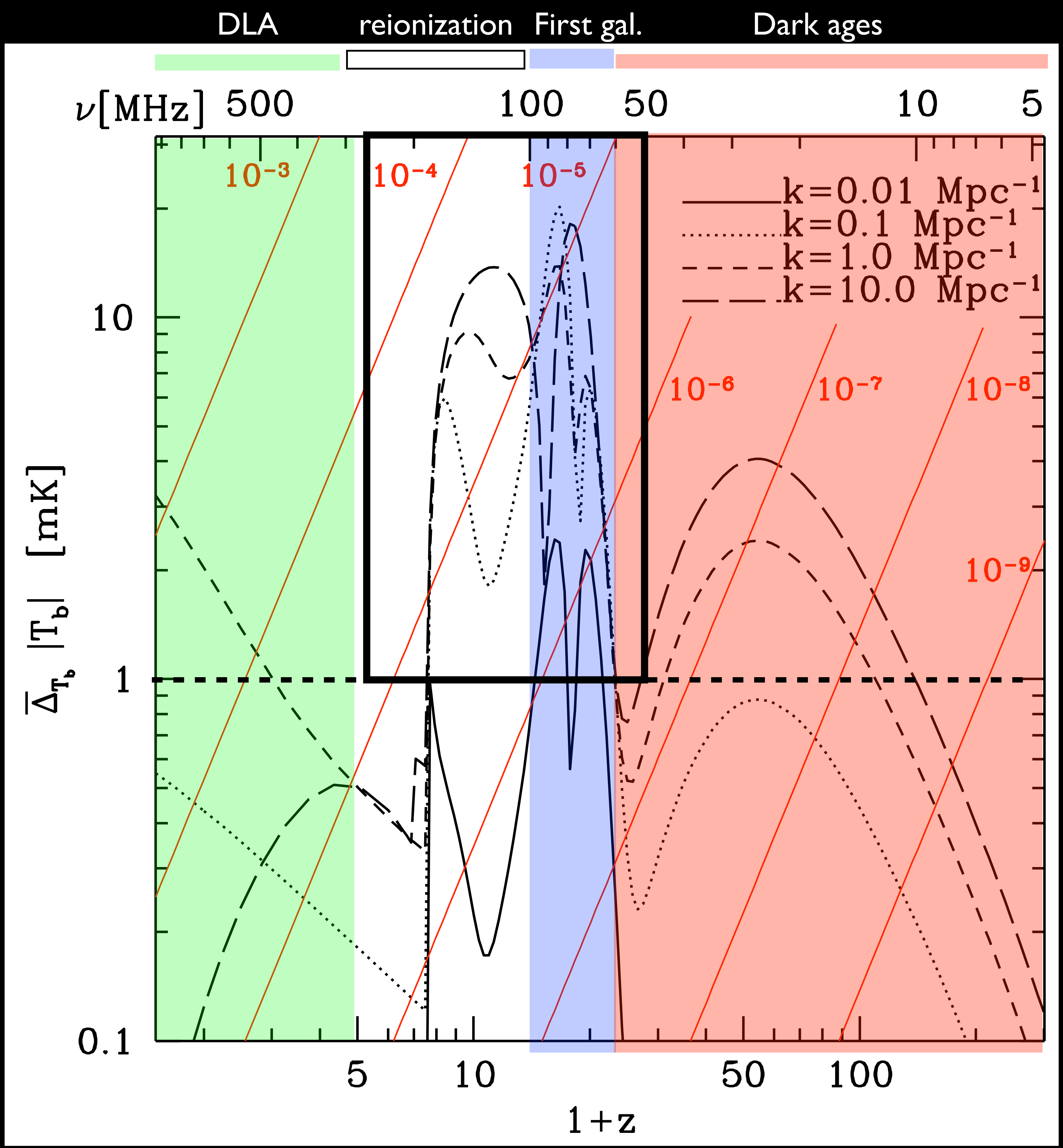
T fluctuations give information on thermal history

clustering/growth of mini-quasars could be very different

Pritchard & Furlanetto 2007



Evolution of power spectrum



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

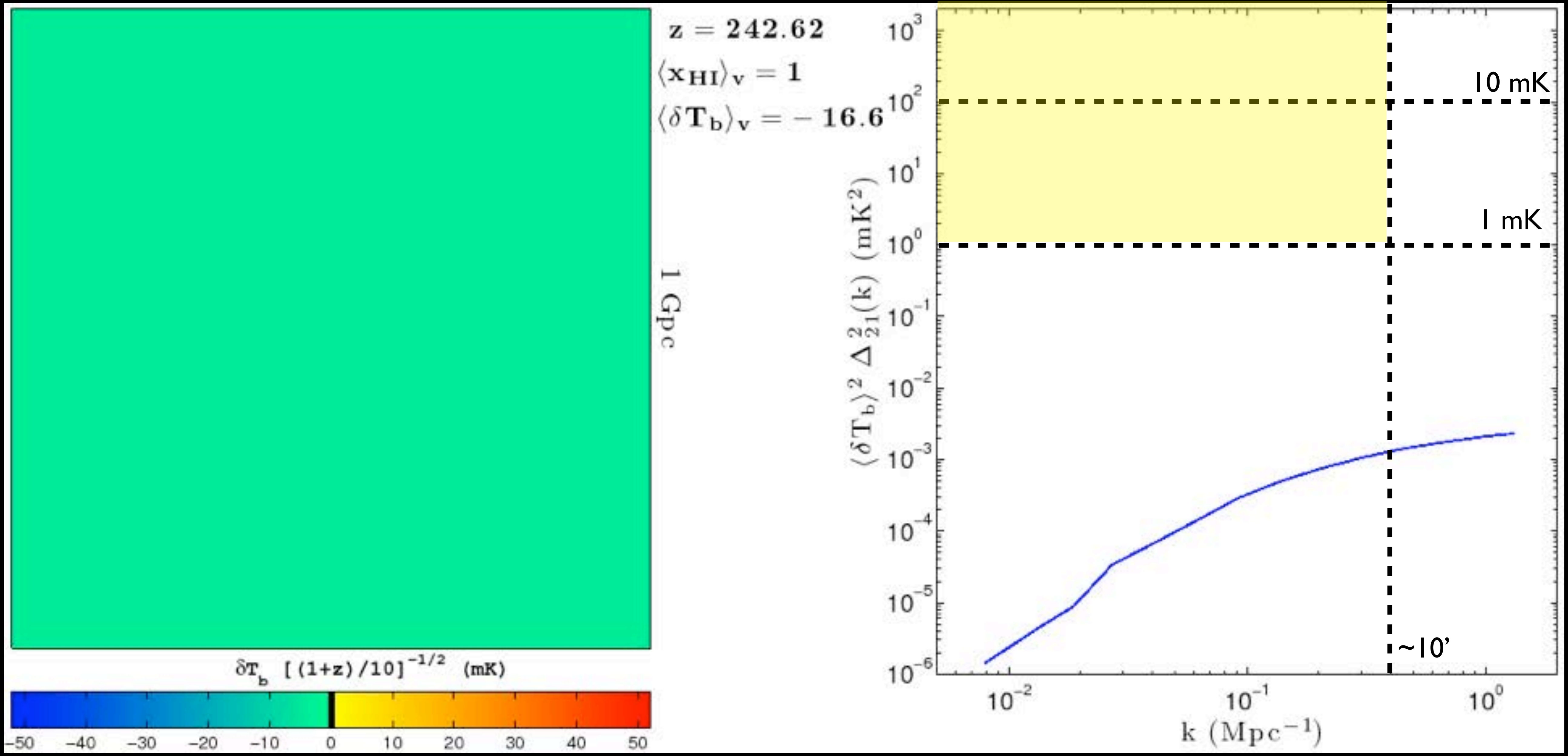
1 mK sensitivity at 1 arcmin scale enough to probe full range

Distinguish different contributions via shape and redshift evolution

z=30-50 range much harder!

Pritchard & Loeb 2008

Evolution of the power spectrum



Need ~1 mK sensitivity on arcmin scales for imaging and power spectrum

Mesinger+ 2010

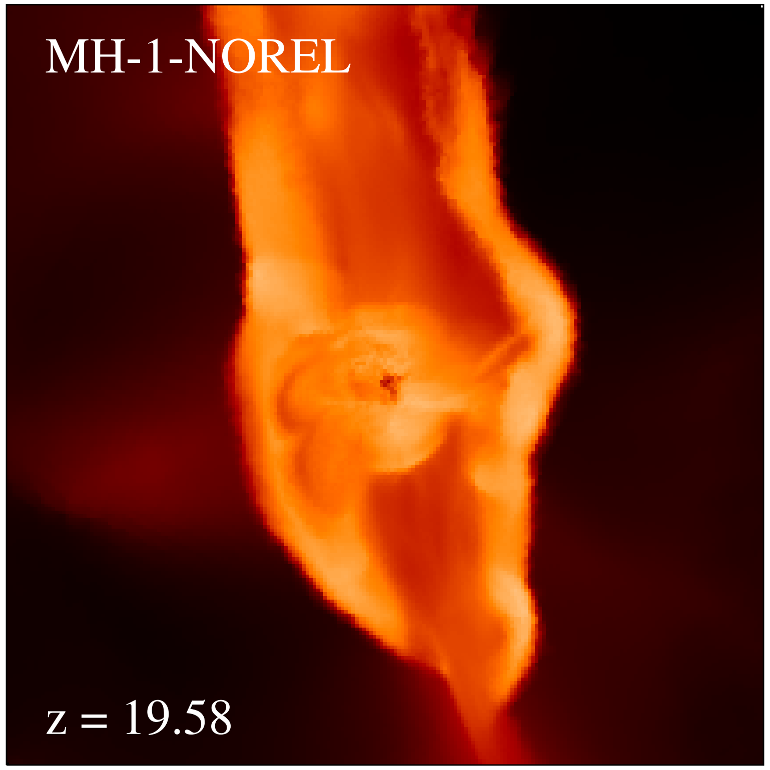
How the wind blows?

Foregoing is modified by new physics at highest redshifts if star formation H2 cooling halos relevant

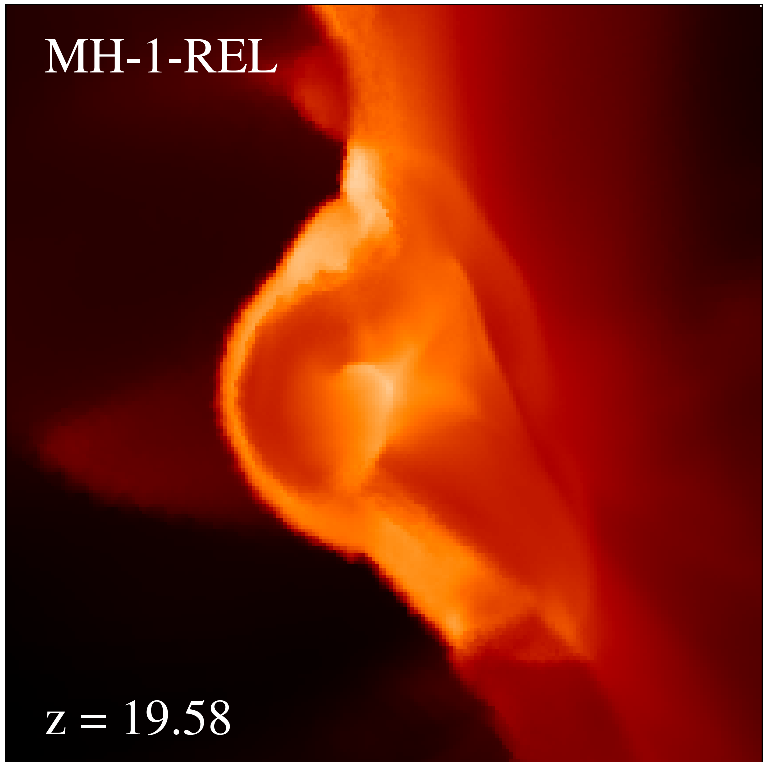
Recombination leads to sudden drop in sound speed
=> coherent supersonic relative motion of baryons and dark matter

Tseliakhovich
& Hirata 2010

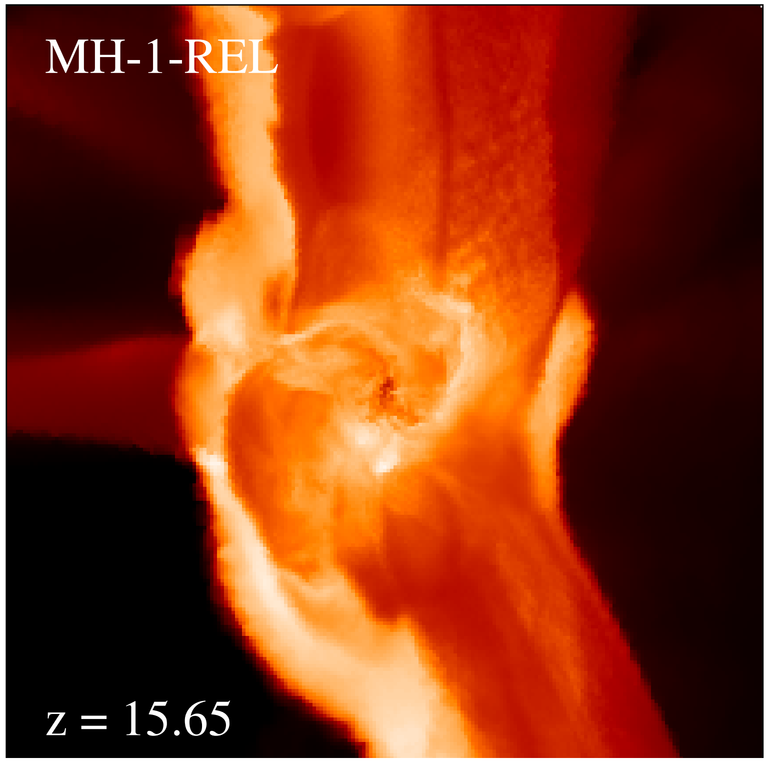
No-rel: galaxy forms at z~20



Rel: snapshot at z~20



Rel: gal formation delayed to z~16



→ flow

Greif+ 2011

Galaxy formation in low mass <10^8 Msol halos delayed

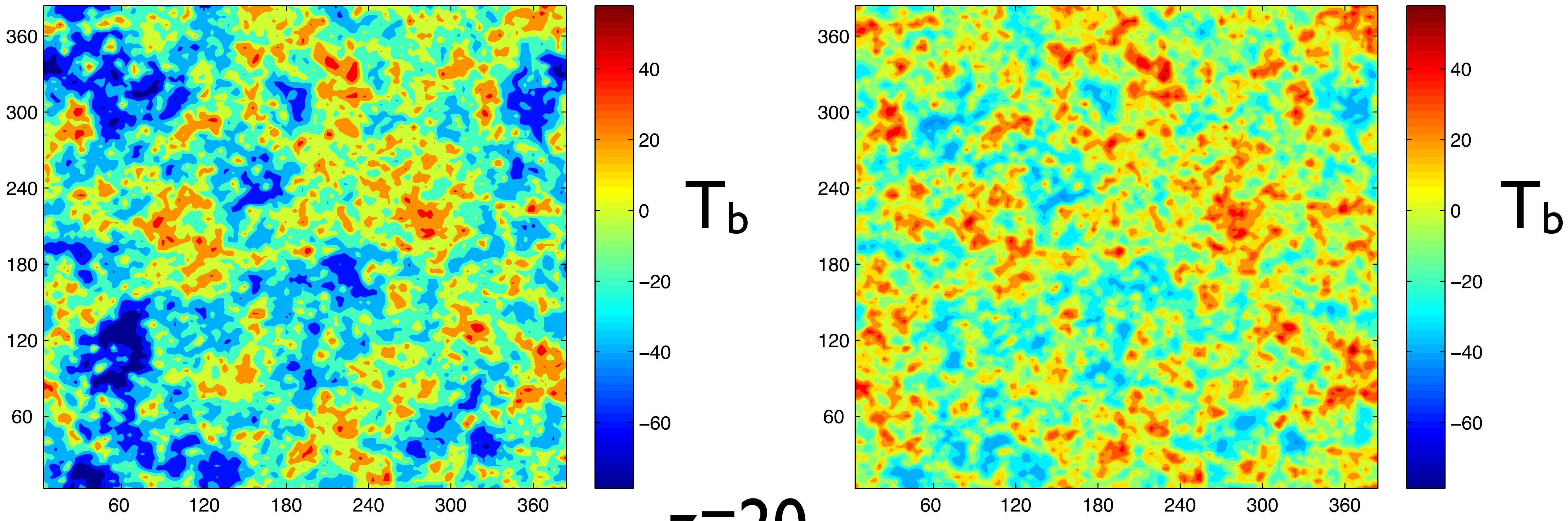
Little effect on higher mass halos => importance of effect decreases at late times

Maio+ 2010, Greif+ 2011, Stacey+2011

Enhanced 21 cm signal with BAO

Coherent modulating early halo abundance on small scales can couple to large scales via Lyman alpha and X-ray fluctuations

Visbal+ 2012



z=20

With velocity effect

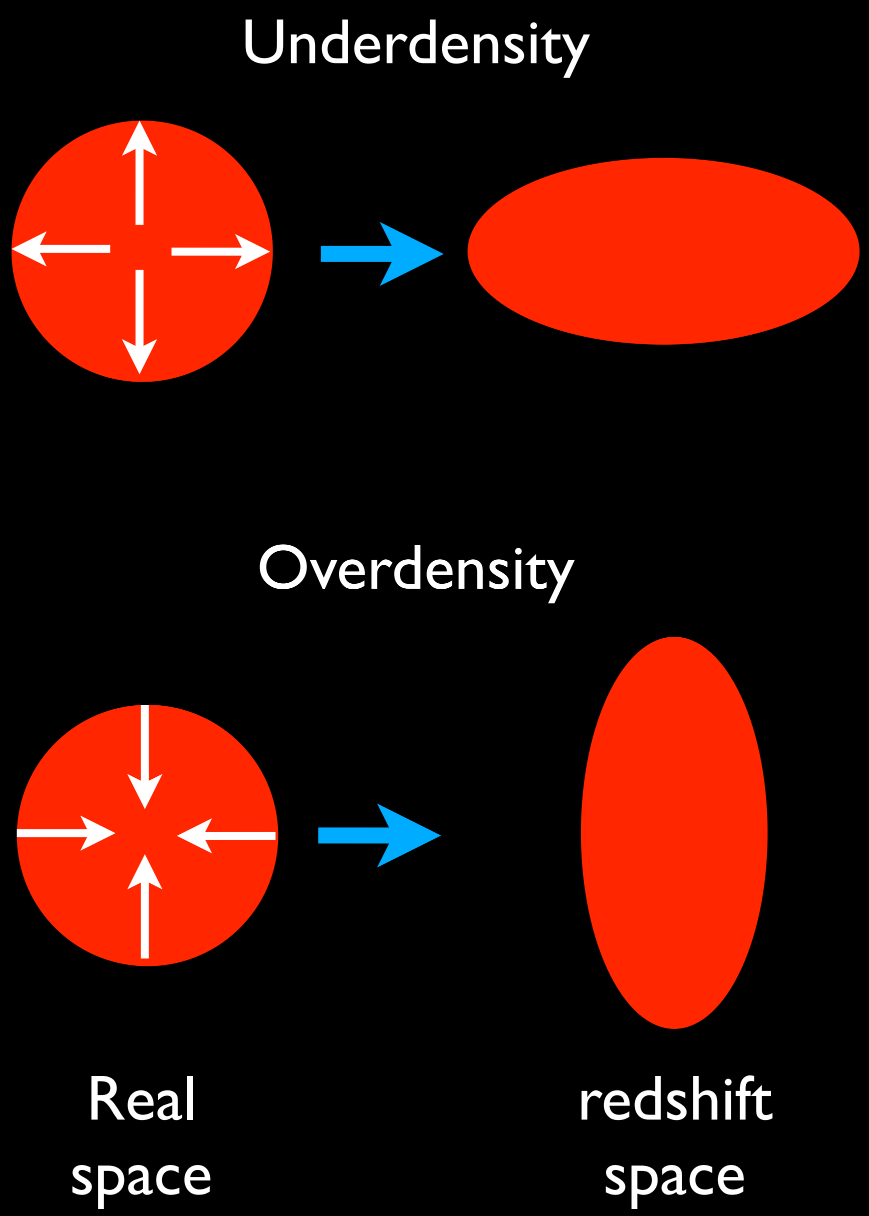
Without velocity effect

velocity patches coherent on ~1 Mpc scales and modulated on sound horizon at ~120/h Mpc

Order of magnitude increase in 21cm fluctuations on large scales at z~20
=> much more detectable signal + enhanced BAO signature

Visbal+ 2012, McQuinn & O'Leary 2012

Redshift distortions



Underdensity

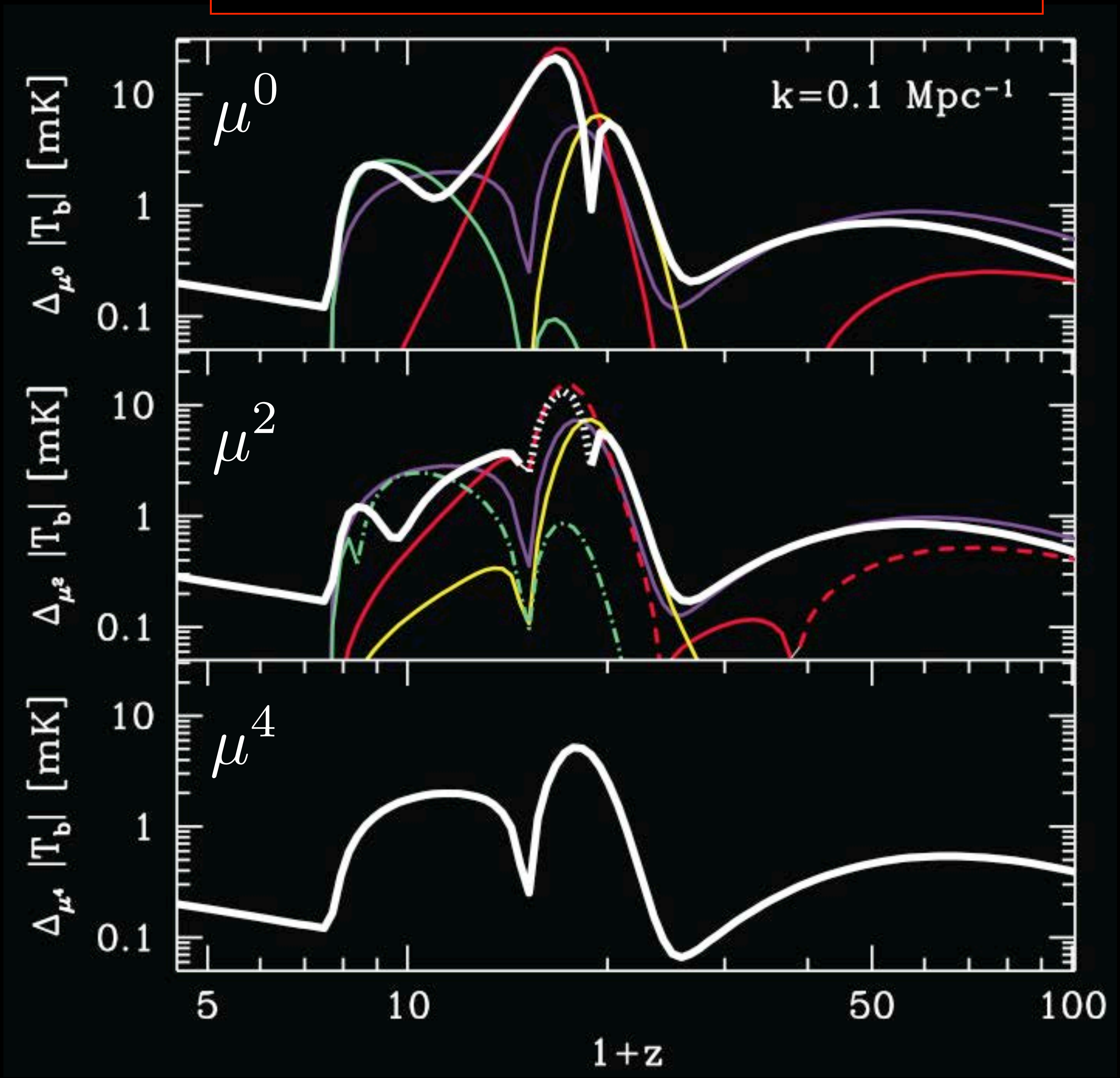
Overdensity

Real space

redshift space

$$\delta_{\partial_r v_r}(k) = -\mu^2 \delta$$

$$P_{T_b}(\mathbf{k}) = \mu^4 P_{\mu^4} + \mu^2 P_{\mu^2} + P_{\mu^0}$$



Power spectrum sensitivity

survey volume

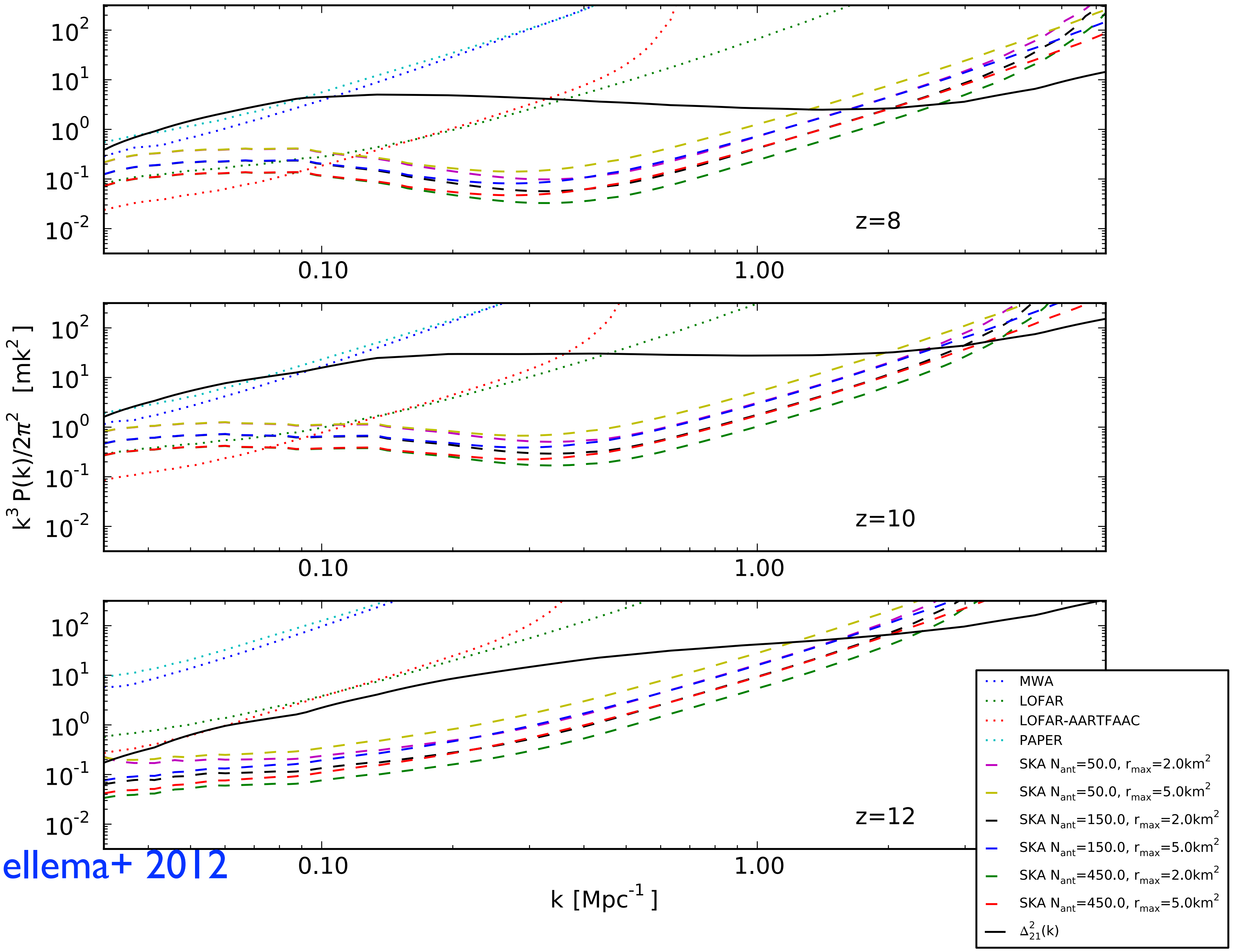
thermal noise

no. visibilities per uv element/2

$$\Delta^2_{\rm Noise} = \left(\frac{2}{\pi}\right) k^{3/2} \left[D_c^2 \Delta D_c \times \Omega_{\rm FoV}\right]^{1/2} \left(\frac{T_{\rm sys}}{\sqrt{B t_{\rm int}}}\right)^2 \left(\frac{A_{\rm core} A_{\rm eff}}{A^2_{\rm coll}}\right)$$

$$(A_{\rm eff}/A_{\rm coll})^2 = N^{-2}_{\rm stat}$$

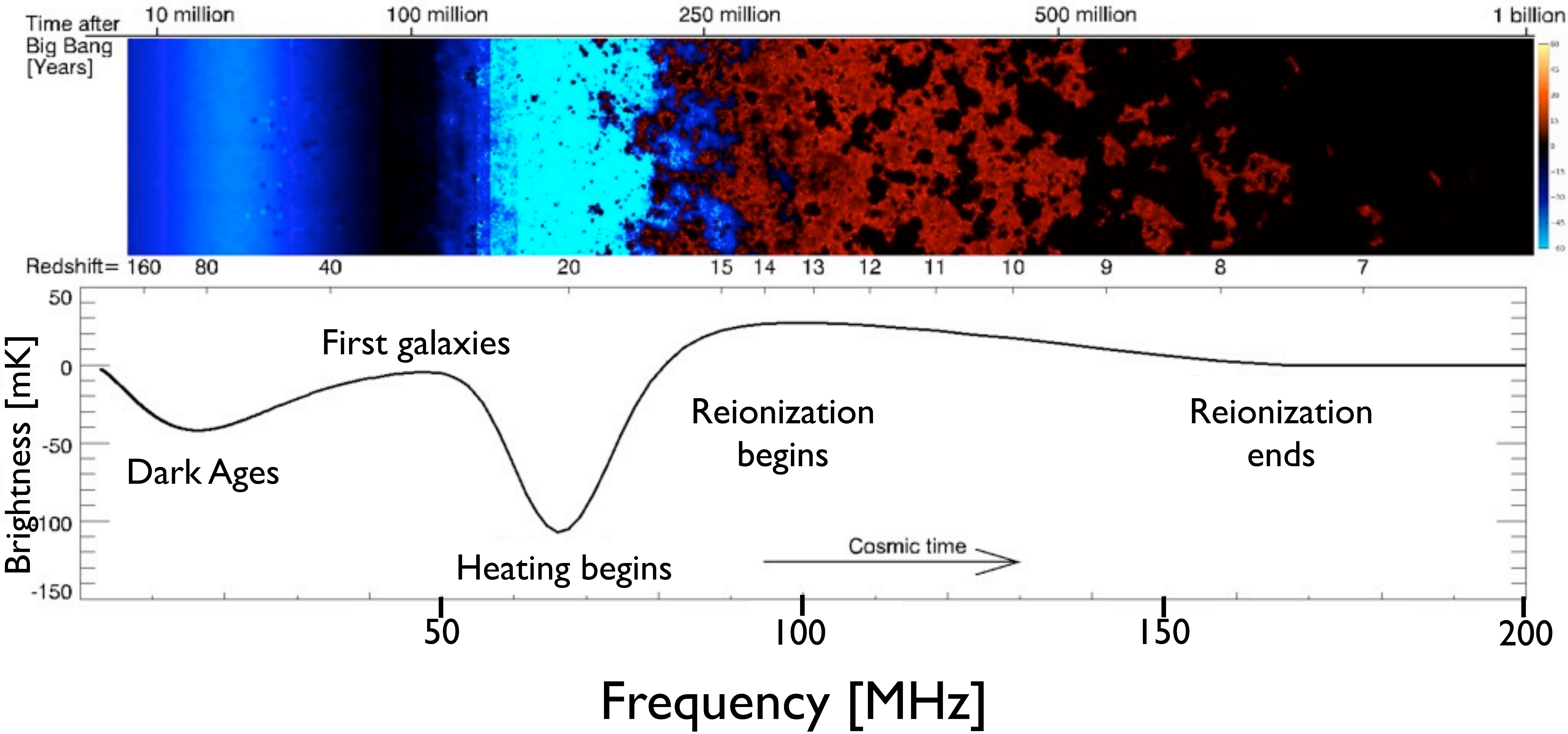
$$(A_{\rm core}/A_{\rm eff})$$



Mellema+ 2012

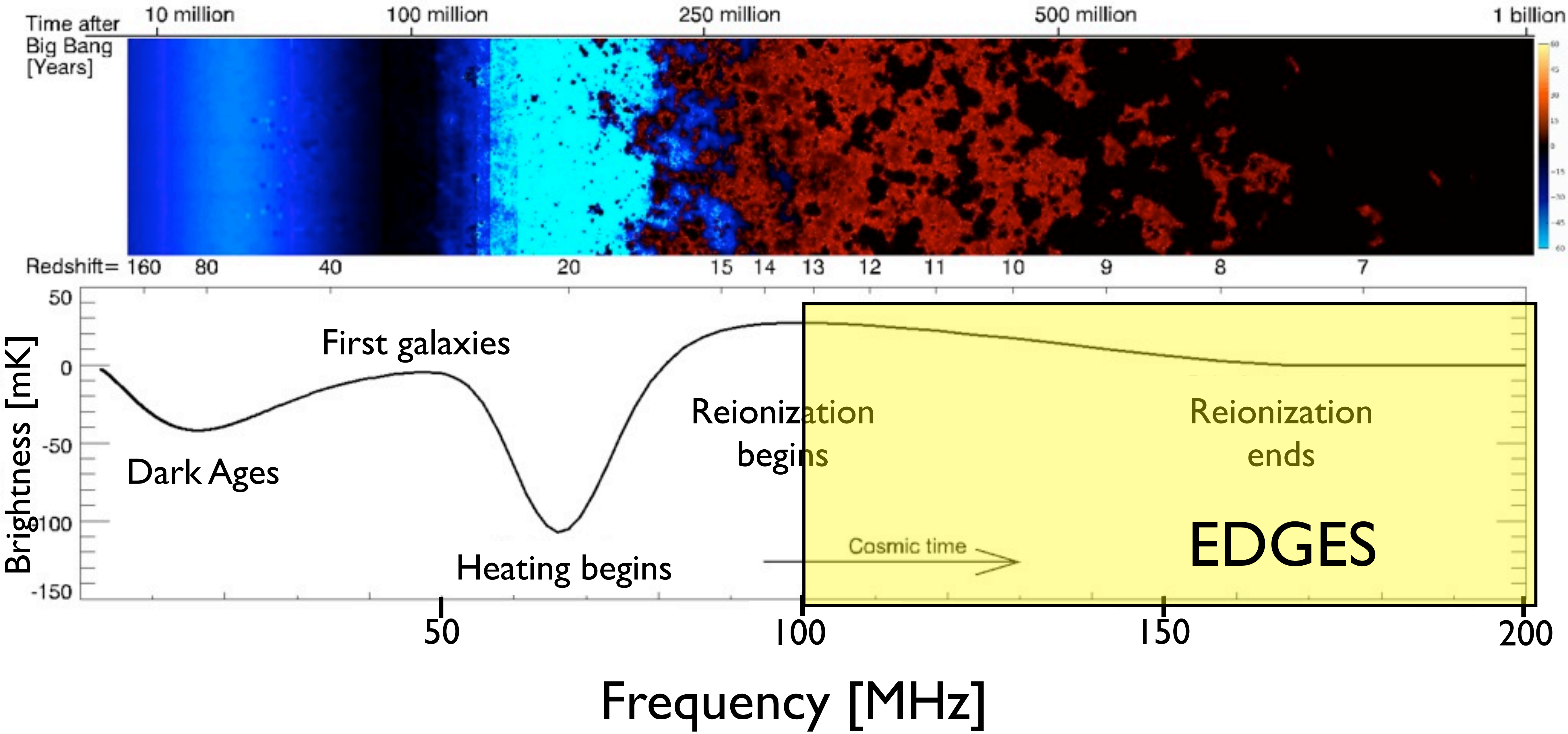
21 cm summary

Pritchard & Loeb 2010



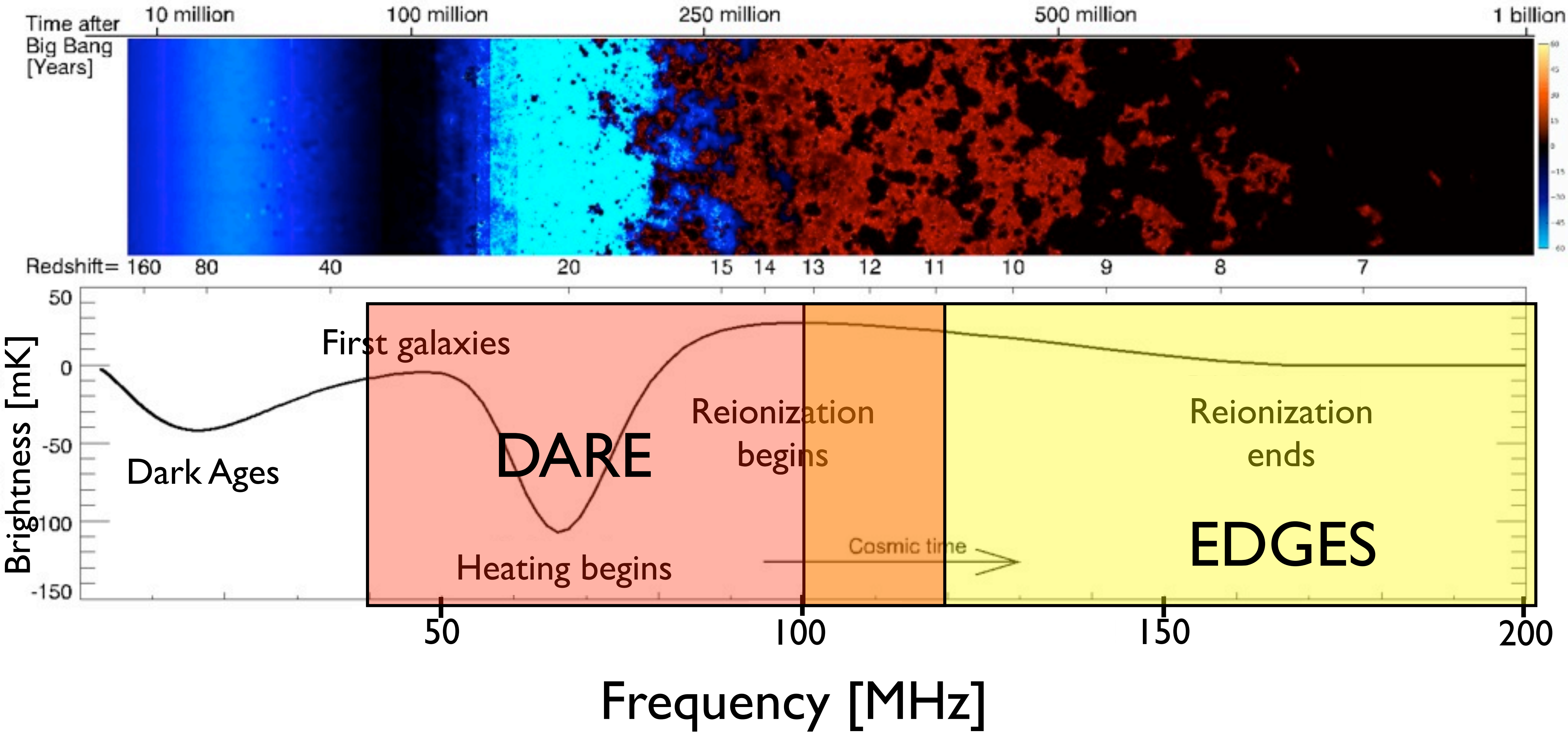
21 cm summary

Pritchard & Loeb 2010



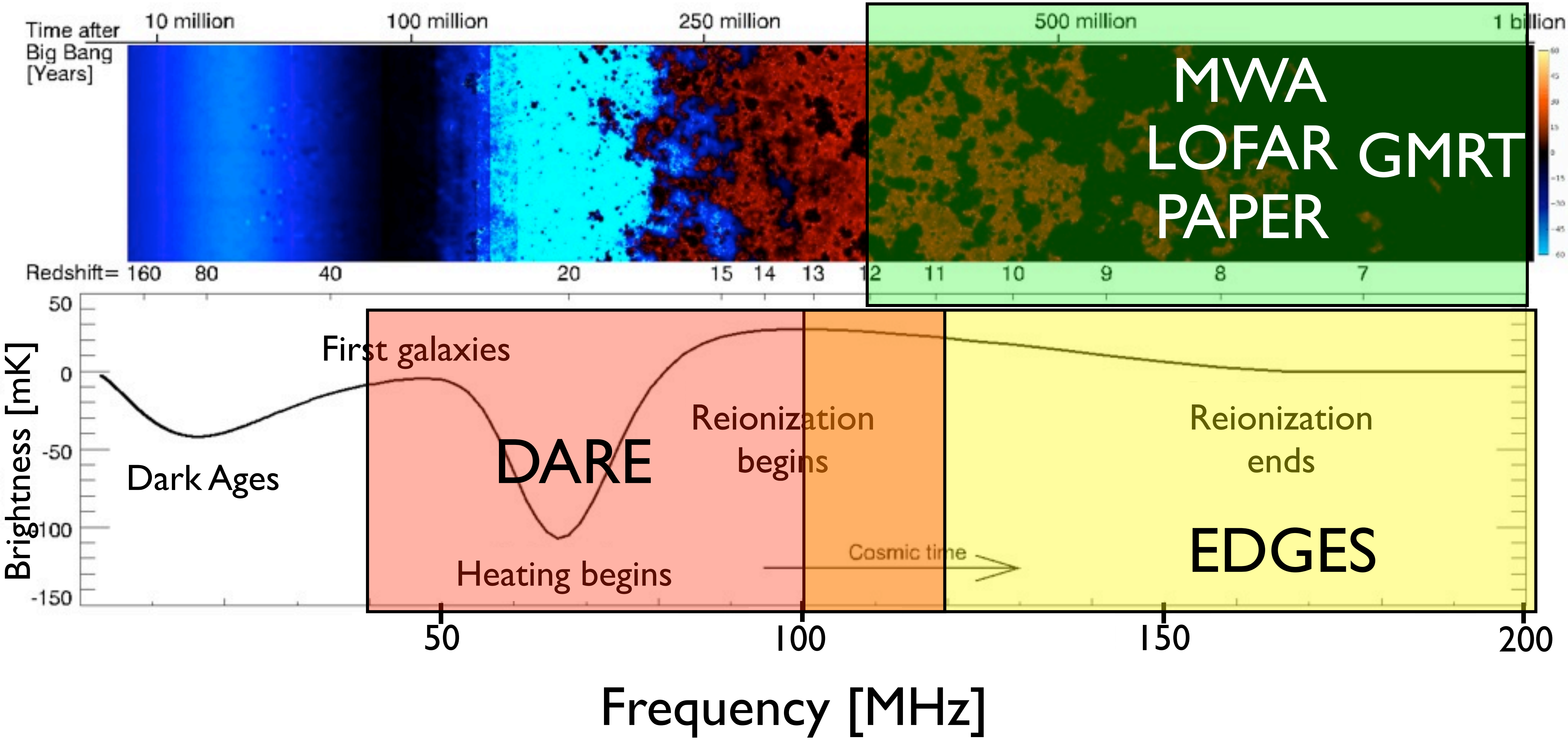
21 cm summary

Pritchard & Loeb 2010



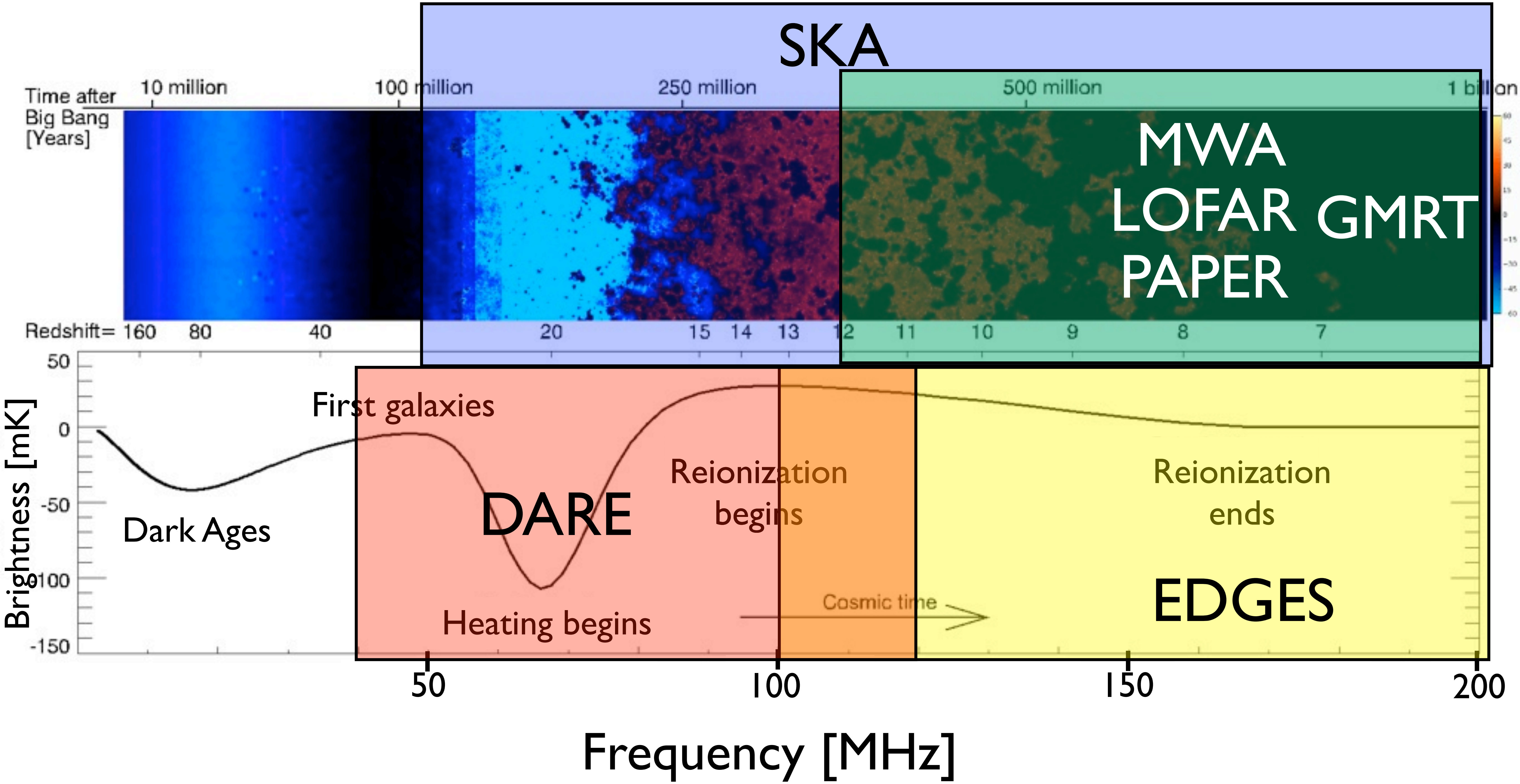
21 cm summary

Pritchard & Loeb 2010



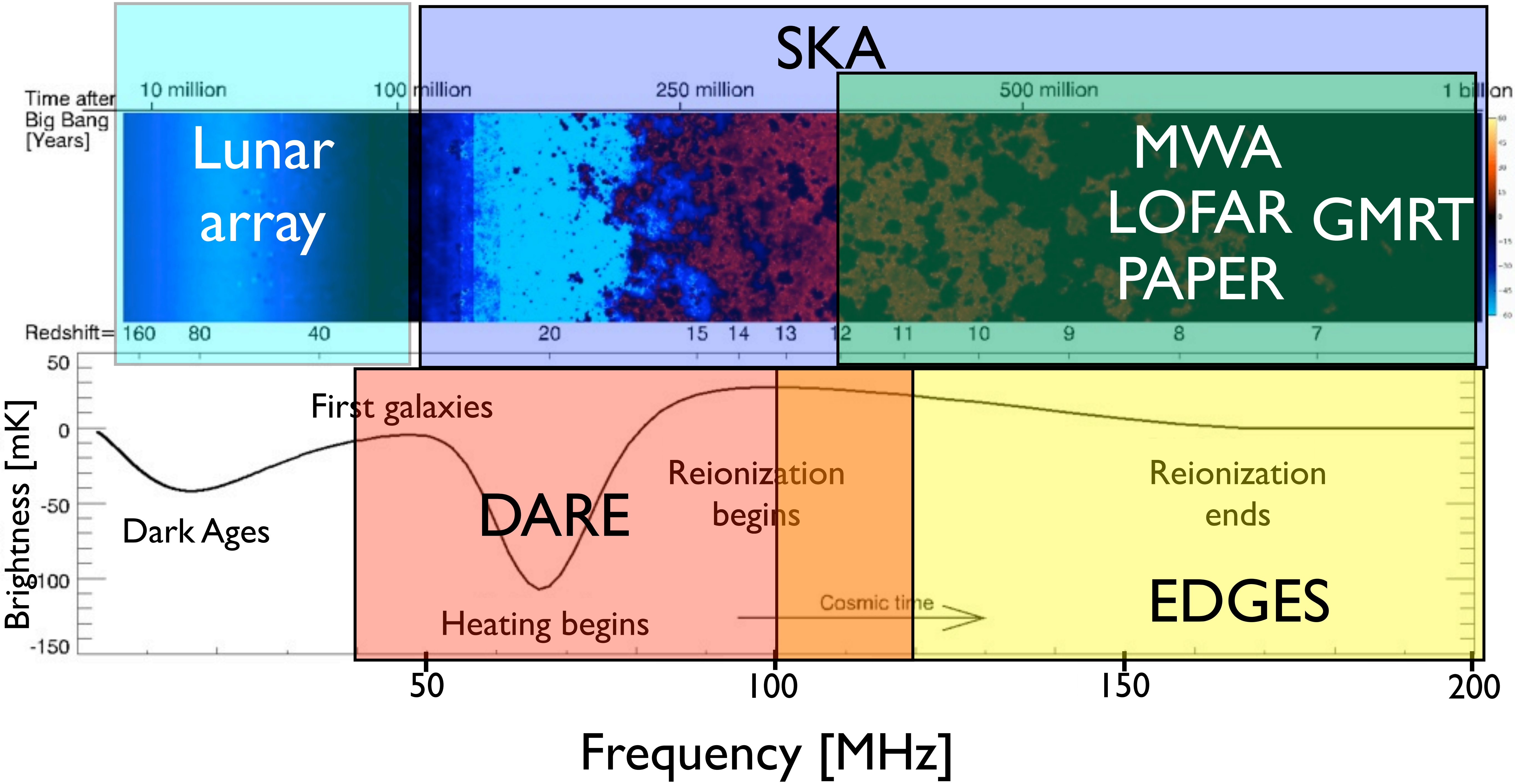
21 cm summary

Pritchard & Loeb 2010



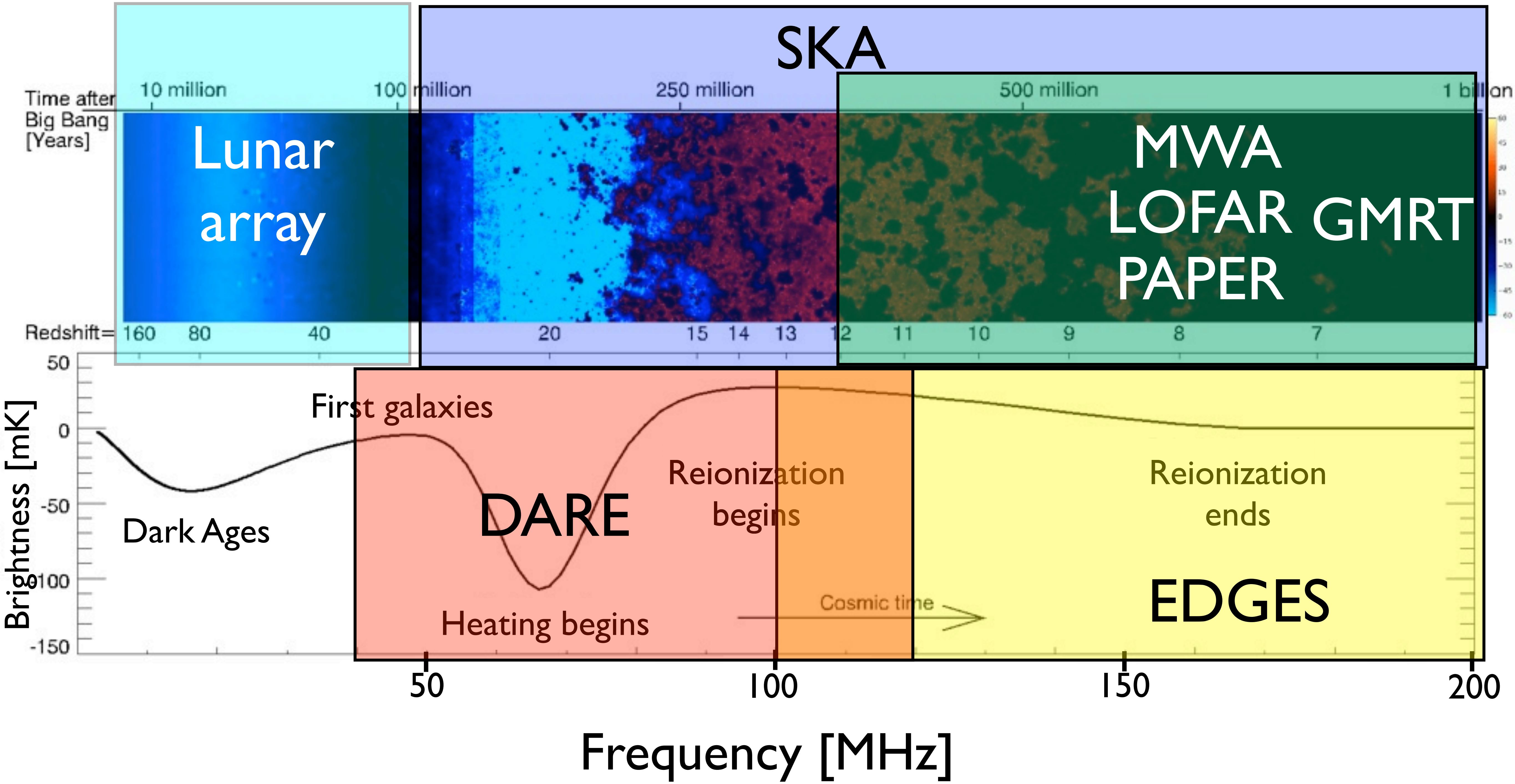
21 cm summary

Pritchard & Loeb 2010

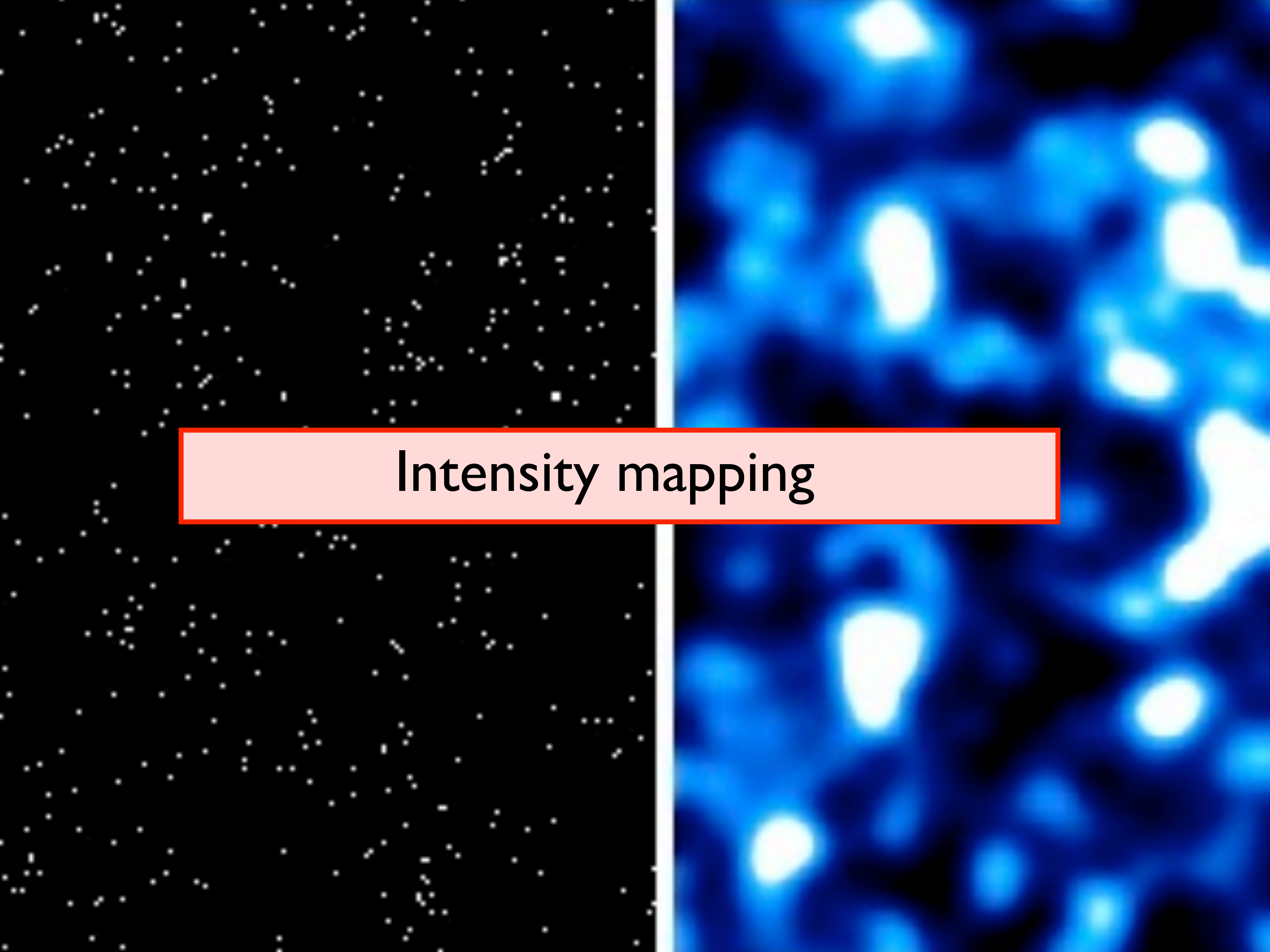


21 cm summary

Pritchard & Loeb 2010

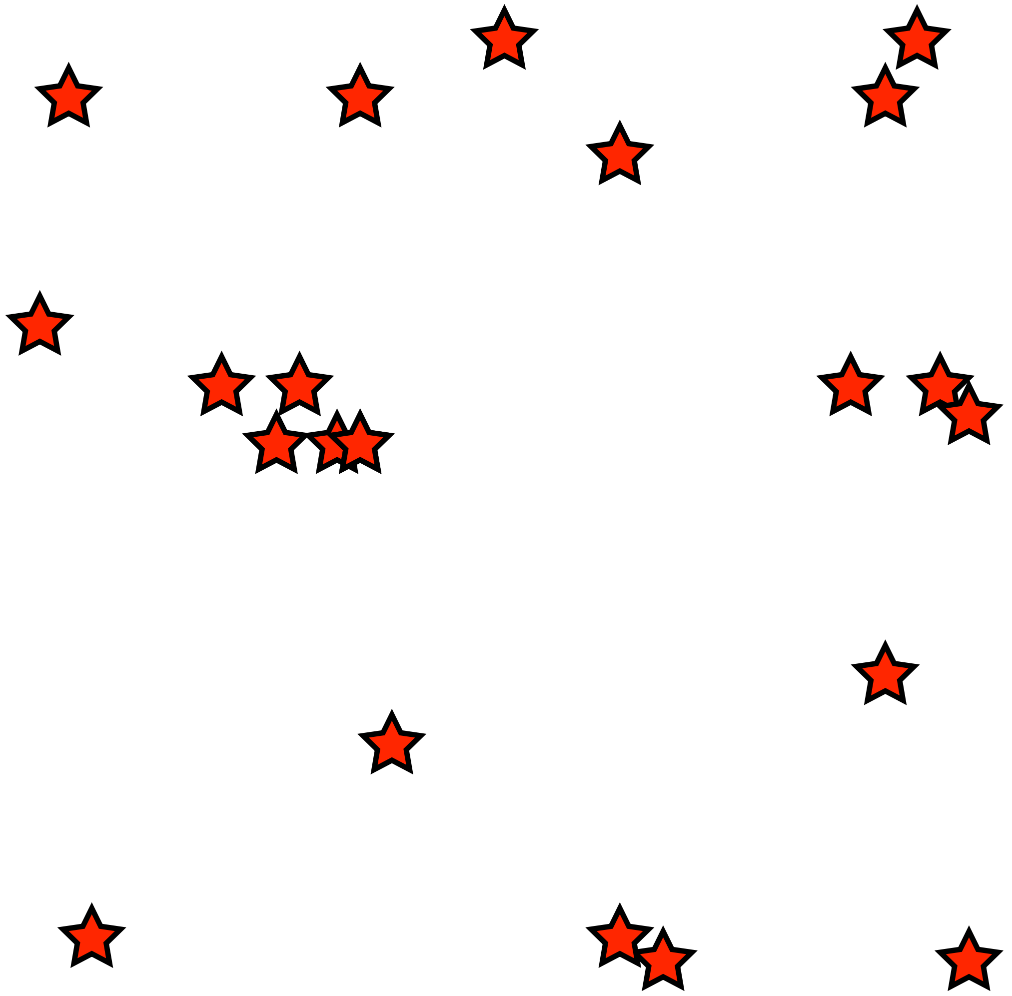


Want to cover full redshift range accessible z<~30



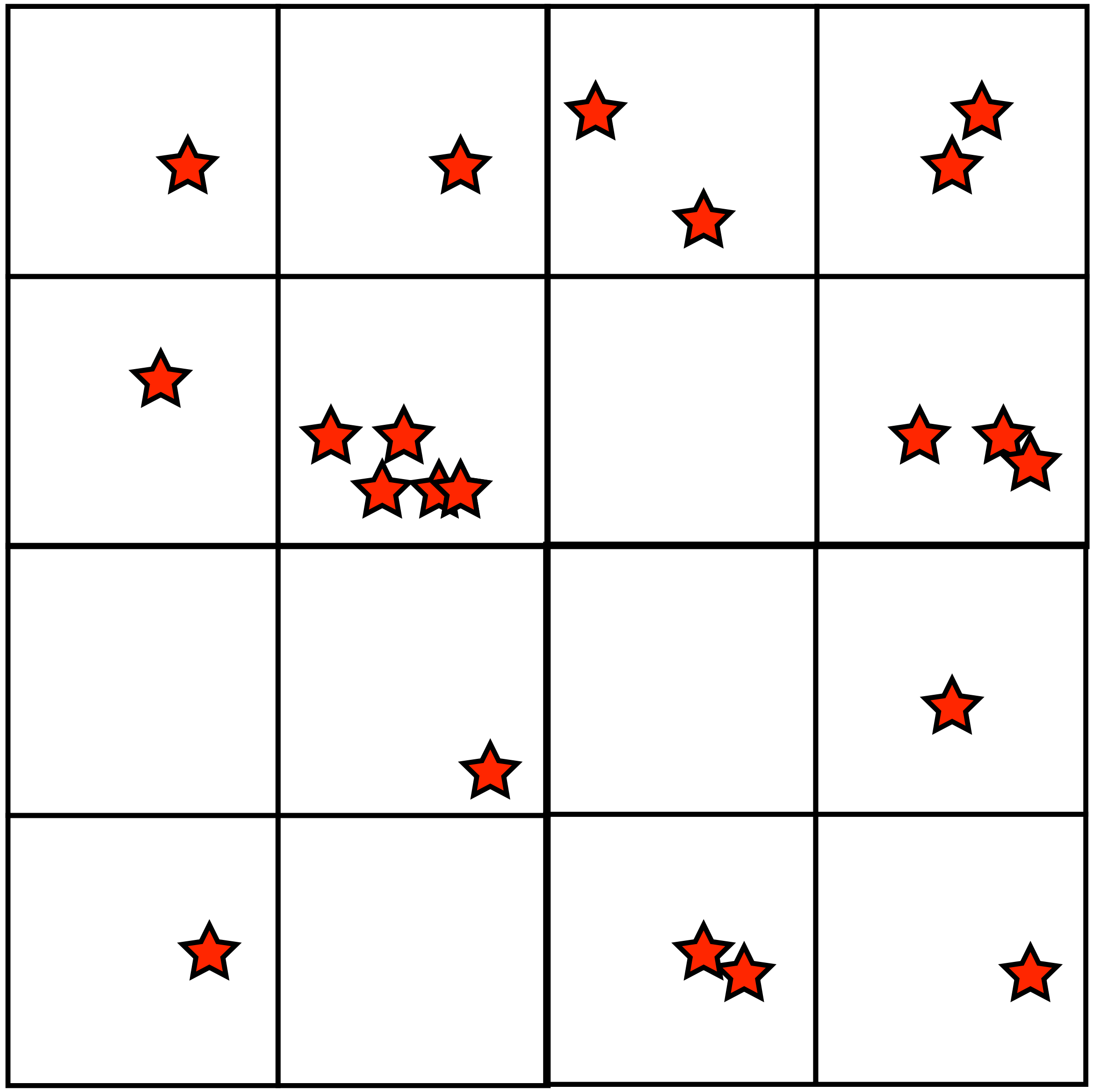
Intensity mapping

Intensity mapping in outline



Traditional galaxy survey identifies individual galaxies

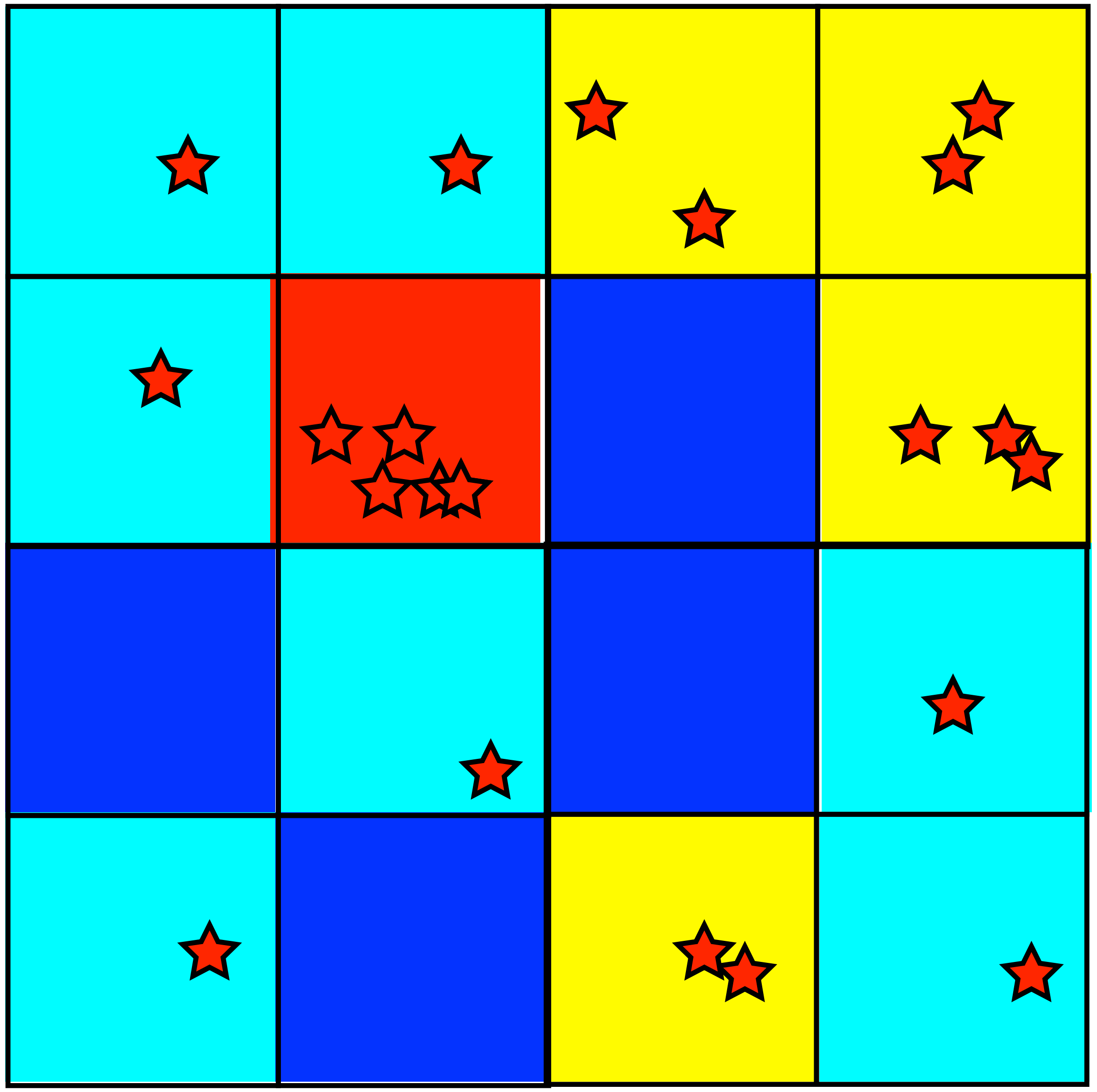
Intensity mapping in outline



Traditional galaxy survey identifies individual galaxies

Bin galaxies to estimate density field

Intensity mapping in outline

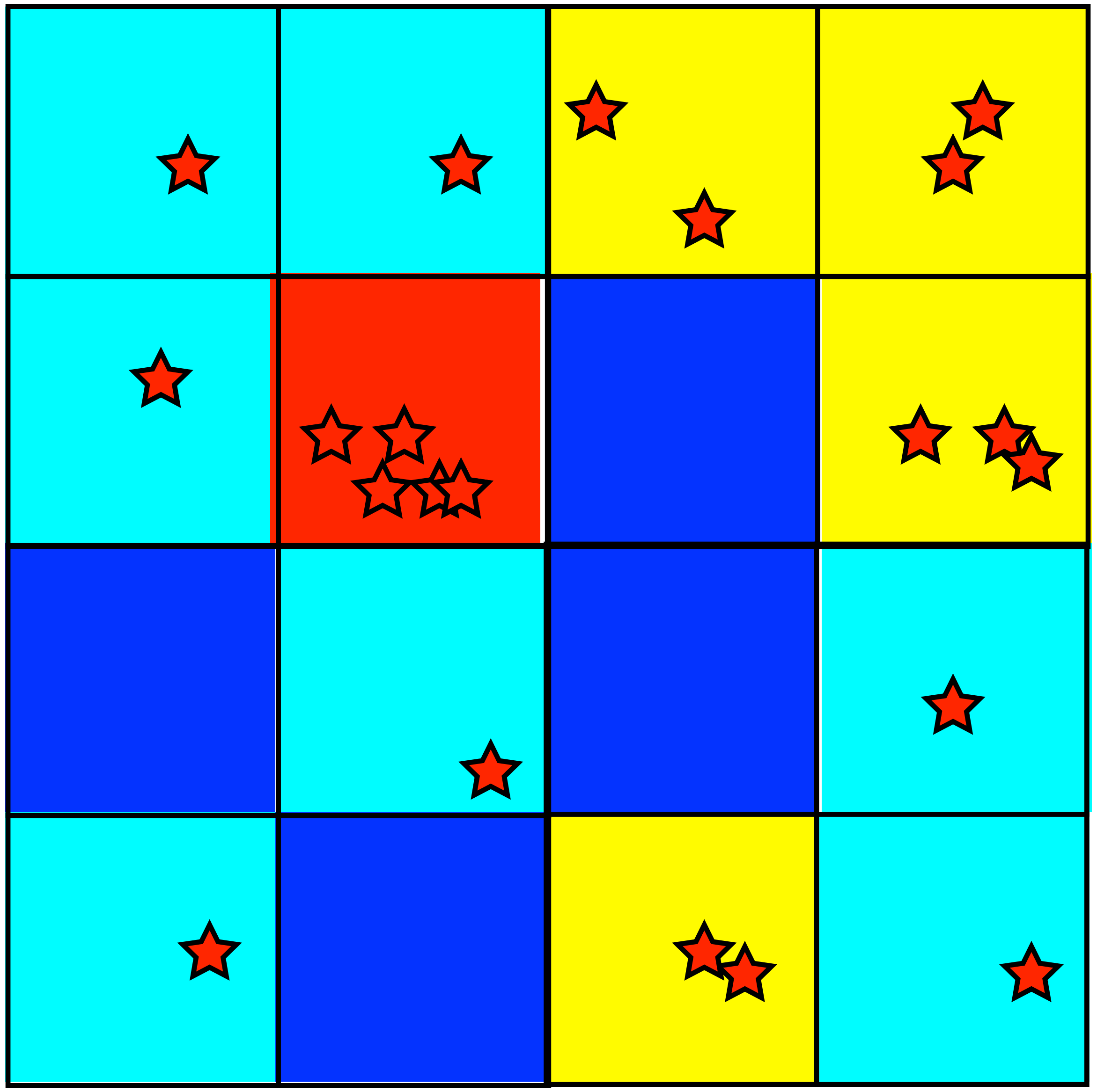


Traditional galaxy survey identifies individual galaxies

Bin galaxies to estimate density field

Intensity mapping integrates flux from all unresolved galaxies

Intensity mapping in outline



Traditional galaxy survey identifies individual galaxies

Bin galaxies to estimate density field

Intensity mapping integrates flux from all unresolved galaxies

Two key uses:

1) z~1: dark energy probe e.g. CHIME, BINGO

2) z~8: high-z galaxy survey + cross-correlation with 21cm

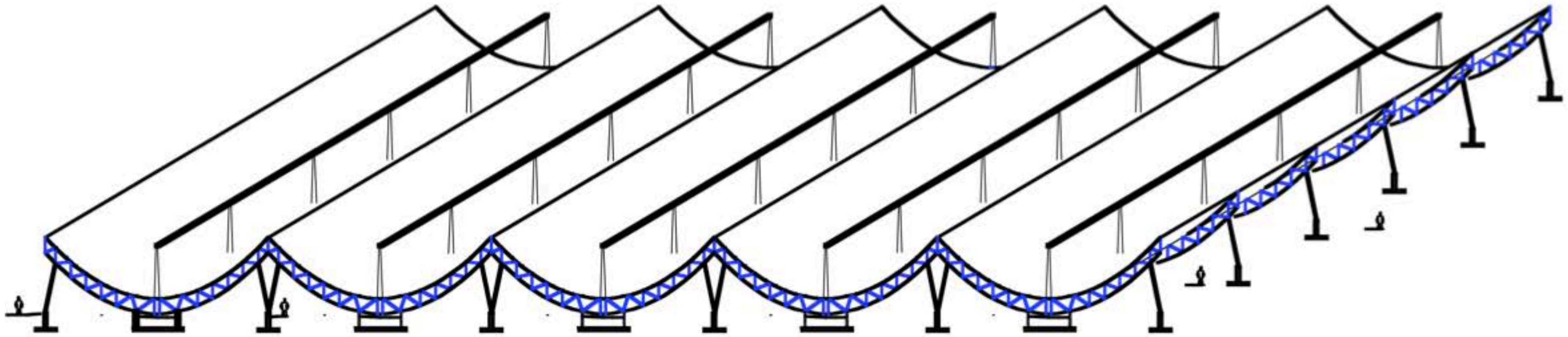
Low-z HI intensity mapping

GBT data and detection of HI intensity fluctuations in cross-correlation with optical galaxies (DEEP2, WiggleZ)

Chang, Pen, Bandura & Peterson 2010, Matsui+2012

Ultimately, target dark energy via BAO/growth of structure

CHIME - Canada - U. Pen
BAOBAB - US - A. Parsons
BINGO - UK - R. Battye
Tianlai - China - X. Chen
BAORadio - France - R. Anzari

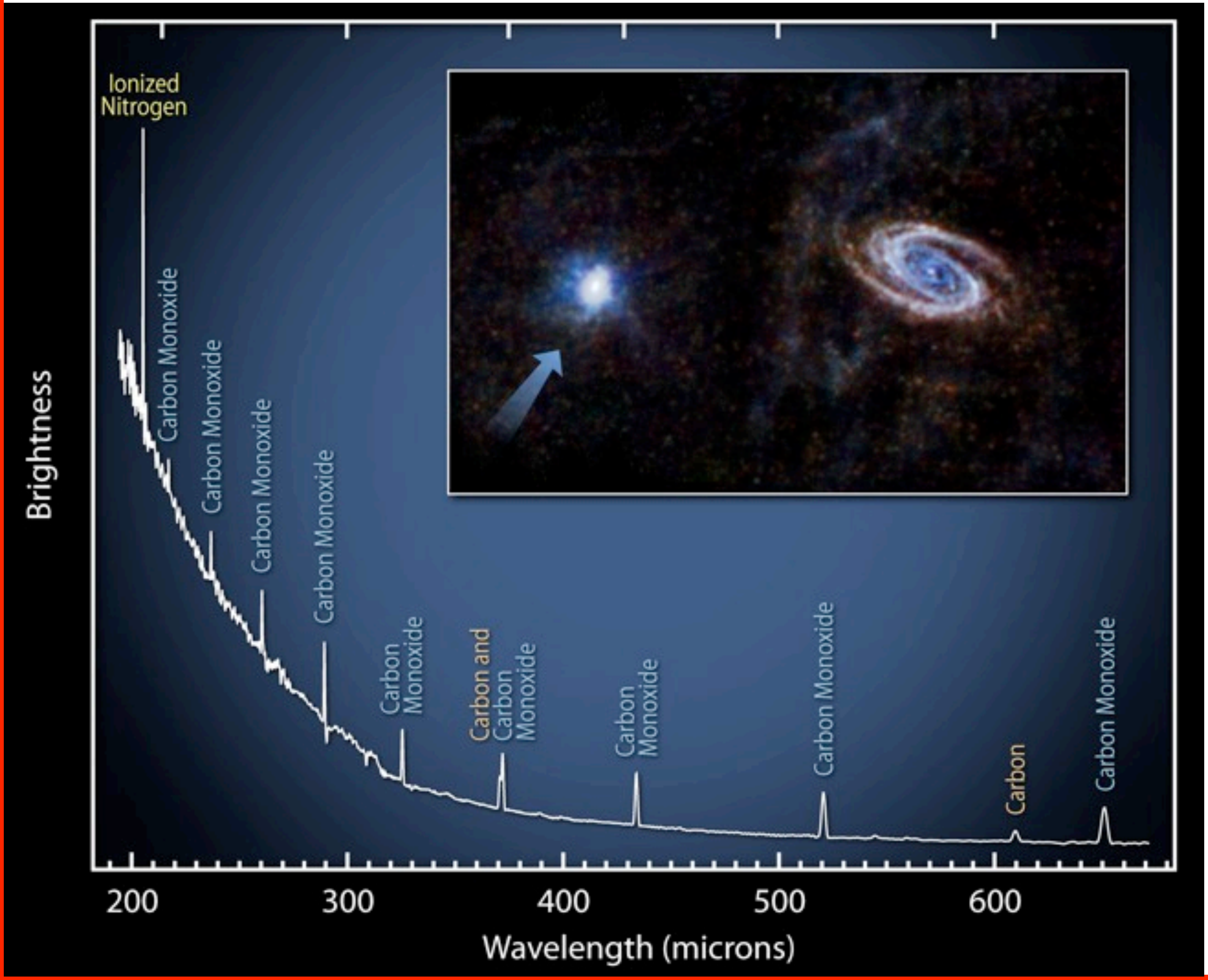


CHIME pathfinder
40m x 40 m due
summer 2013

High-z intensity mapping

Key difference is where the rest frame line falls in observing frequencies

Lyman alpha CO H_2 [CII]



Righi+ 2008,
Visbal & Loeb 2010
Carilli 2011,
Gong+ 2011
Lidz+ 2011
Silva+ 2012

M82

Herschel/
SPIRE

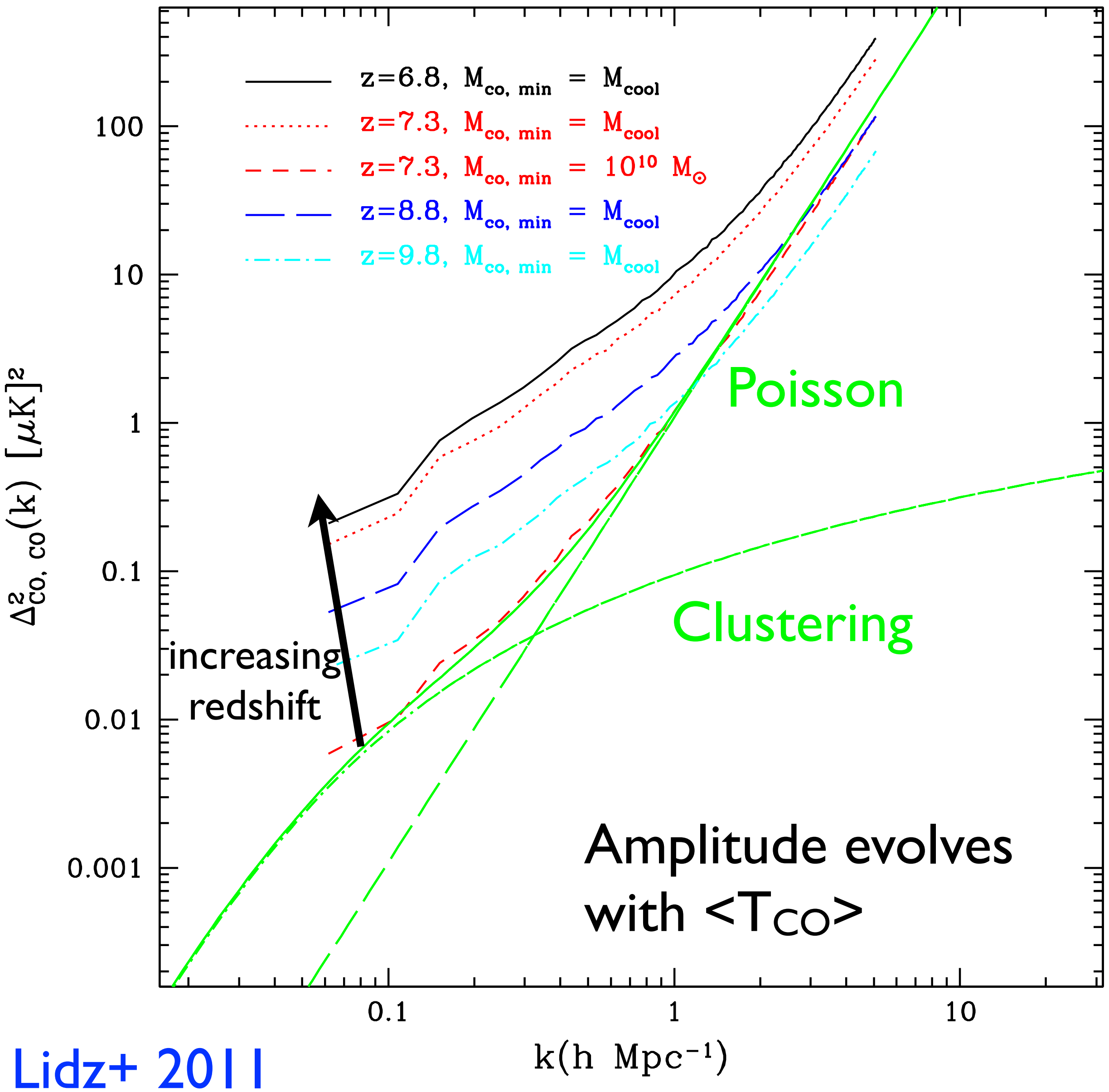
CO autocorrelation

Empirically link CO luminosity to star formation somehow

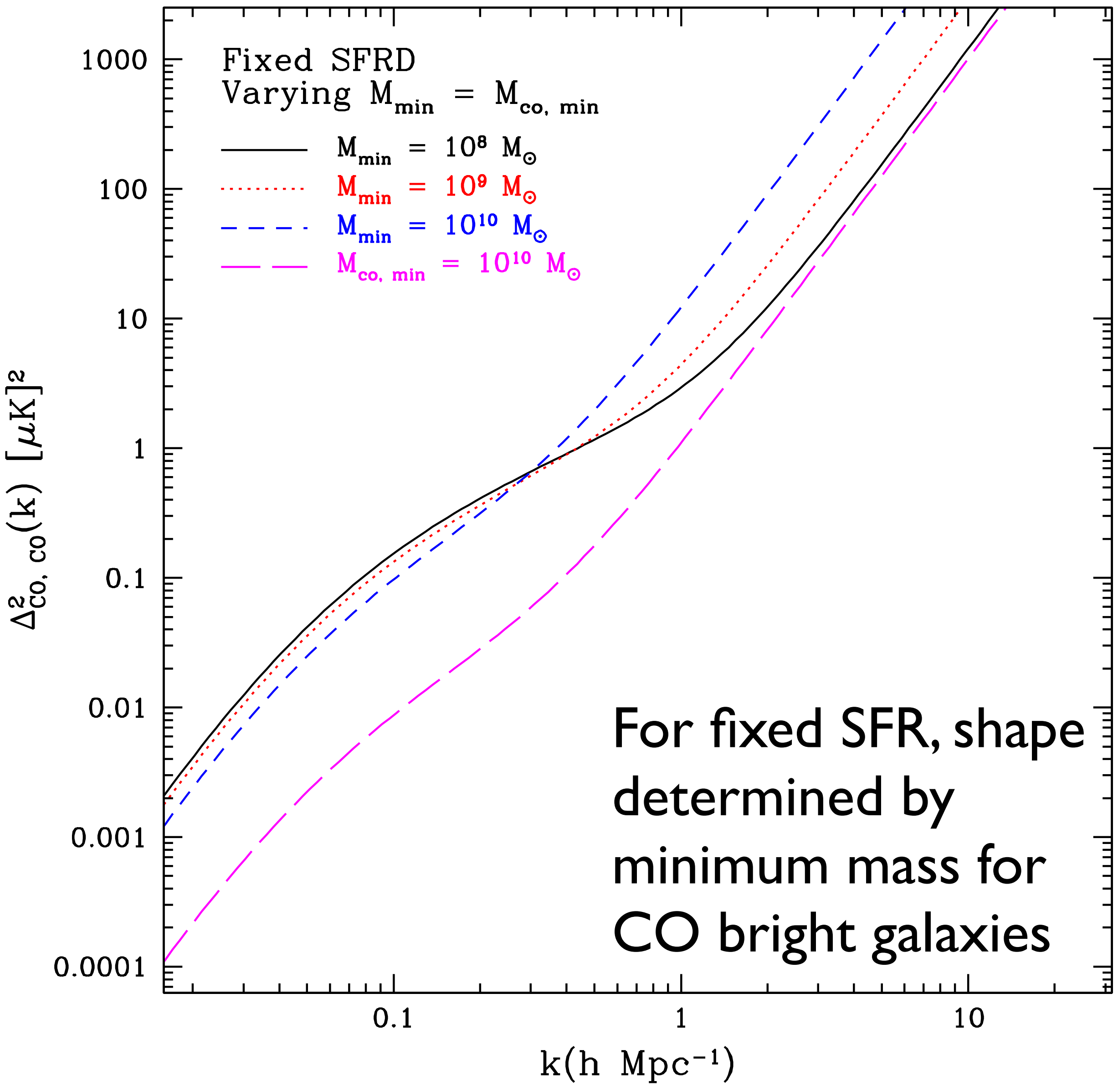
Mean brightness ~0.1-1 μK at z=8

$$L_{\rm CO(1-0)} = 3.2 \times 10^4 L_\odot \left[\frac{\rm SFR}{M_\odot {\rm yr}^{-1}}\right]^{3/5}.$$

Postprocess simulations (McQuinn+ 2007) or use halo model to investigate fluctuations



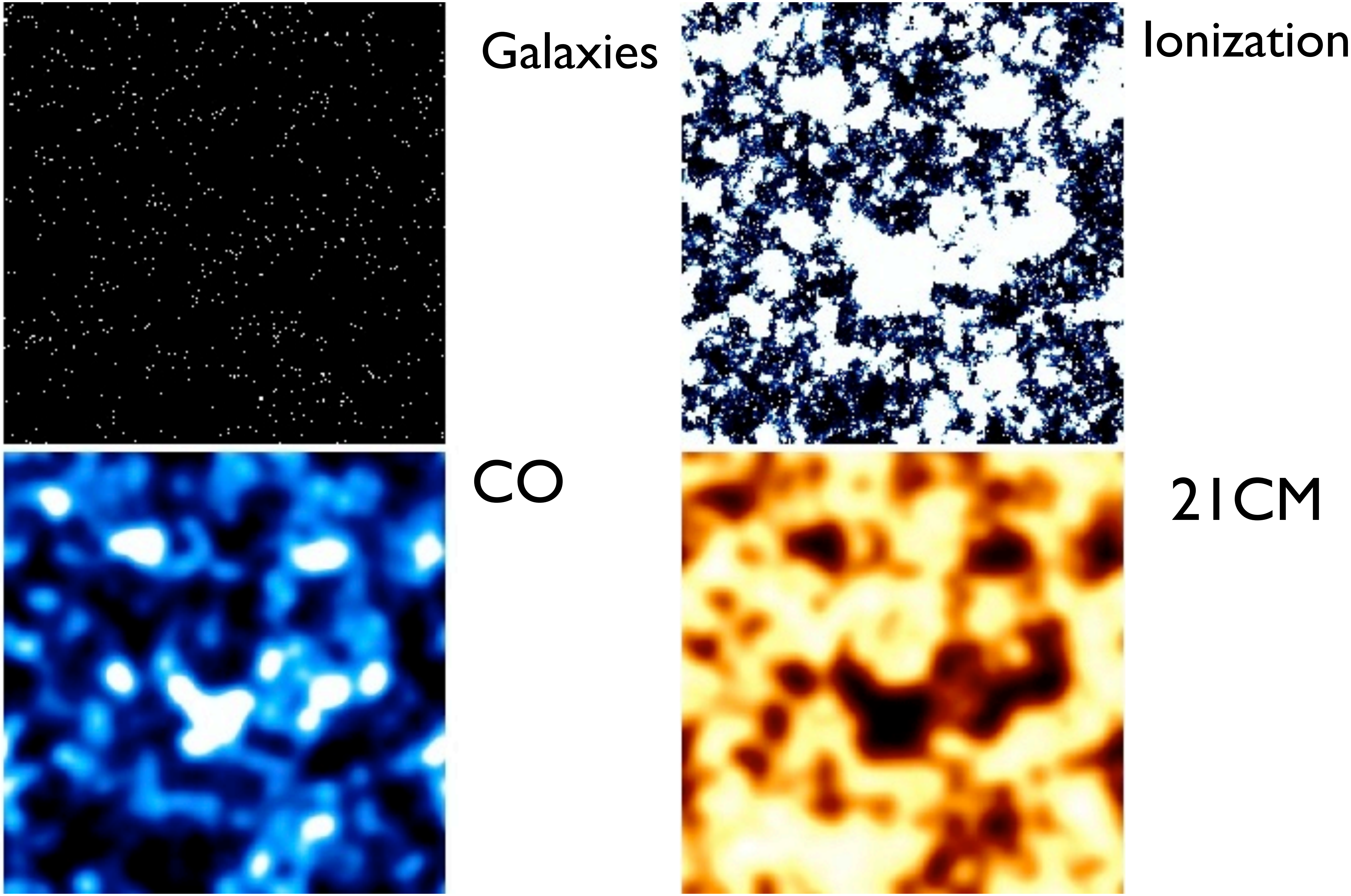
Amplitude evolves with $<T_{\rm CO}>$



For fixed SFR, shape determined by minimum mass for CO bright galaxies

Lidz+ 2011

CO-21cm cross-correlation

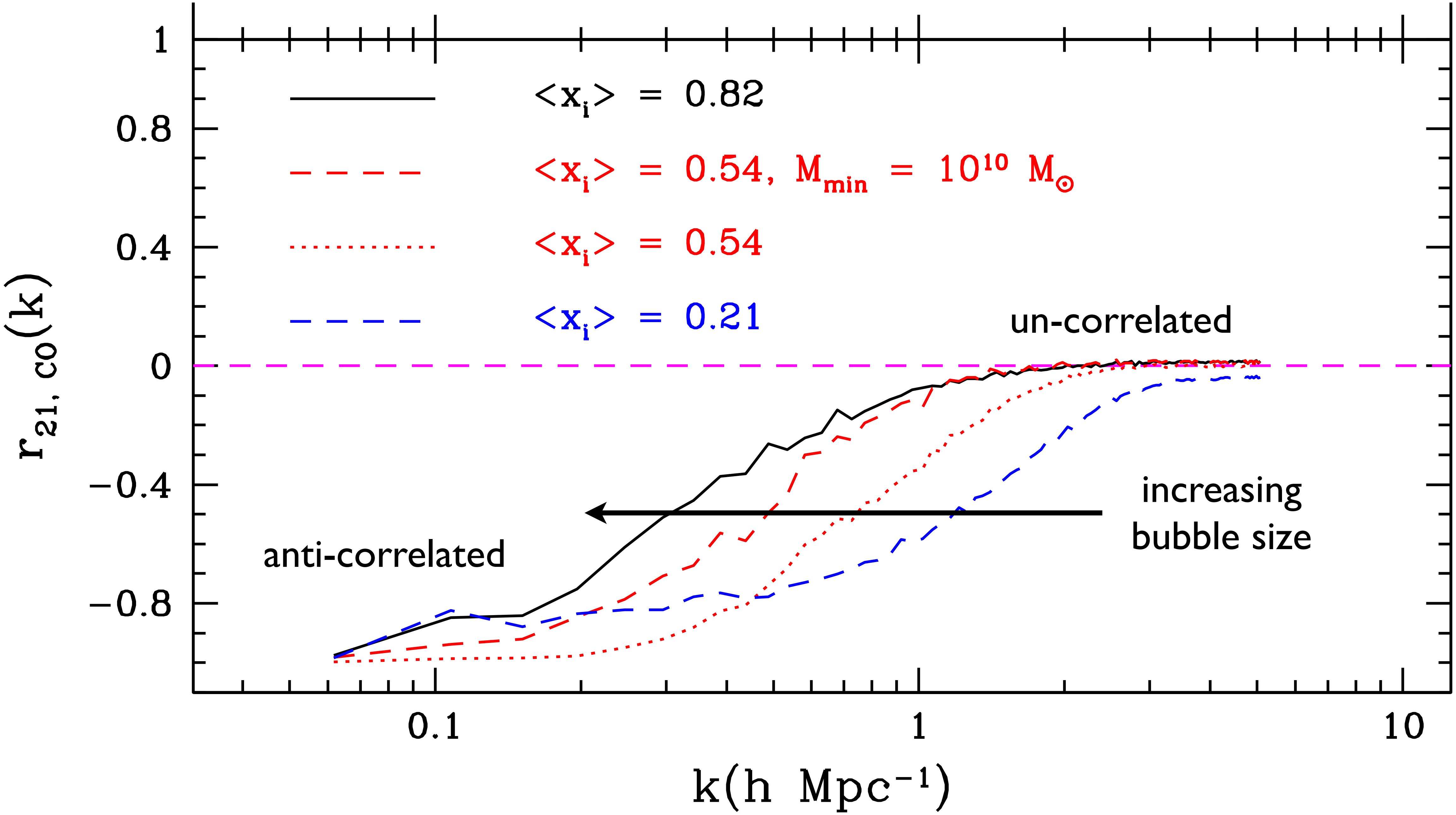


Also recent work by: Righi+ 2008, Carilli 2011, Gong+ 2011

CO-21cm cross-spectrum

Cross-spectrum more robust to systematics than auto-spectrum

$$r_{21,\mathrm{CO}}(k) = P_{21,\mathrm{CO}}(k)/\left[P_{\mathrm{CO,CO}}(k)P_{21,21}(k)\right]^{1/2}$$



Other galaxy catalogs: LBG? Euclid? LAE?

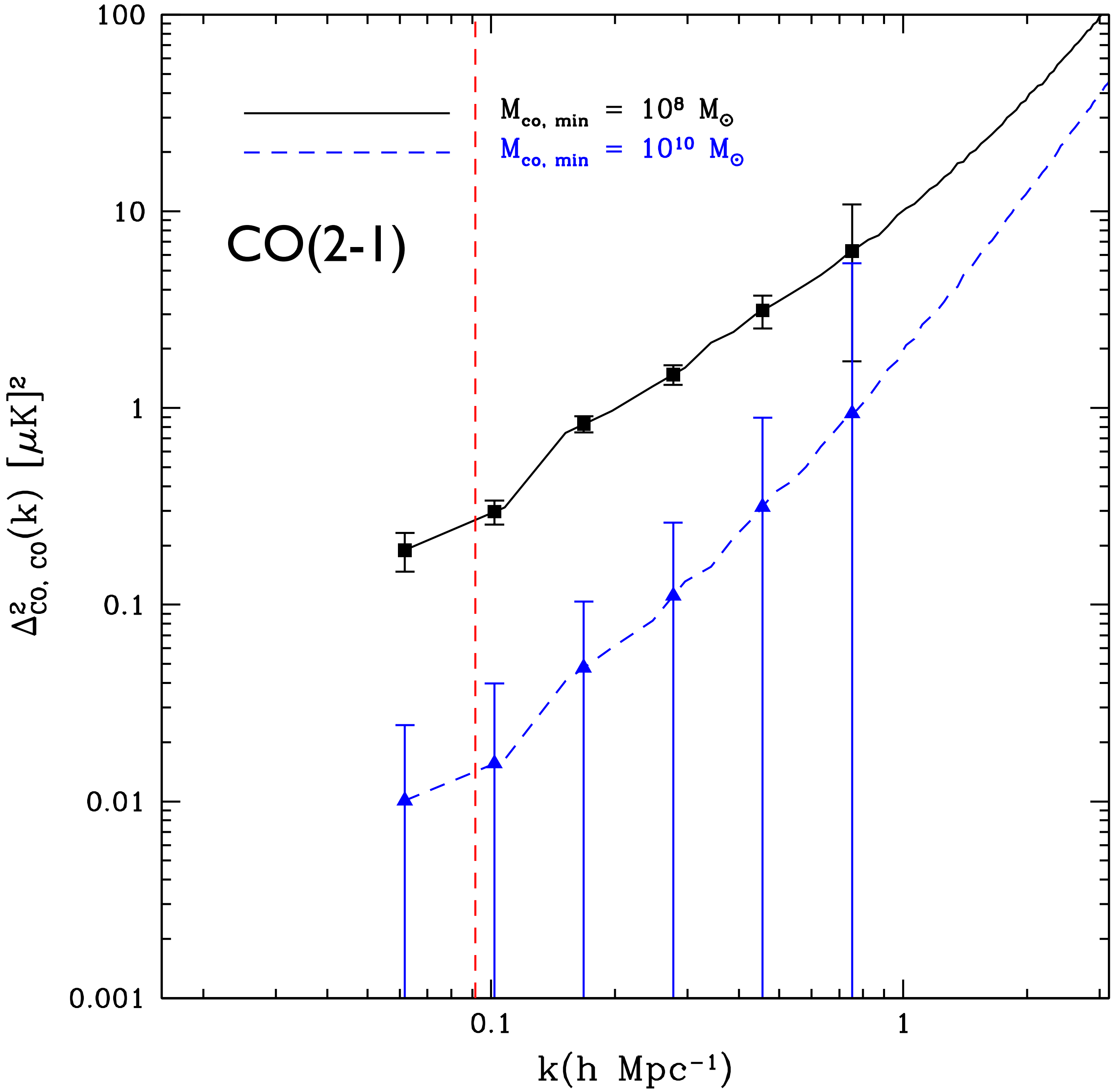
Lidz+ 2009, Wiersma+ 2012

Autocorrelation sensitivity

Desiderata: ~25deg^2 survey, ~6 arcmin resolution
dν/ν~0.003, noise ~0.1-1μK

For CO(2-1) at z=7, ν_{obs}~30GHz, λ_{obs}=1cm,
=> $D_{antennae}$~12cm, D_{max}~6m

=> need filled array with ~900 antennaes to get 1μK noise (~80 times VSA/CBI)



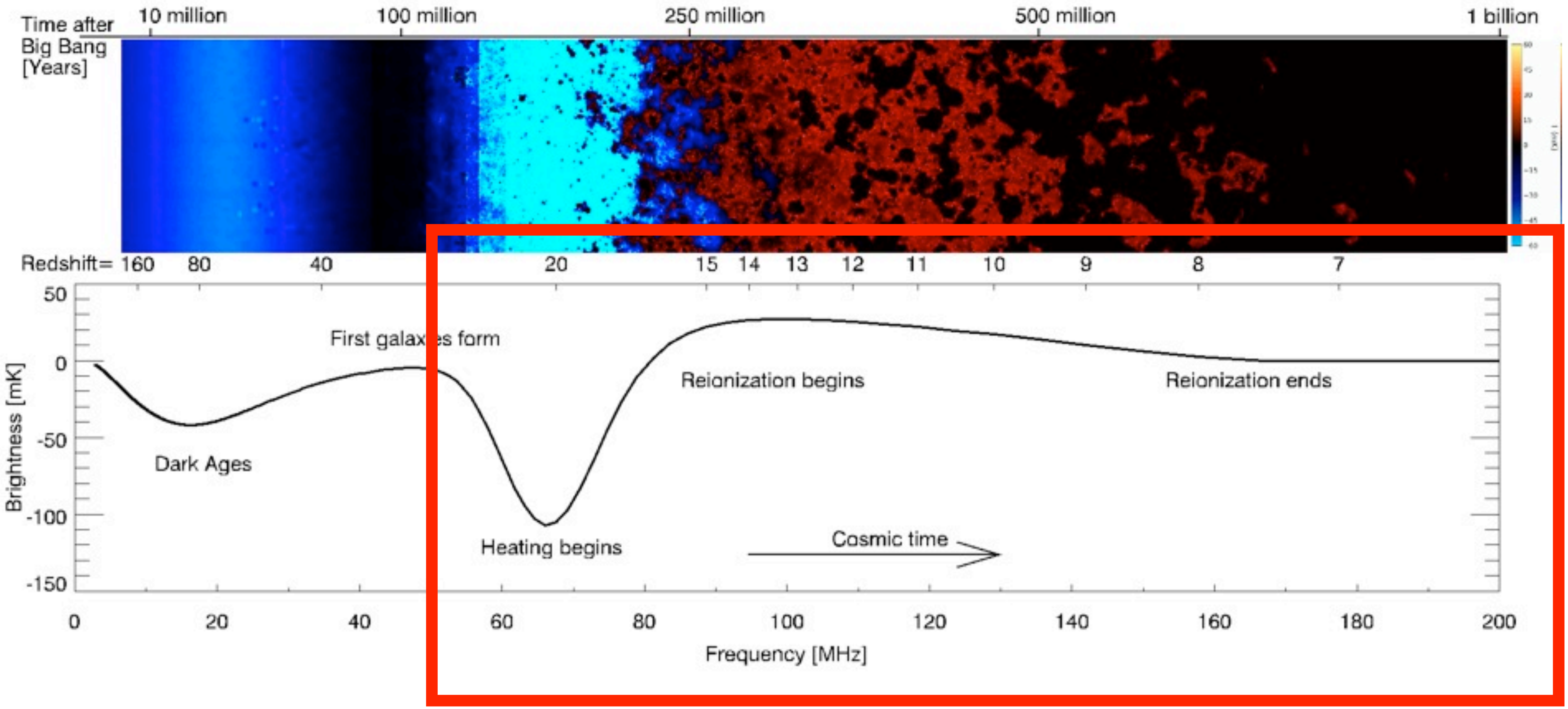
Very Small Array VSA)

Cosmic Background Imager (CBI):

Clean measurement of autocorrelation determines mass threshold for CO luminous galaxies

Cross-correlation of maps in different lines selects galaxies at desired redshift

21 cm global signal

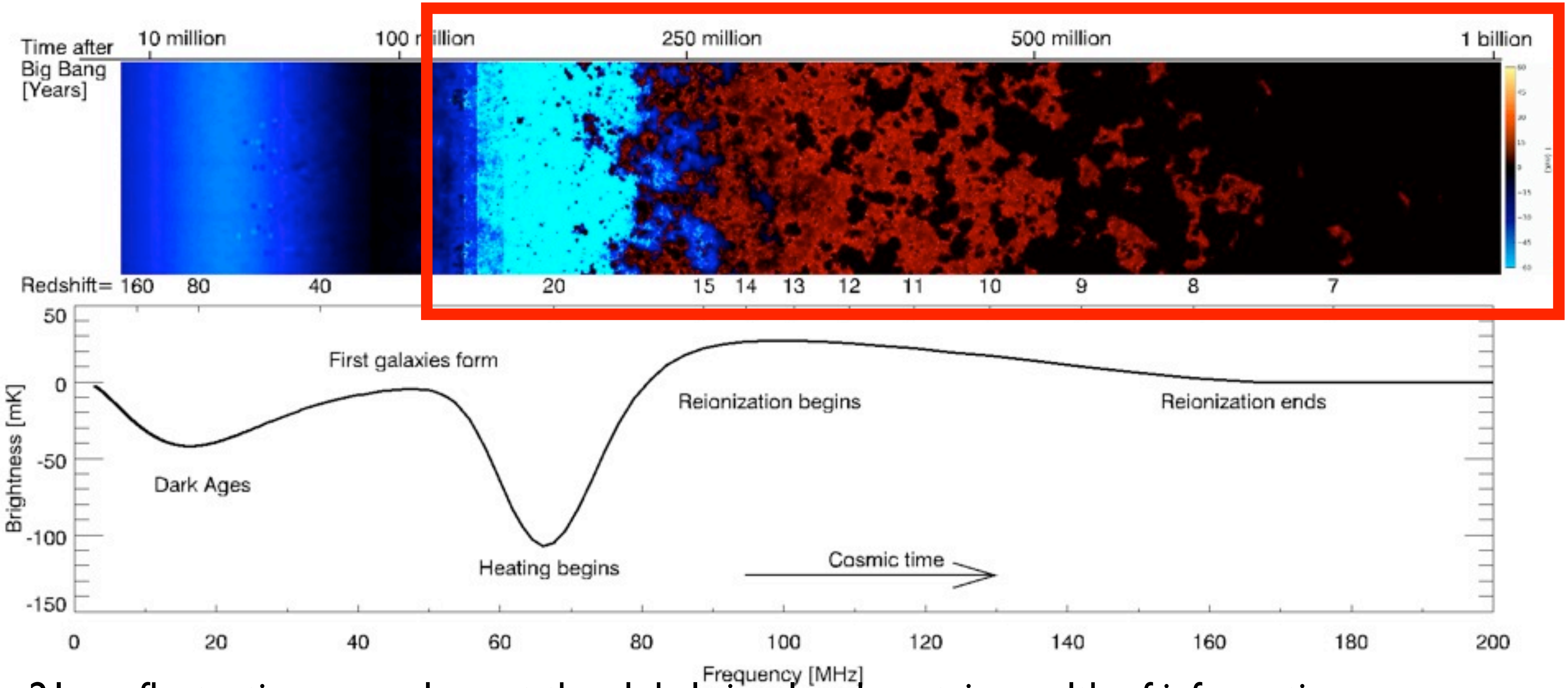


- 21 cm global signal is complementary to fluctuations/imaging - may provide infomation on major transitions: formation of first galaxies, cold/hot, neutral/ionized

- SKA needs to ensure full redshift range is covered i.e. z<30, nu>50 MHz

- Sensitivity requirement set by amplitude of 21 cm fluctuations to ~1 mK

21 cm fluctuations



- 21 cm fluctuations complement the global signal and contain wealth of information
  - Lyman alpha fluctuations => star formation rate and first galaxies
  - Temperature fluctuations => X-ray sources and first black holes
  - Neutral fraction fluctuations => topology of reionization
  - Baryonic winds? Dark matter?

- SKA should resolve 21 cm fluctuations and be capable of imaging structures during EoR
  - angular resolution ~1 arcmin, frequency resolution ~0.1 MHz to resolve bubbles
  - field of view to encompass large structures required to be few degrees

Key Questions for SKA?

- By 2020 should know reionization history & have directly observed brightest sources
- Topology of reionization?
- Contribution of faint sources?
- Details of sources at $z>13$?
- Environments of galaxies?
- Galaxy emission at different frequencies? e.g. X-rays, Lya