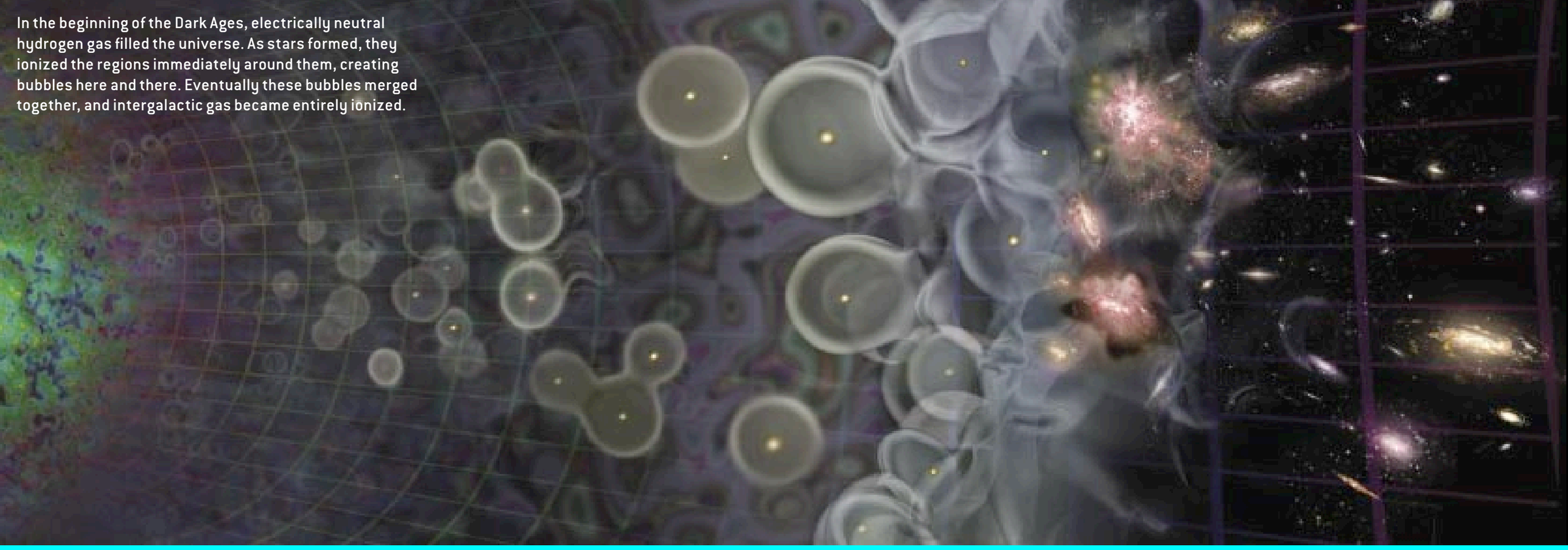
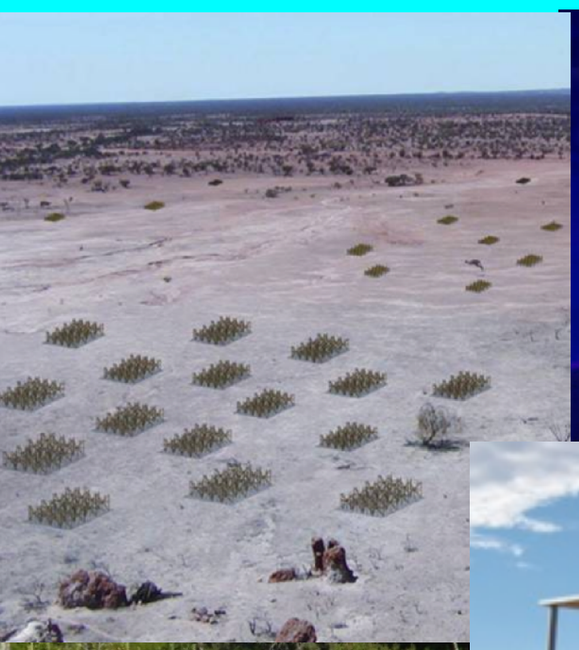
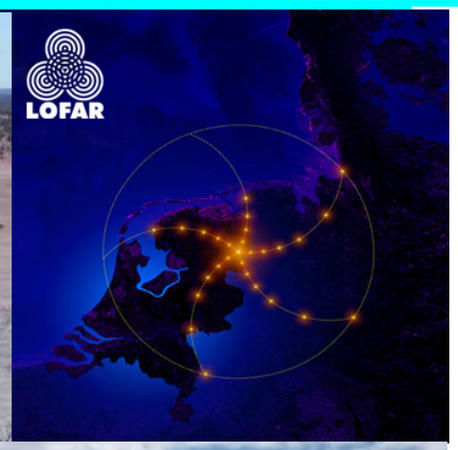


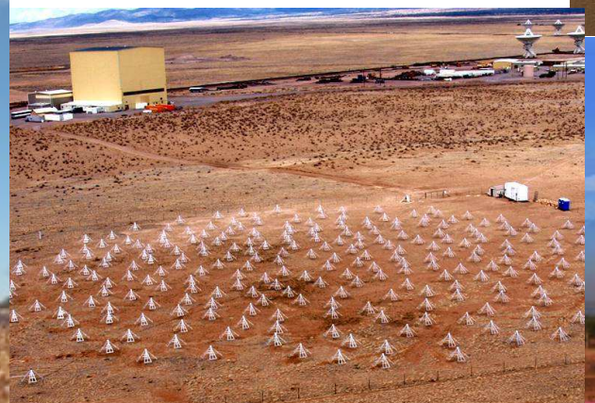
In the beginning of the Dark Ages, electrically neutral hydrogen gas filled the universe. As stars formed, they ionized the regions immediately around them, creating bubbles here and there. Eventually these bubbles merged together, and intergalactic gas became entirely ionized.

Prospects for future 21 cm surveys

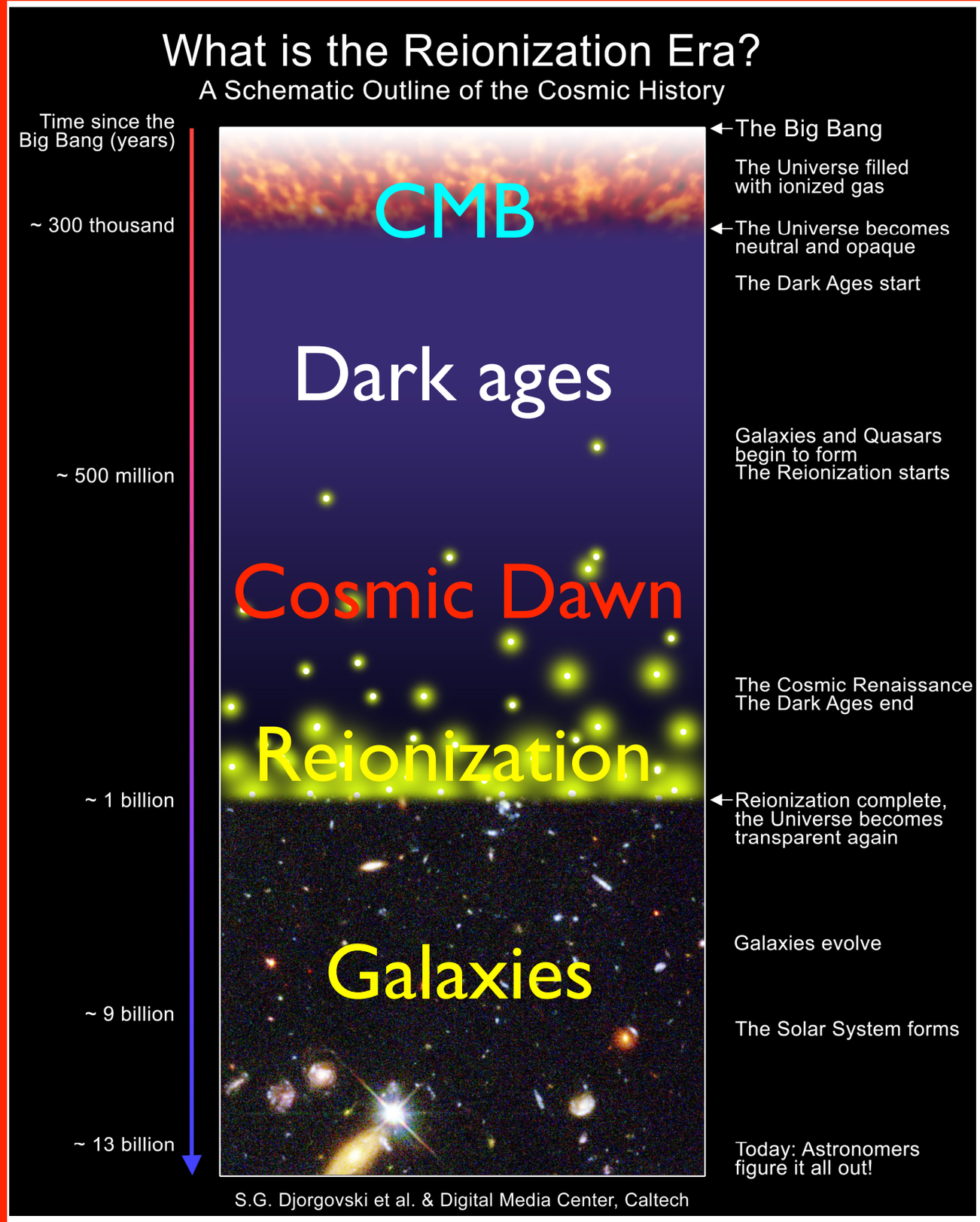




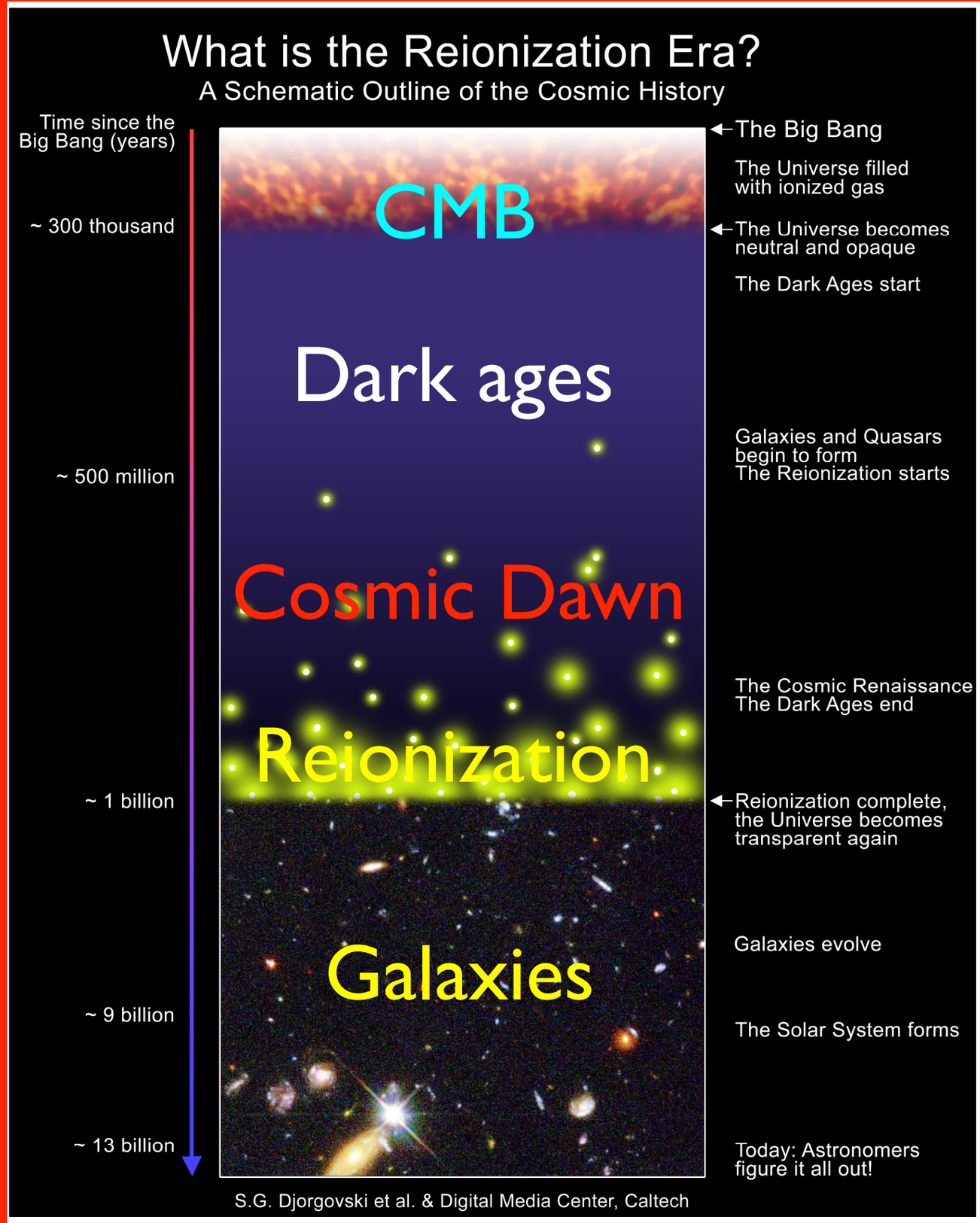
Jonathan Pritchard
ITC Fellow
CfA



The first billion years

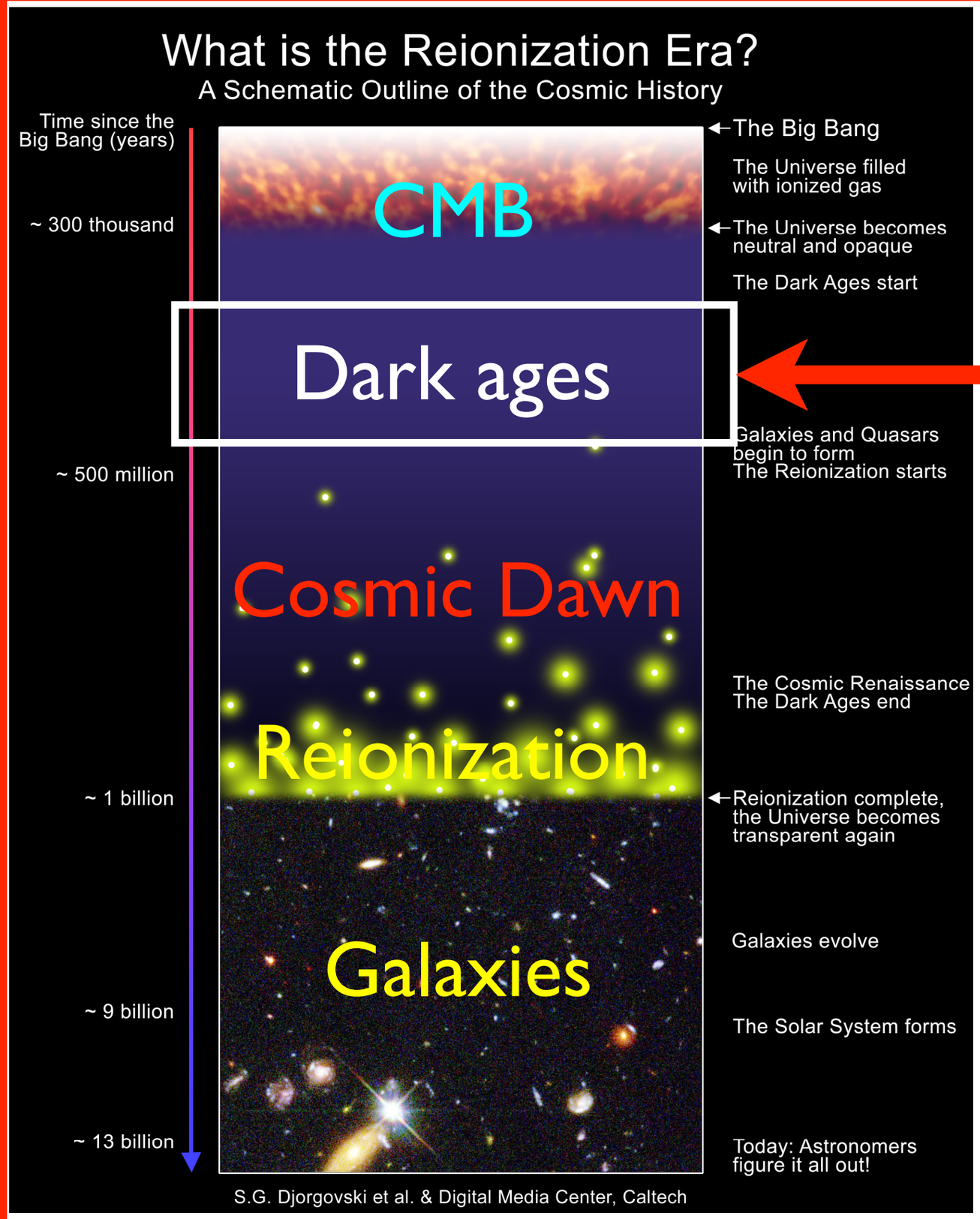


The first billion years



21 cm global signal

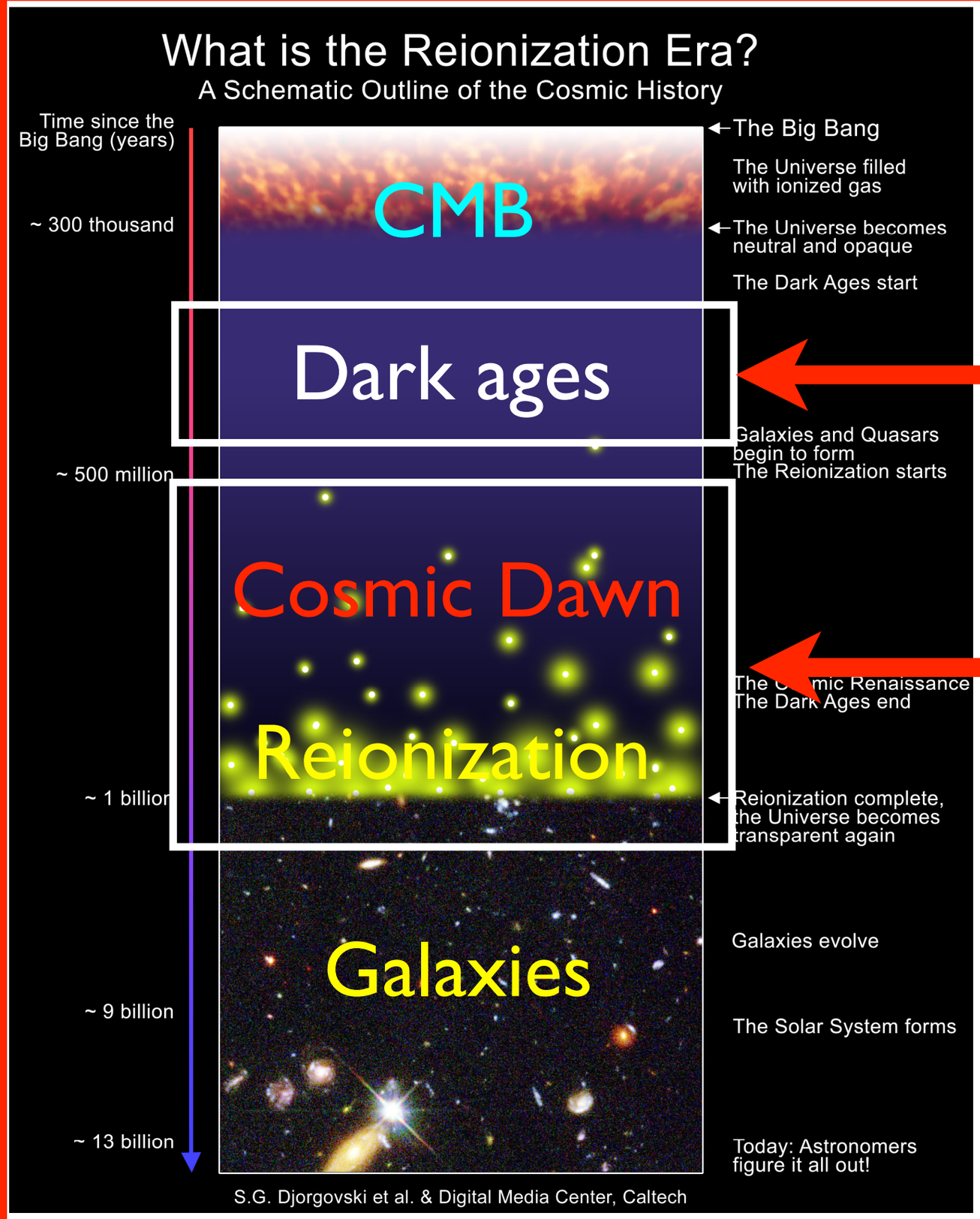
The first billion years



21 cm global signal

21 cm tomography
z~30-50

The first billion years

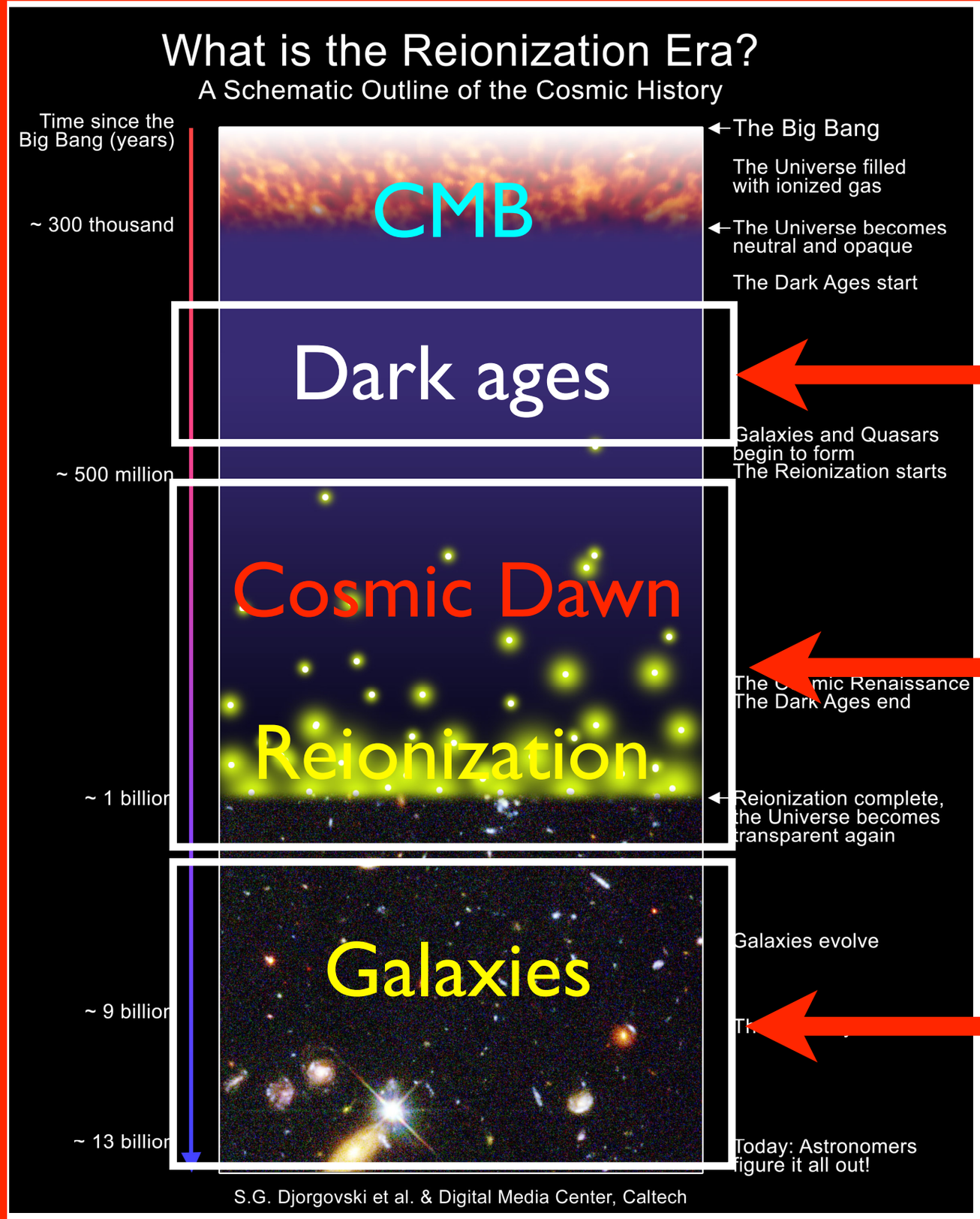


21 cm global signal

21 cm tomography
z~30-50

21 cm tomography
z~6-30

The first billion years



21 cm global signal

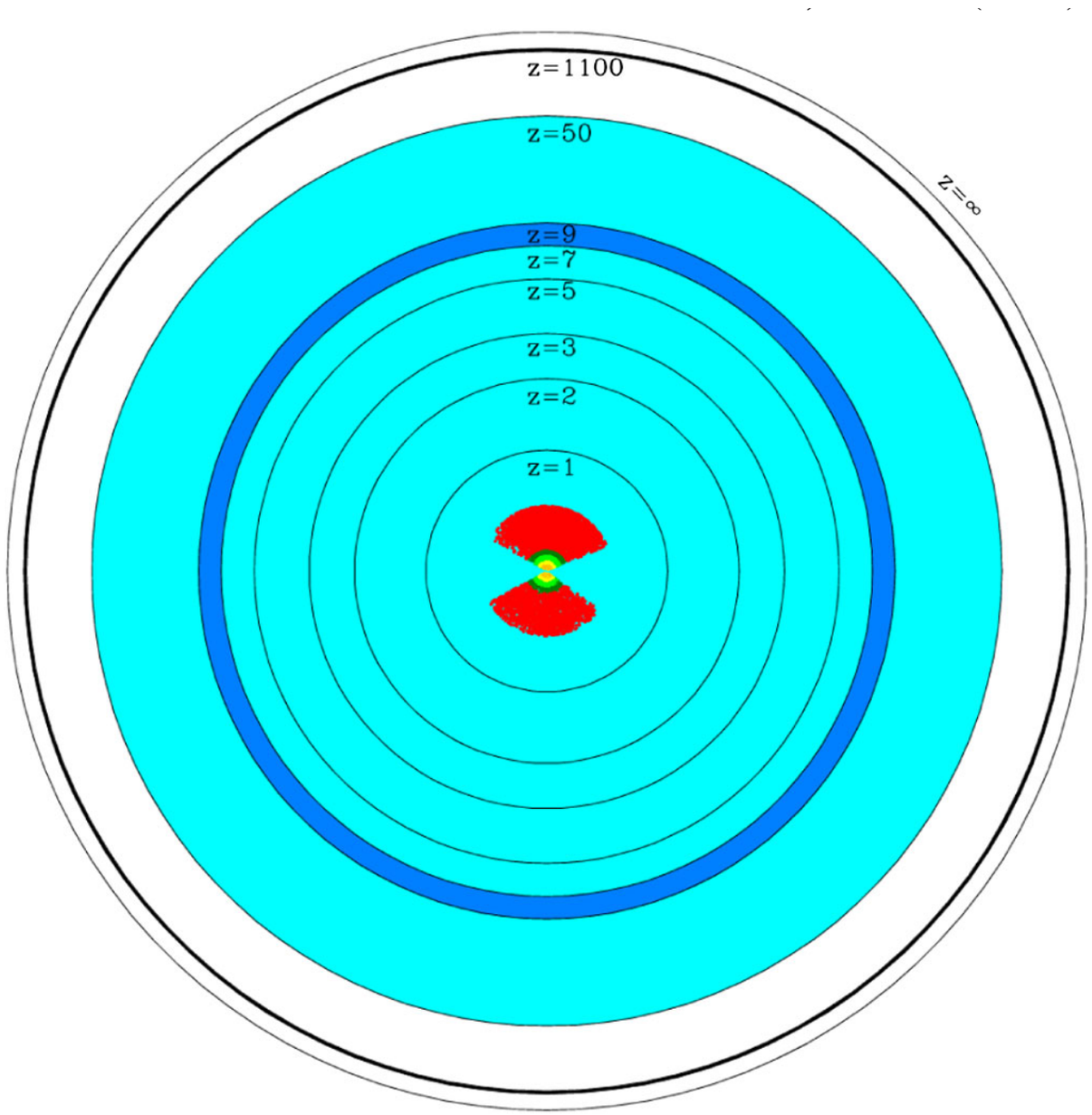
21 cm tomography
z~30-50

21 cm tomography
z~6-30

Intensity mapping
z~1-3

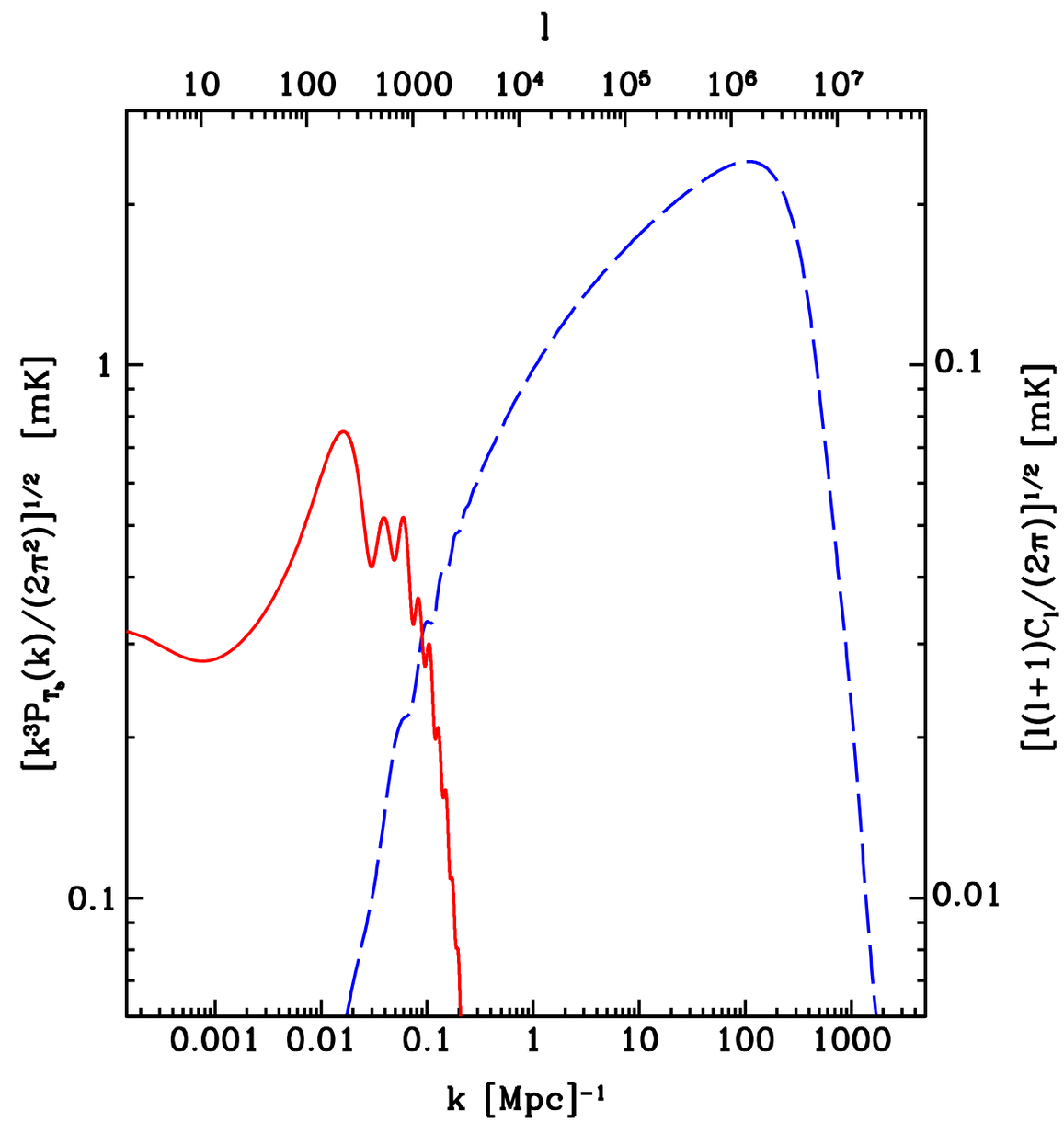
Improving cosmological measurements

More volume



Tegmark & Zaldarriaga 2009

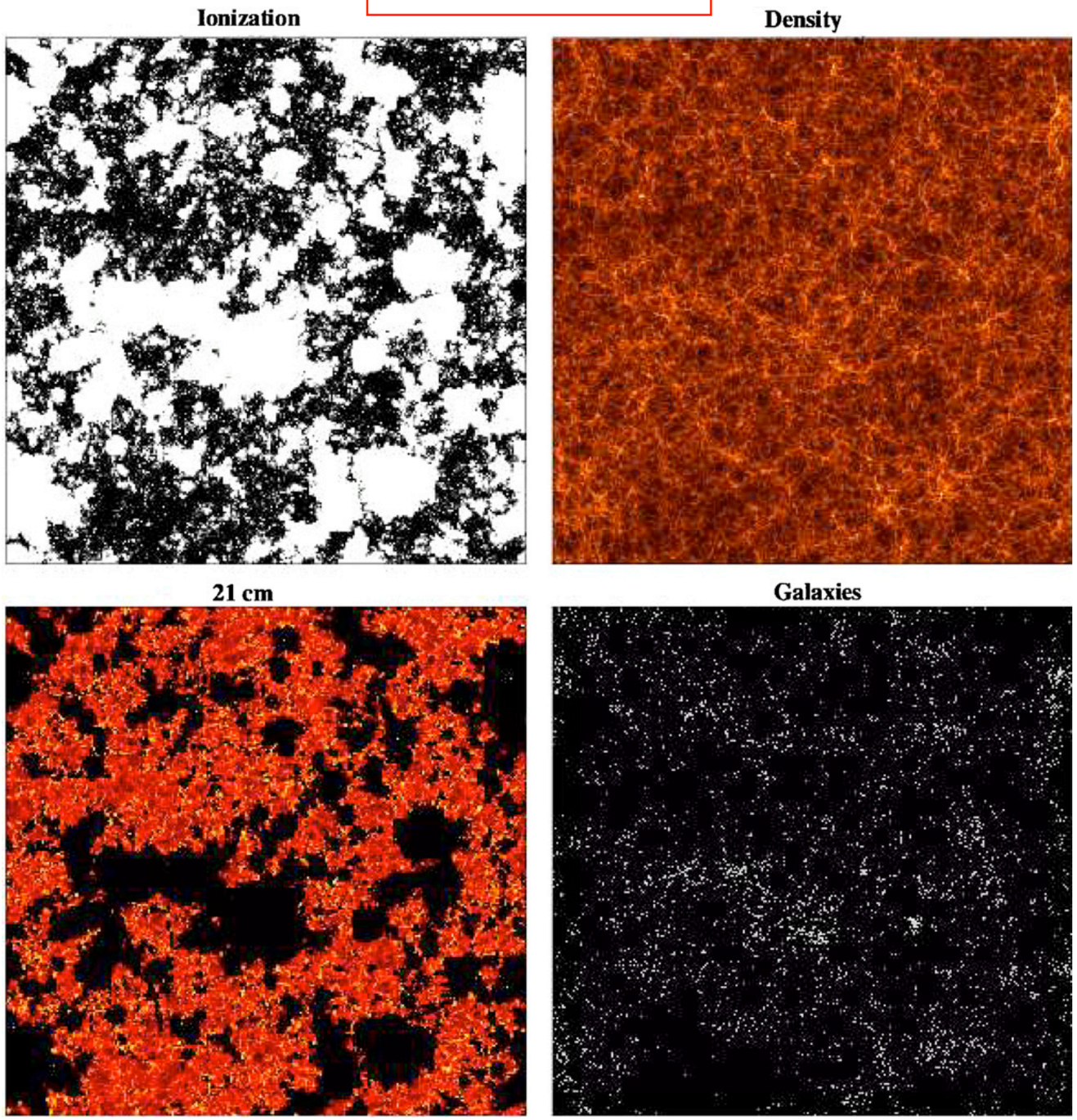
More scales



Kleban+ 2007

Astrophysics versus Cosmology

$z=7.32 \quad x_i=0.54$



Density
+
Ionization
↓
21 cm

Lidz+ 2009

130/h Mpc=1.2 deg

Astrophysics versus Cosmology

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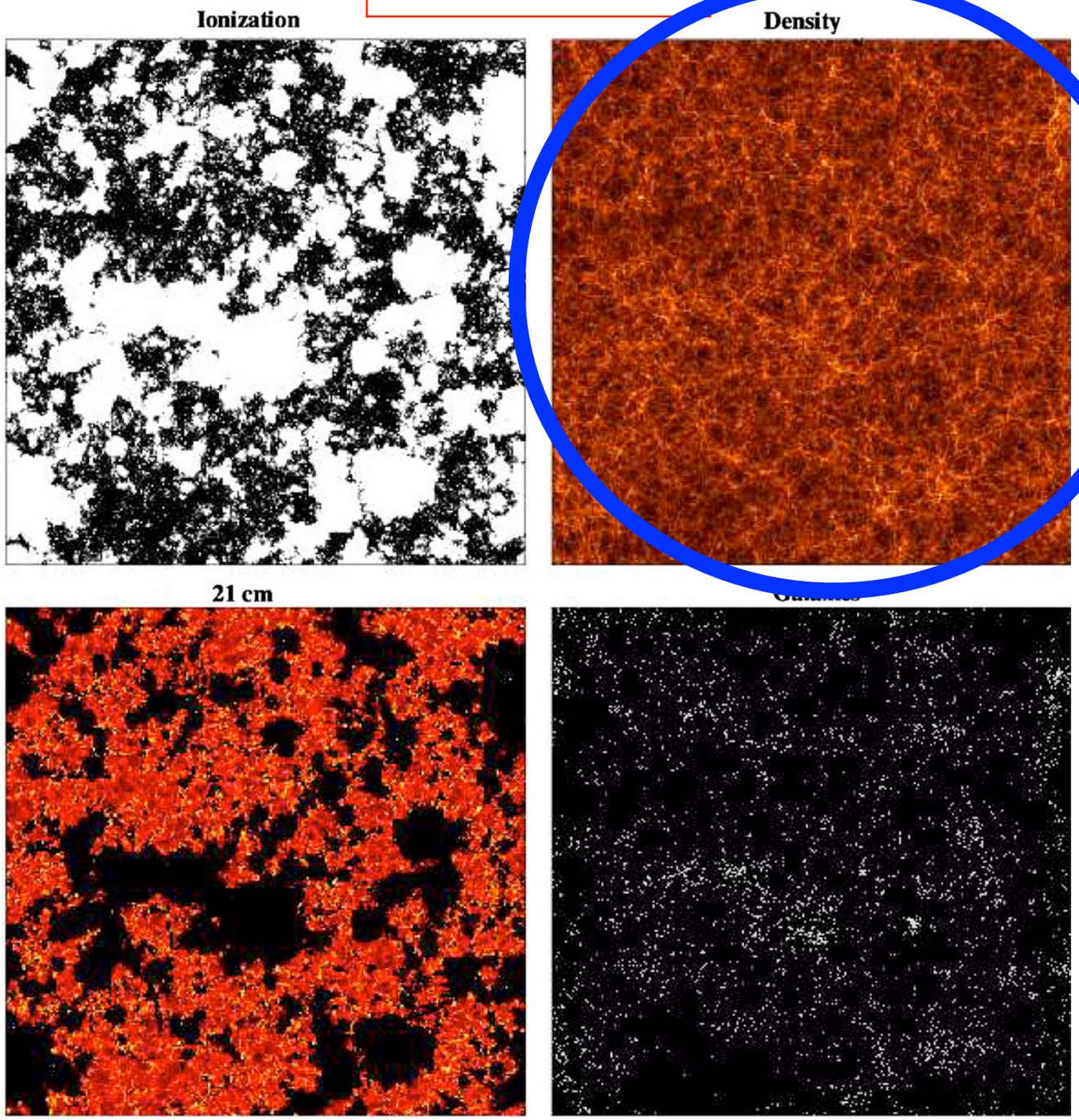


Cosmology = Good!

Density + Ionization

21 cm

Lidz+ 2009

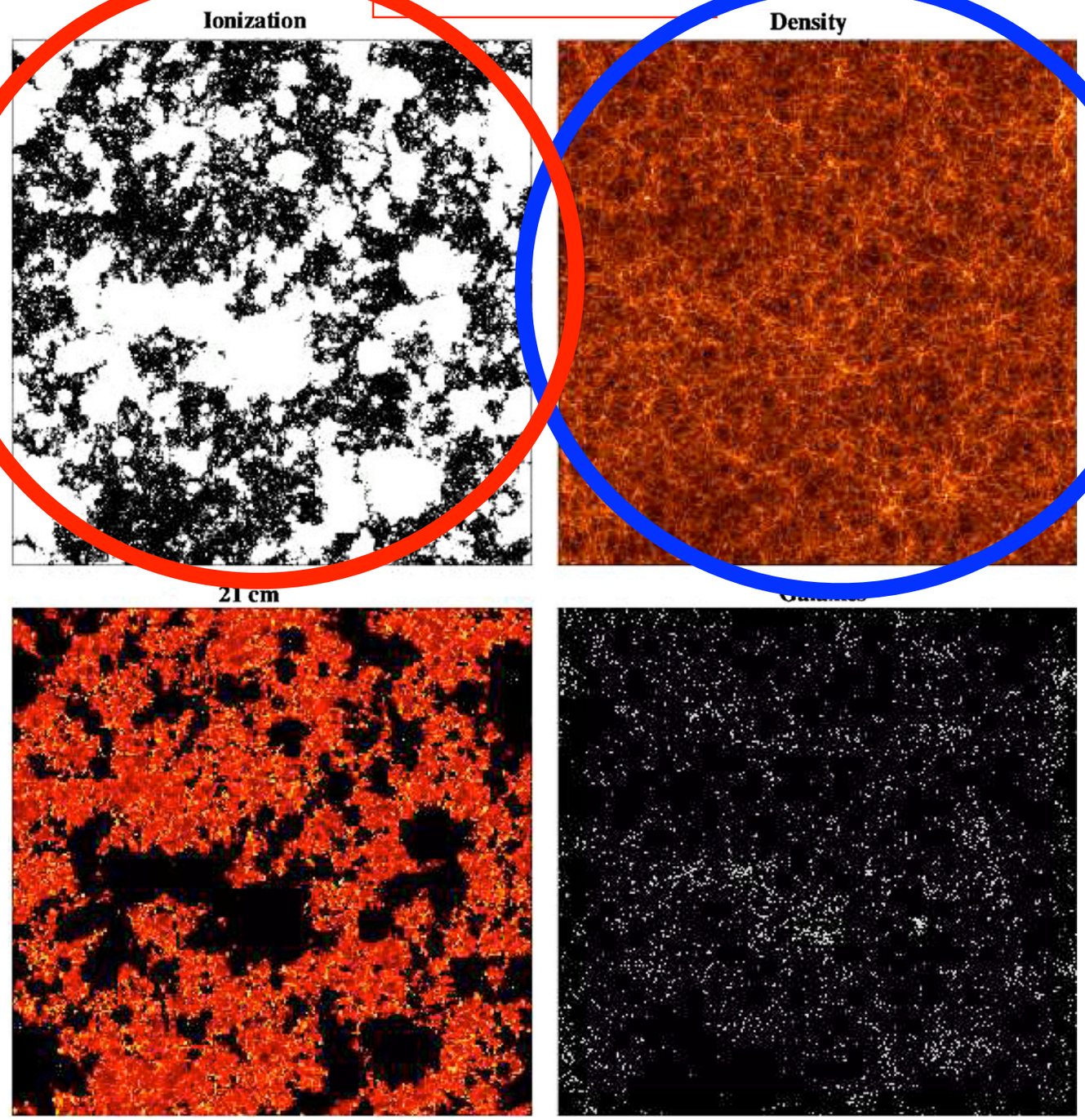
130/h Mpc=1.2 deg

Astrophysics versus Cosmology

$z=7.32 \quad x_i=0.54$

Astrophysics = Bad!

Cosmology = Good!



Density + Ionization → 21 cm

Lidz+ 2009

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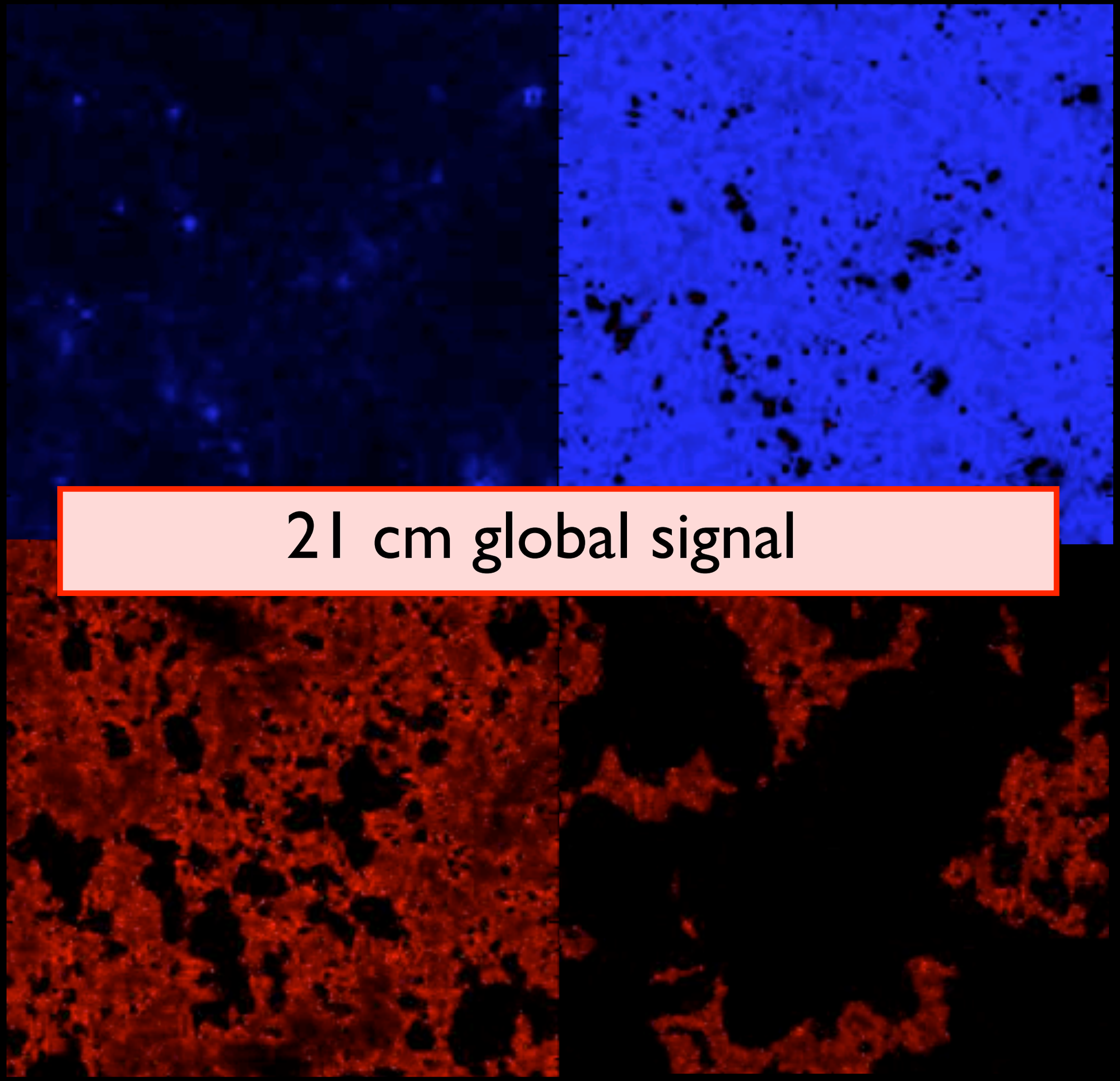
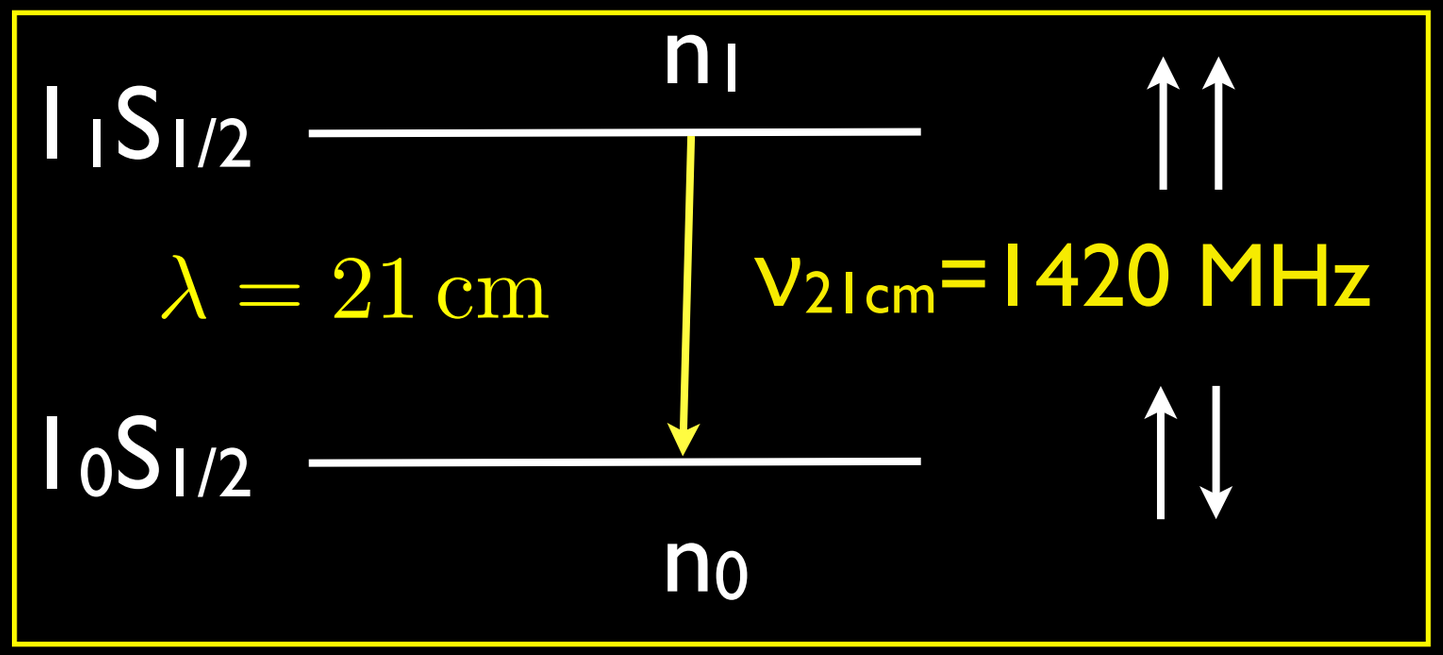


21 cm global signal

21 cm basics

Hyperfine transition of neutral hydrogen



Spin temperature describes relative occupation of levels

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

Useful numbers:

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

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

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

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

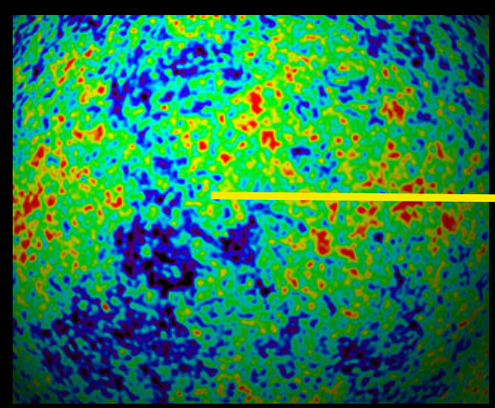
$$T_b = 27 x_{\mathrm{HI}}(1+\delta_b)\left(\frac{T_S - T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\right)^{1/2}\left[\frac{\partial_r v_r}{(1+z)H(z)}\right]^{-1}\mathrm{mK}$$

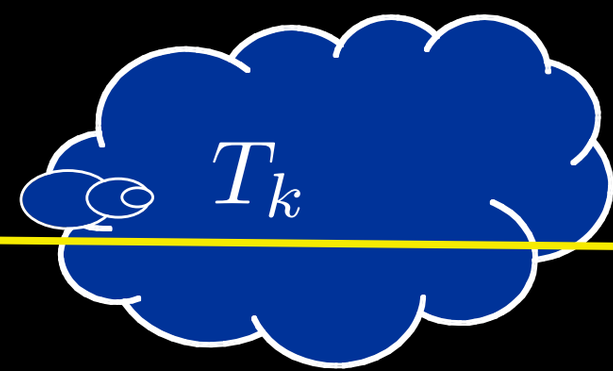
spin temperature set by different mechanisms:

Radiative transitions (CMB)	$T_S \to T_{CMB}$
Collisions	$T_S \to T_K$
Wouthysen-Field effect	$T_S \to T_K$

21 cm line in cosmology

T_γ T_S T_b





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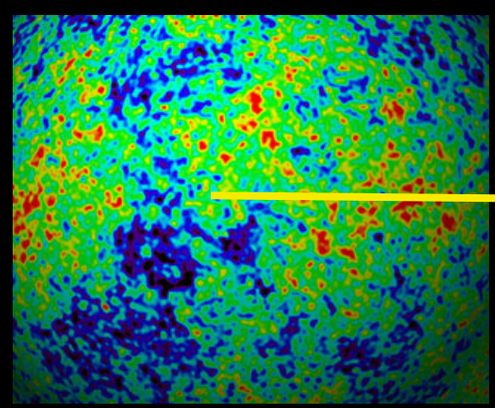

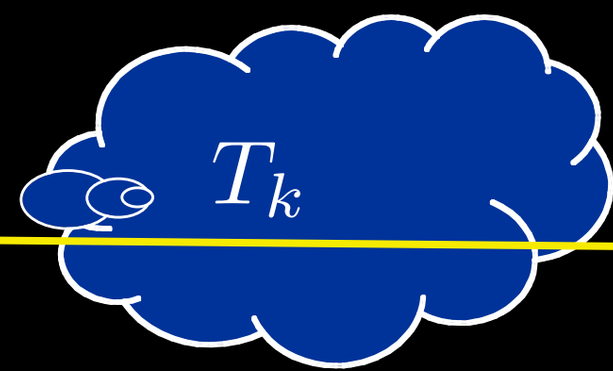

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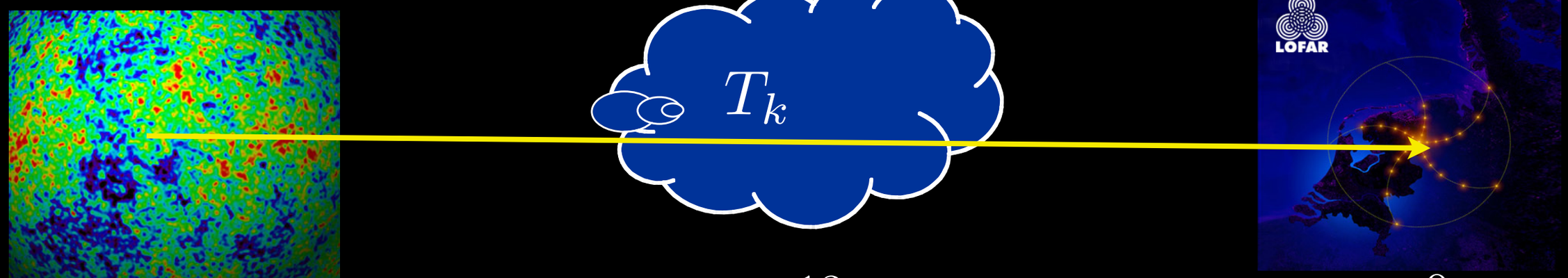

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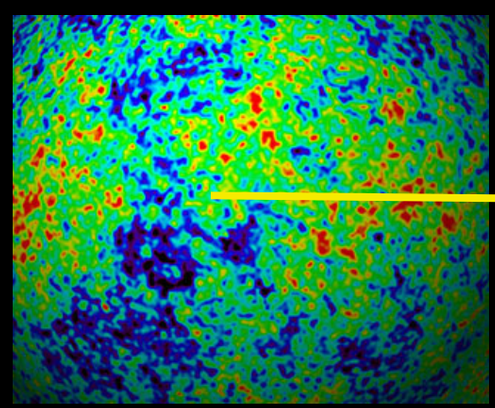

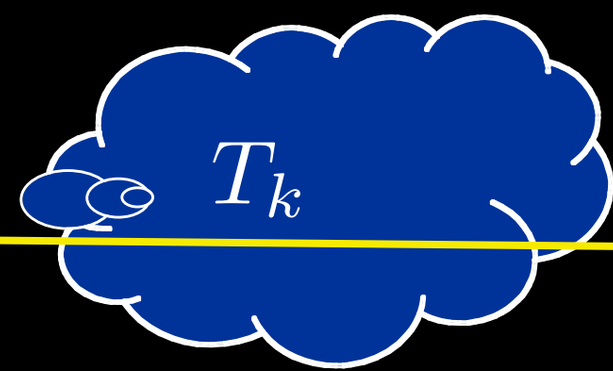

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peculiar velocities

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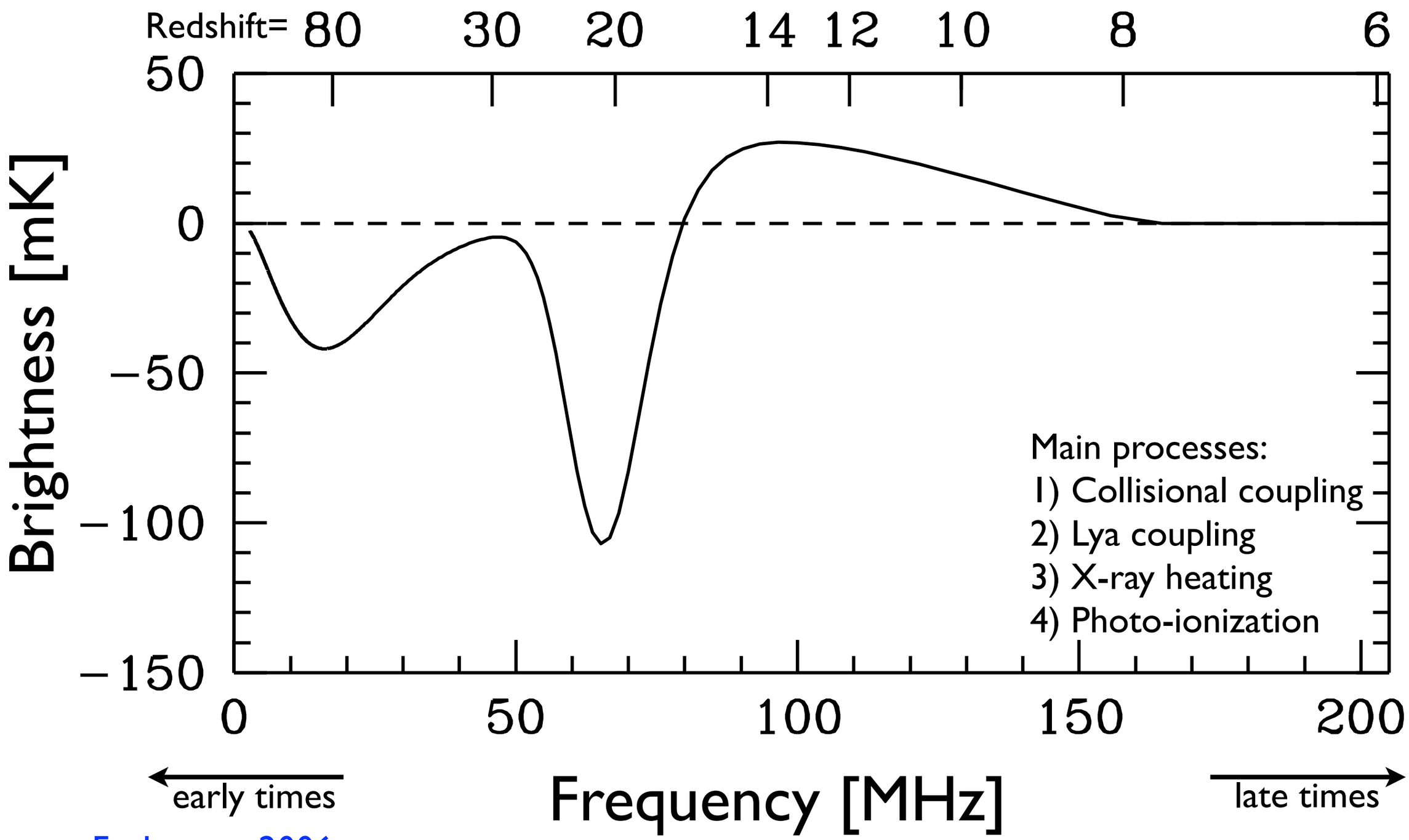
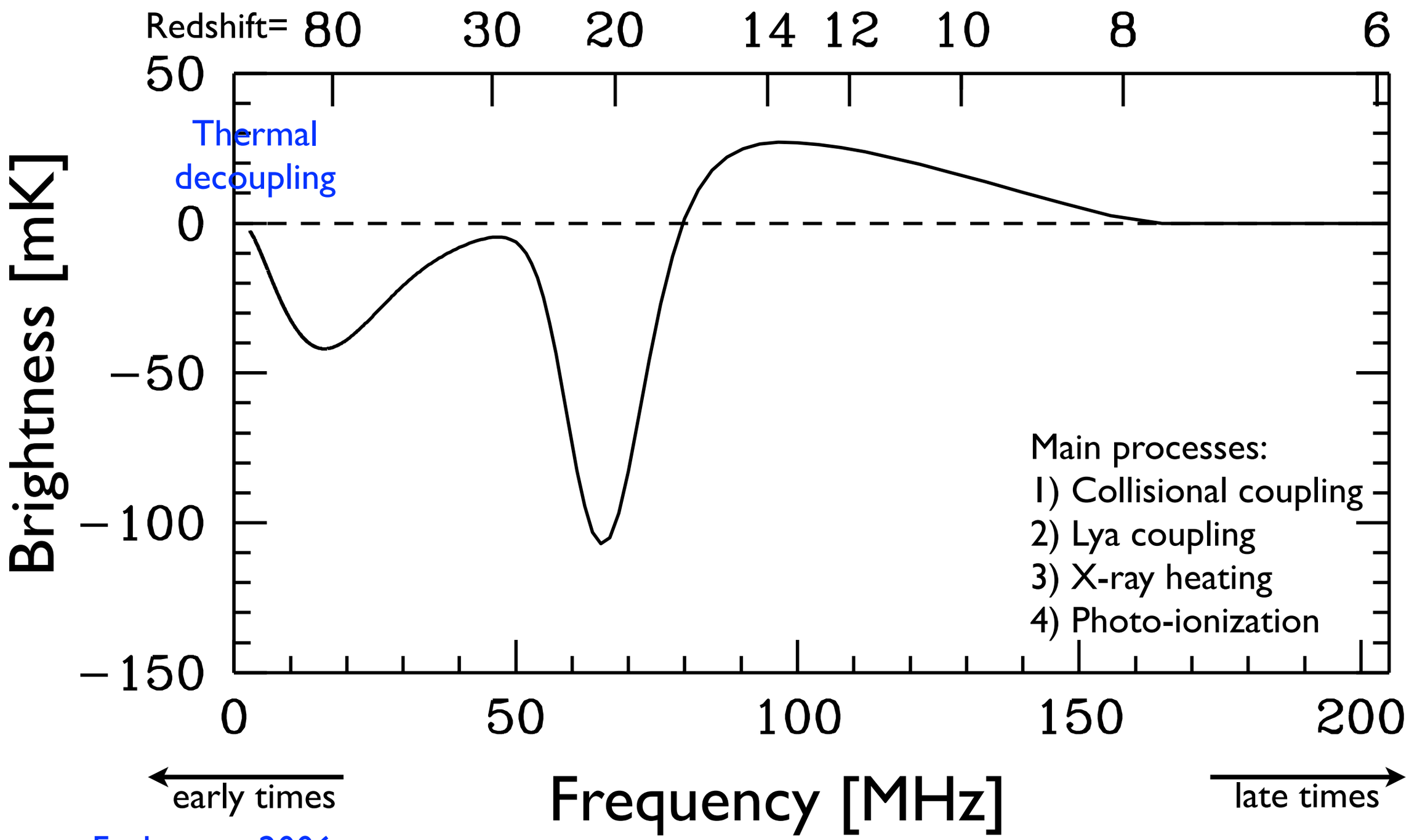
21 cm global signal



Furlanetto 2006
Pritchard & Loeb 2010

21 cm global signal



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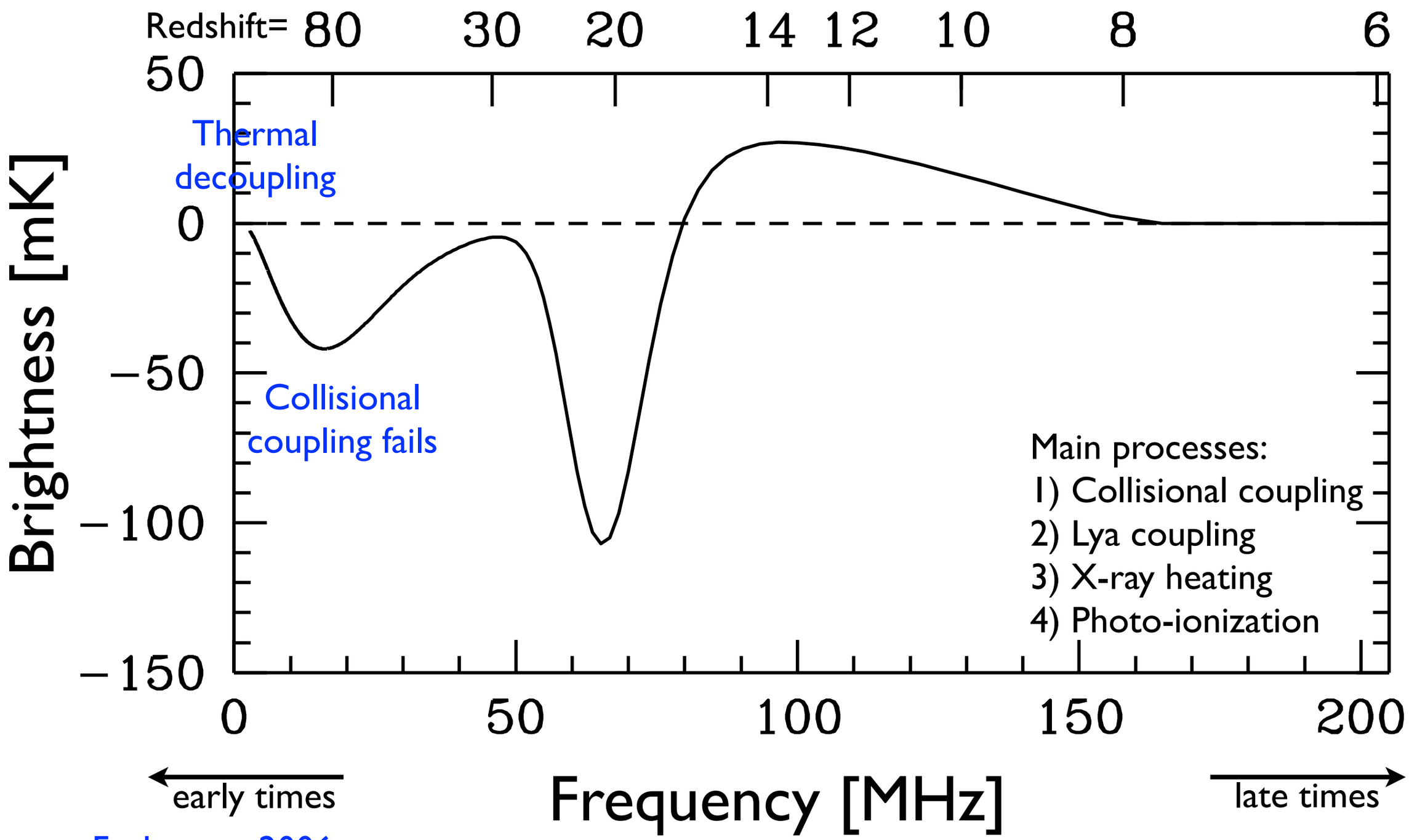

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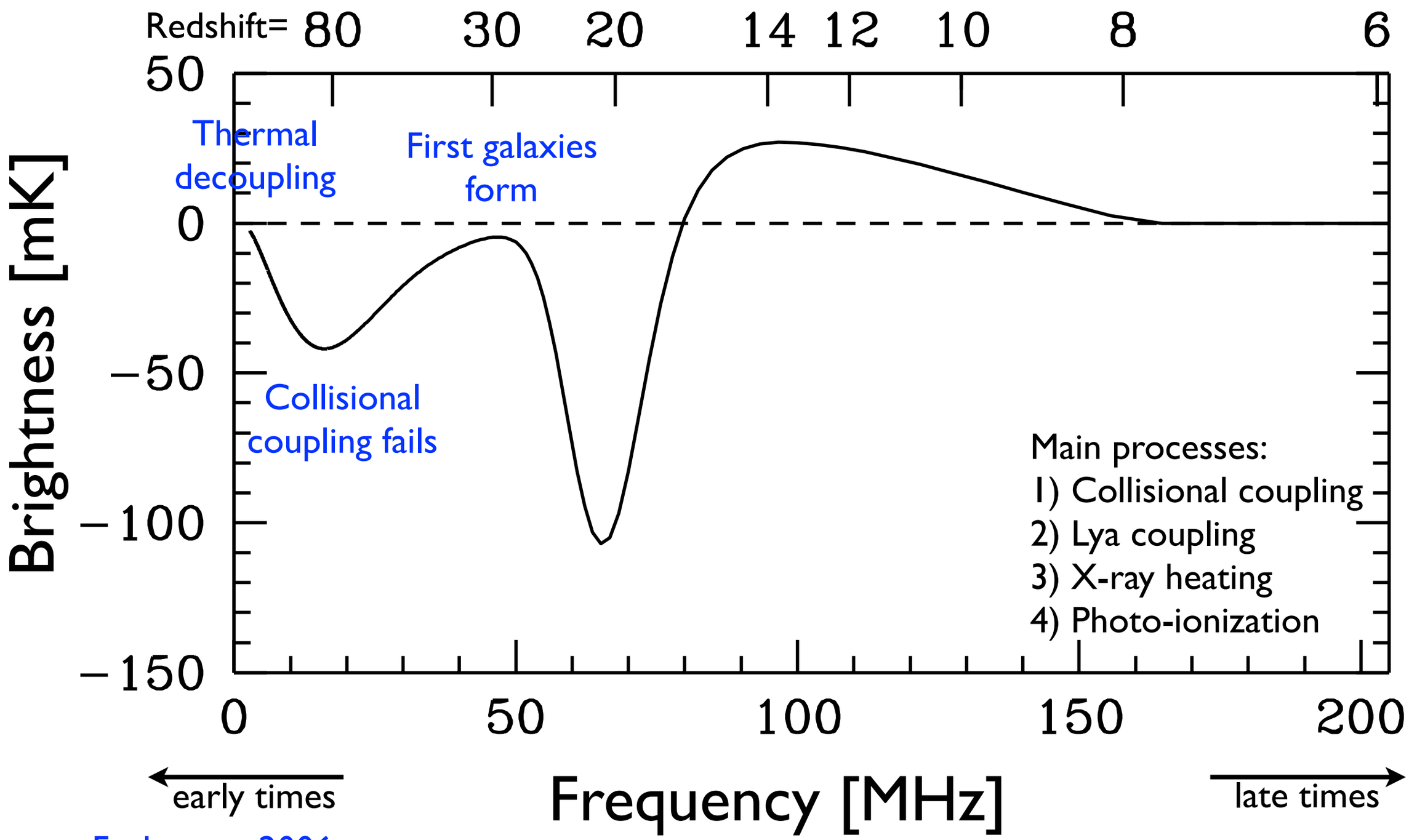

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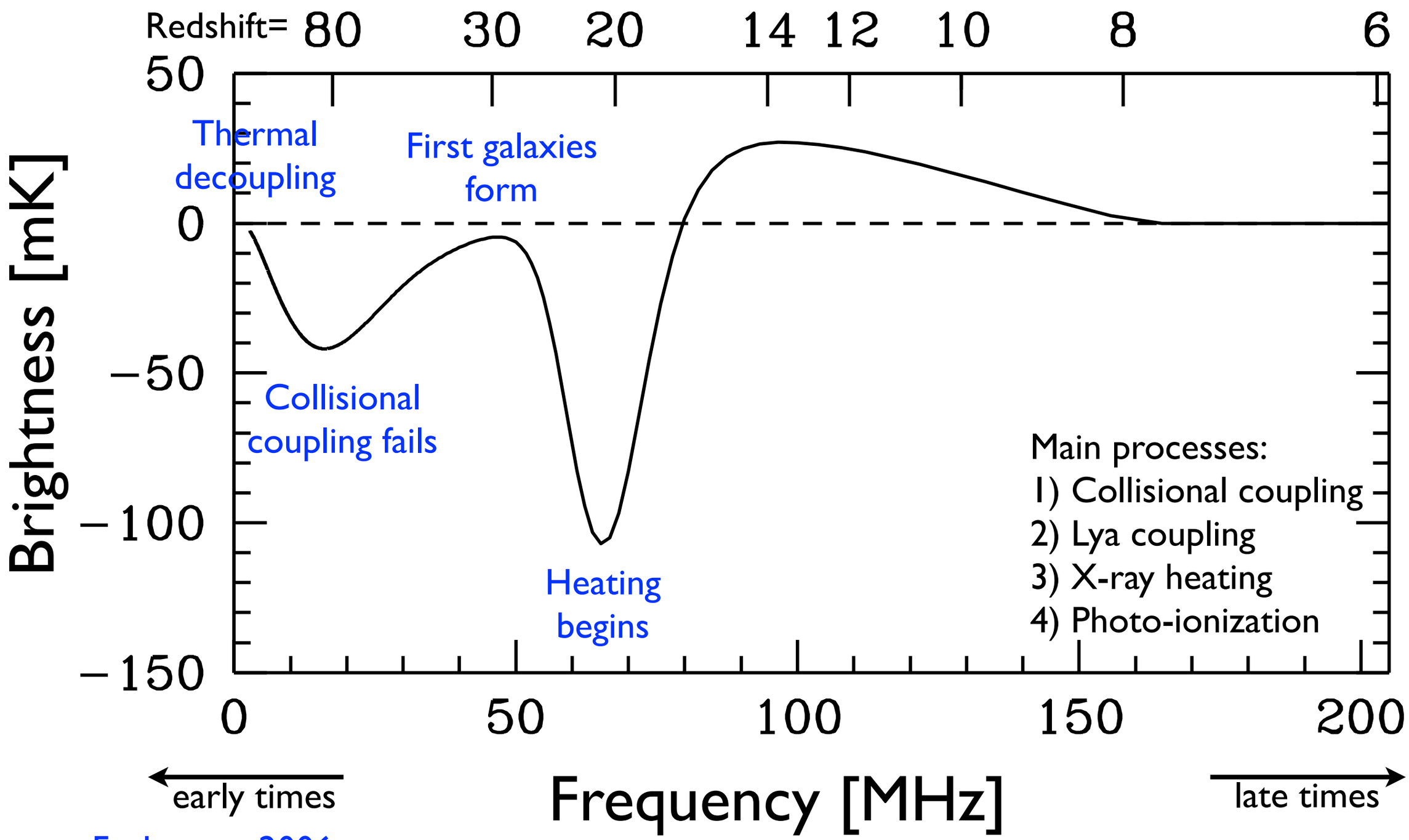

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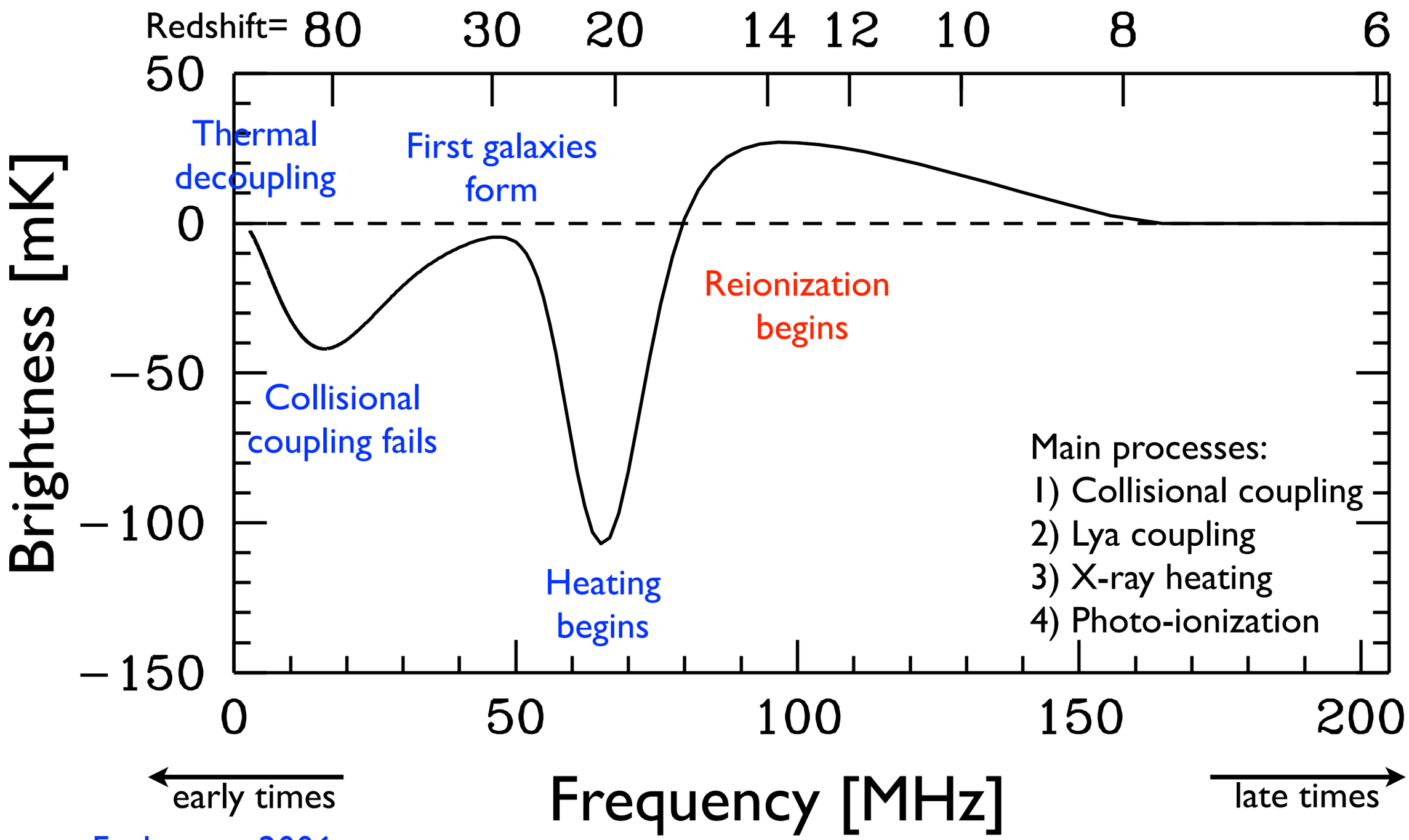

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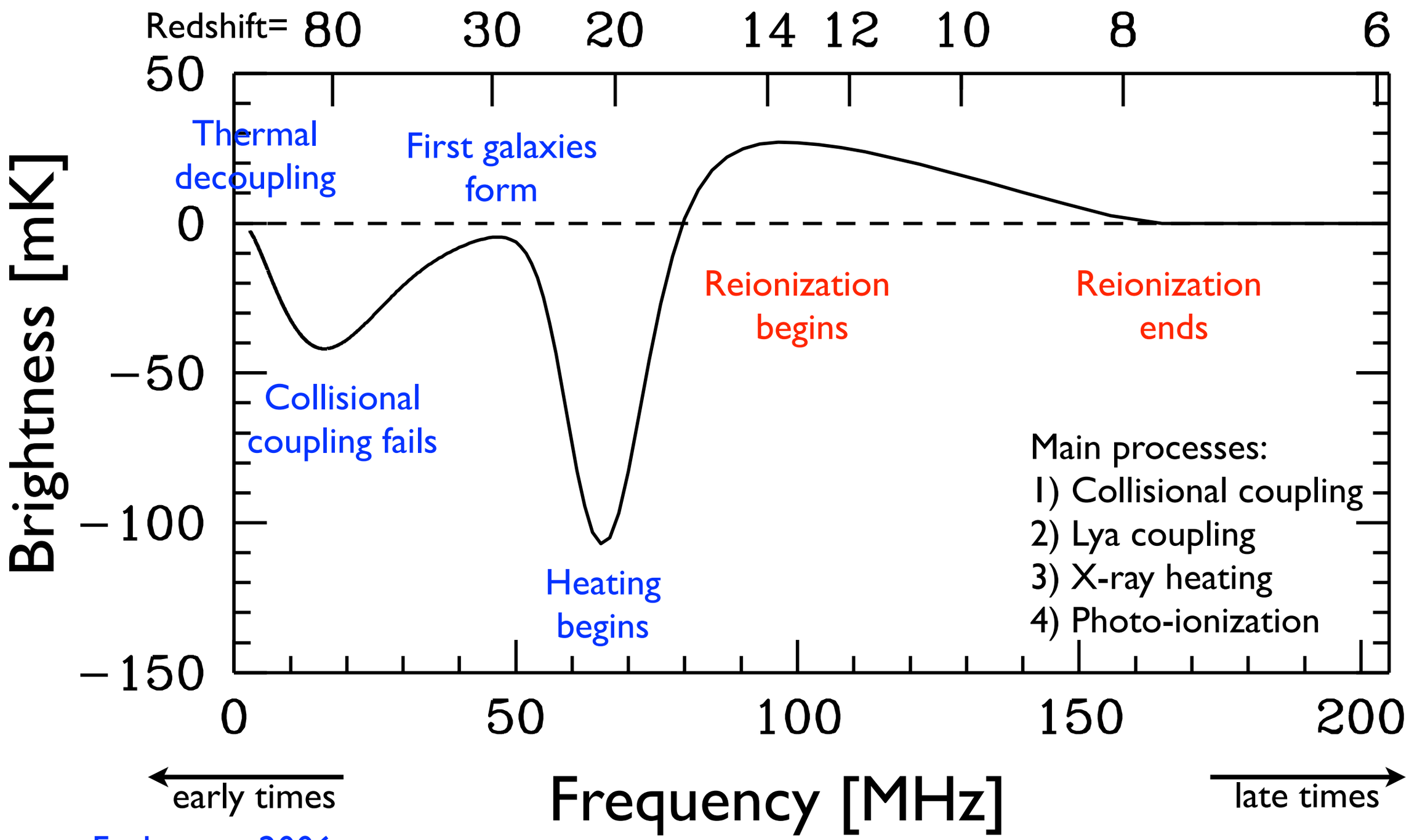

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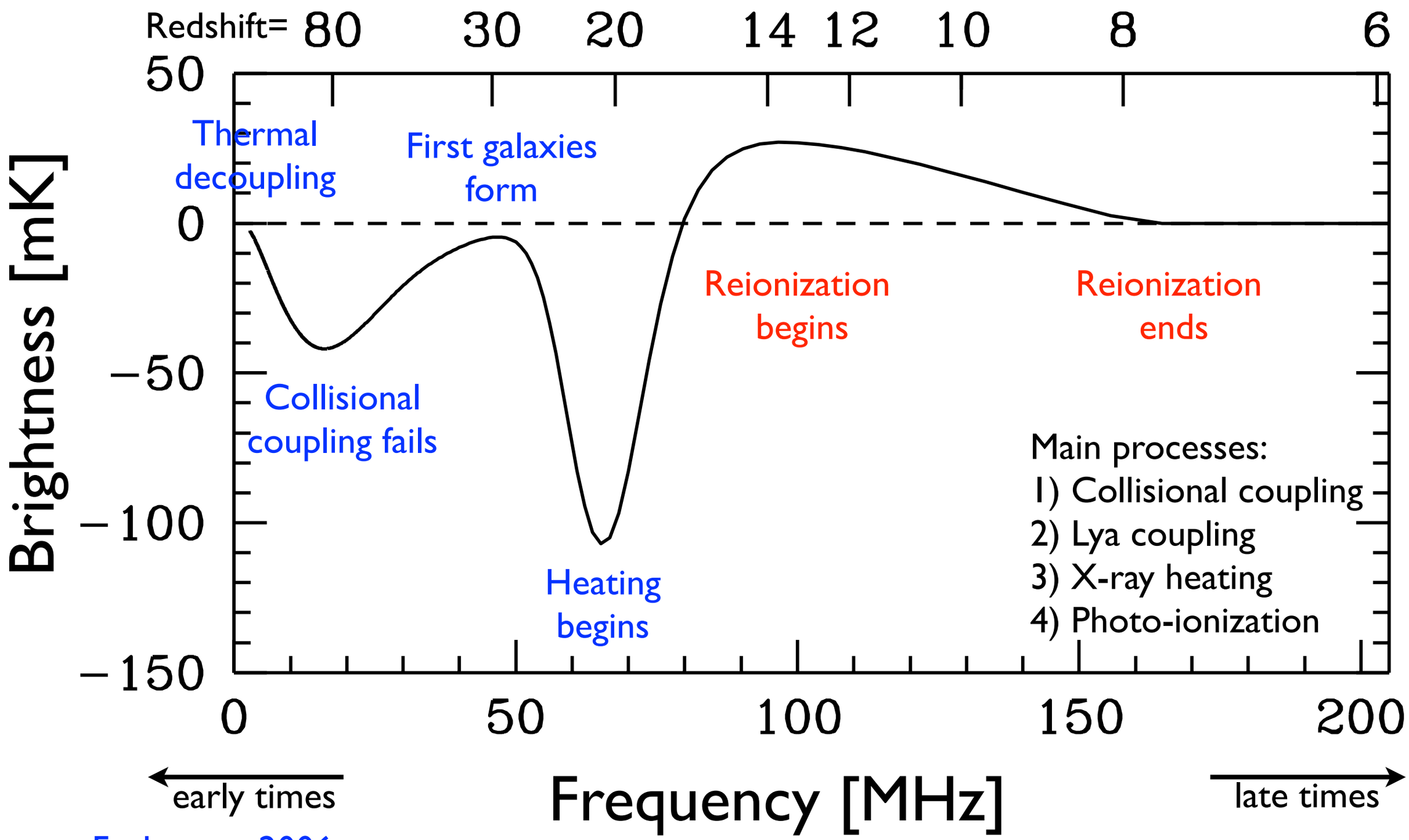
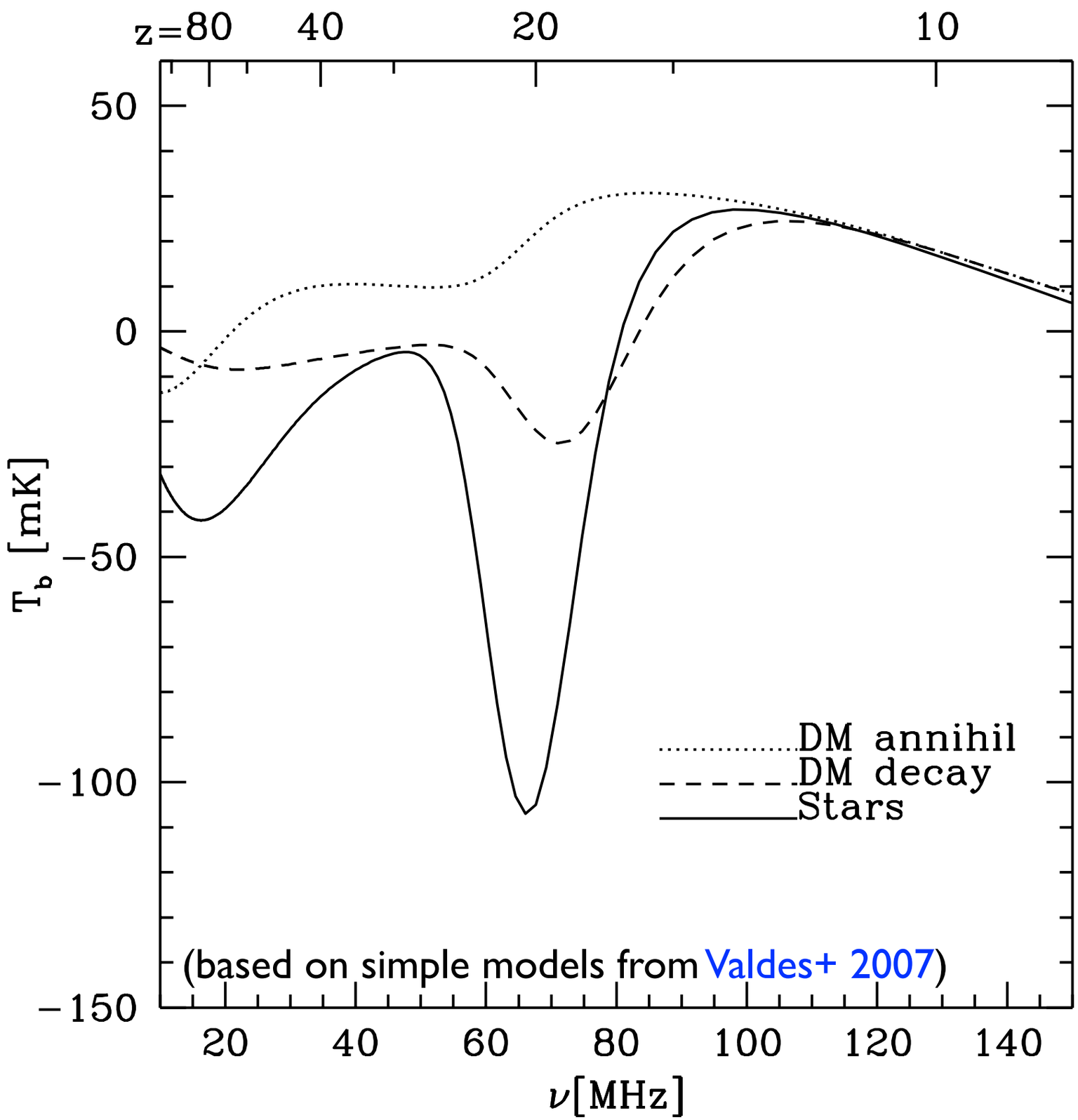


Furlanetto 2006
Pritchard & Loeb 2010

measurement would constrain thermal history and galaxies

The Universe as a calorimeter



Possibilities for exotic energy injection:

DM annihiliation/decay
Furlanetto+ 2006
Valdes+ 2007

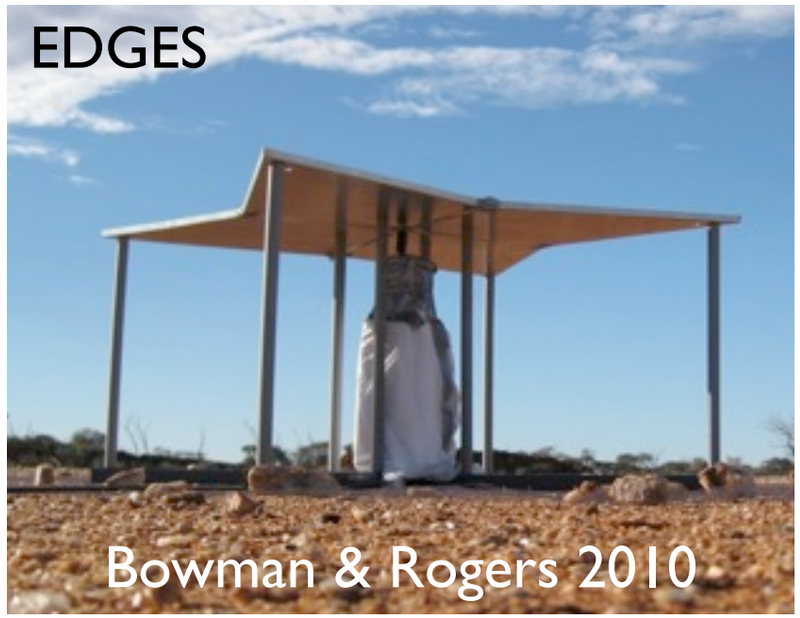
Excited DM relaxation
Finkbeiner+ 2008

Evaporating primodial BH
Mack+ 2008

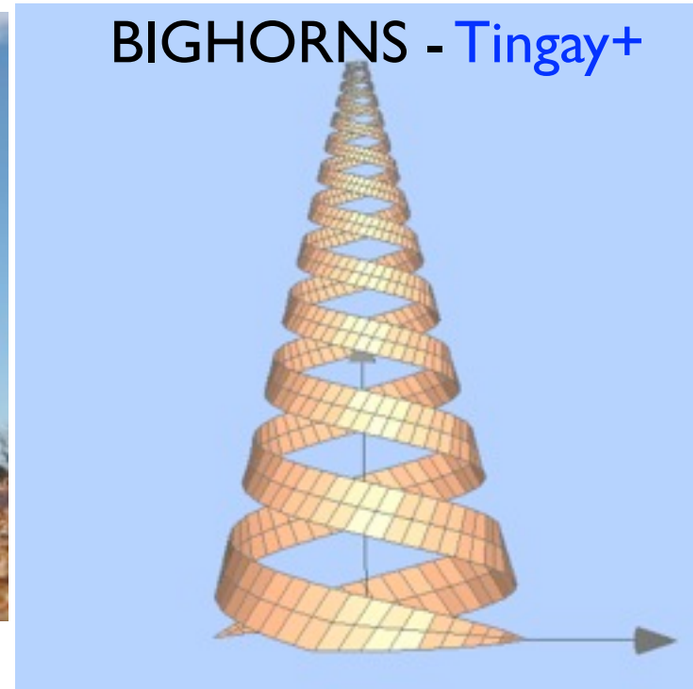
Cosmic string wakes
Brandenburger+ 2010

...

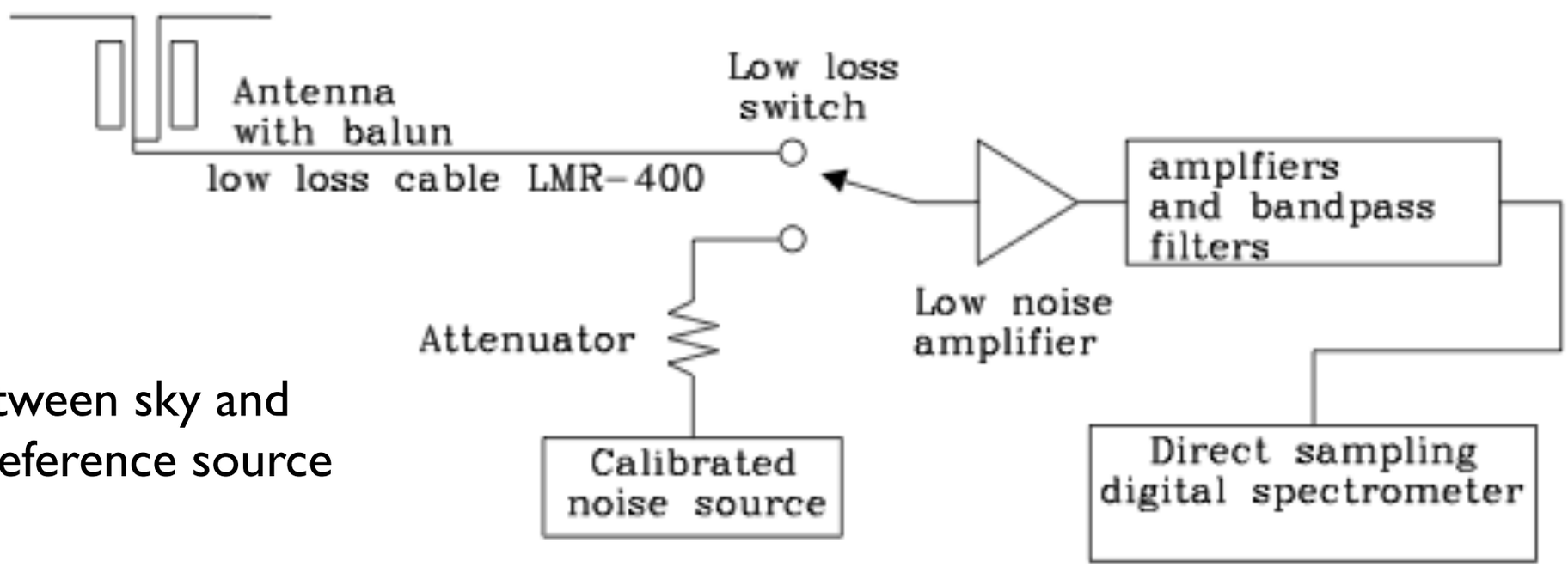
Absolute temperature measurements



also CoRE - Ekers+



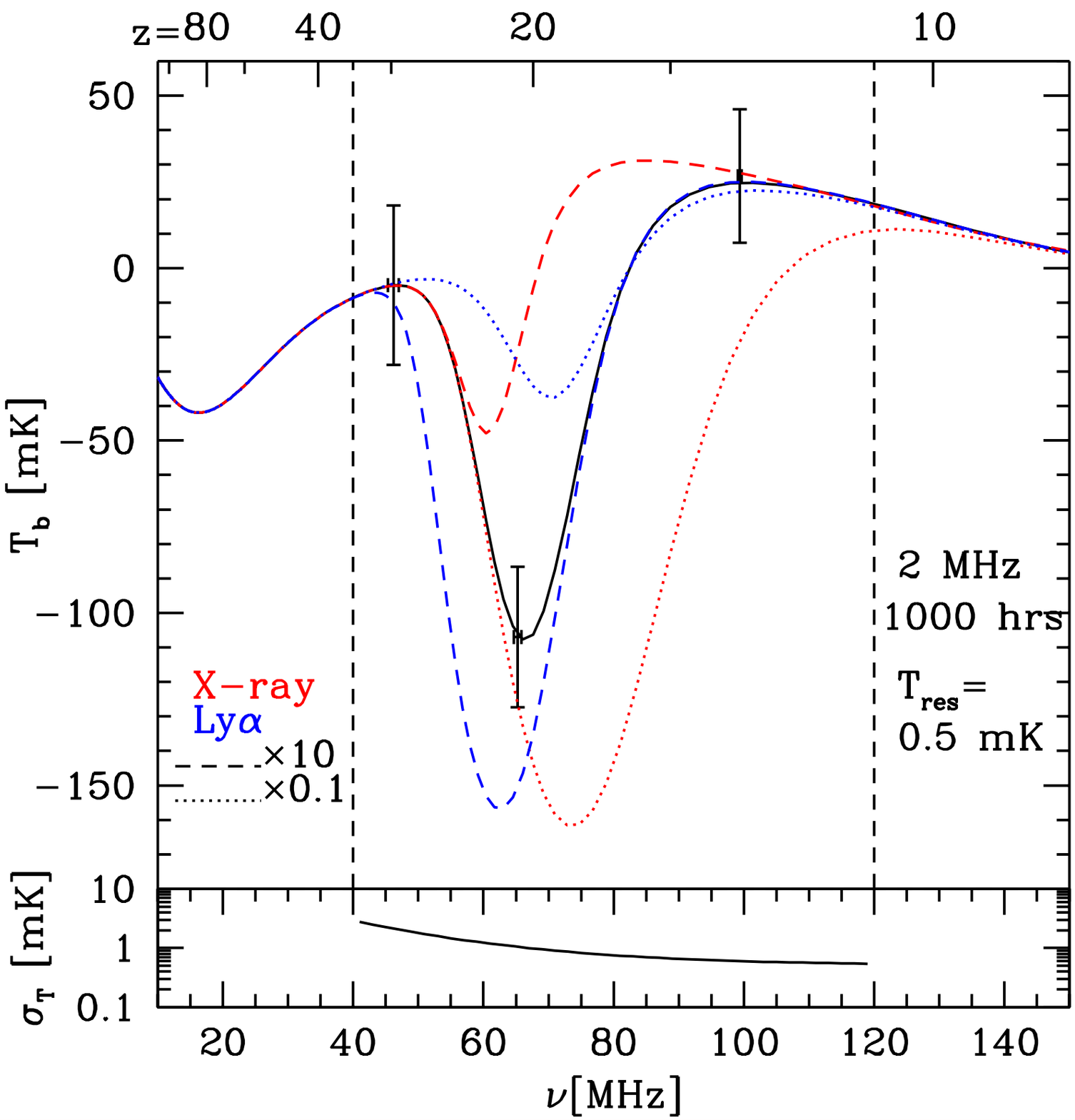
Burns+



Switch between sky and calibrated reference source

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

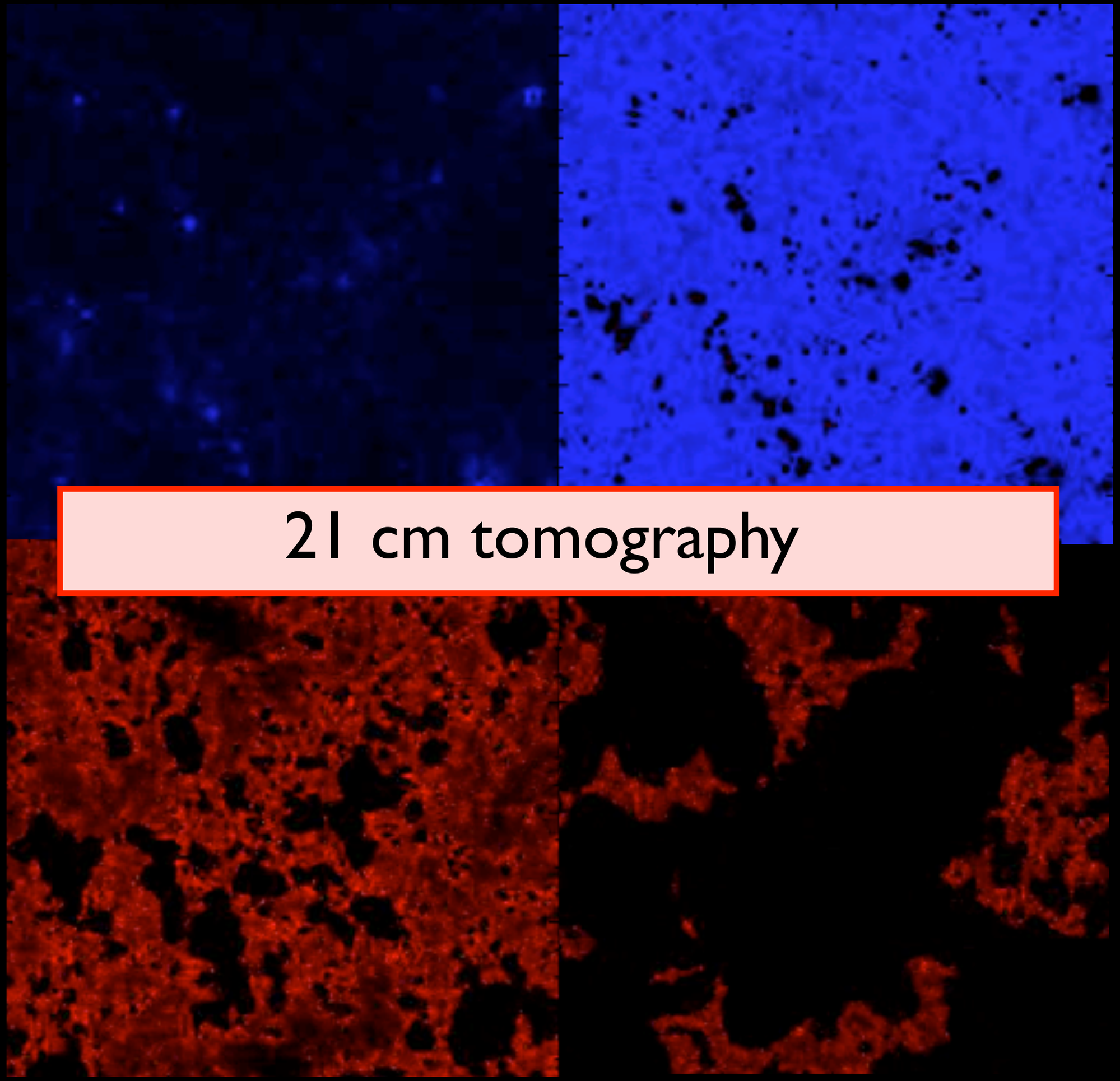
Thermal history



Fisher matrix predictions for constraints including foreground removal

Pritchard & Loeb 2010

Unless early, degeneracy with heating by galaxies
=> potentially useful upper bounds



21 cm tomography

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

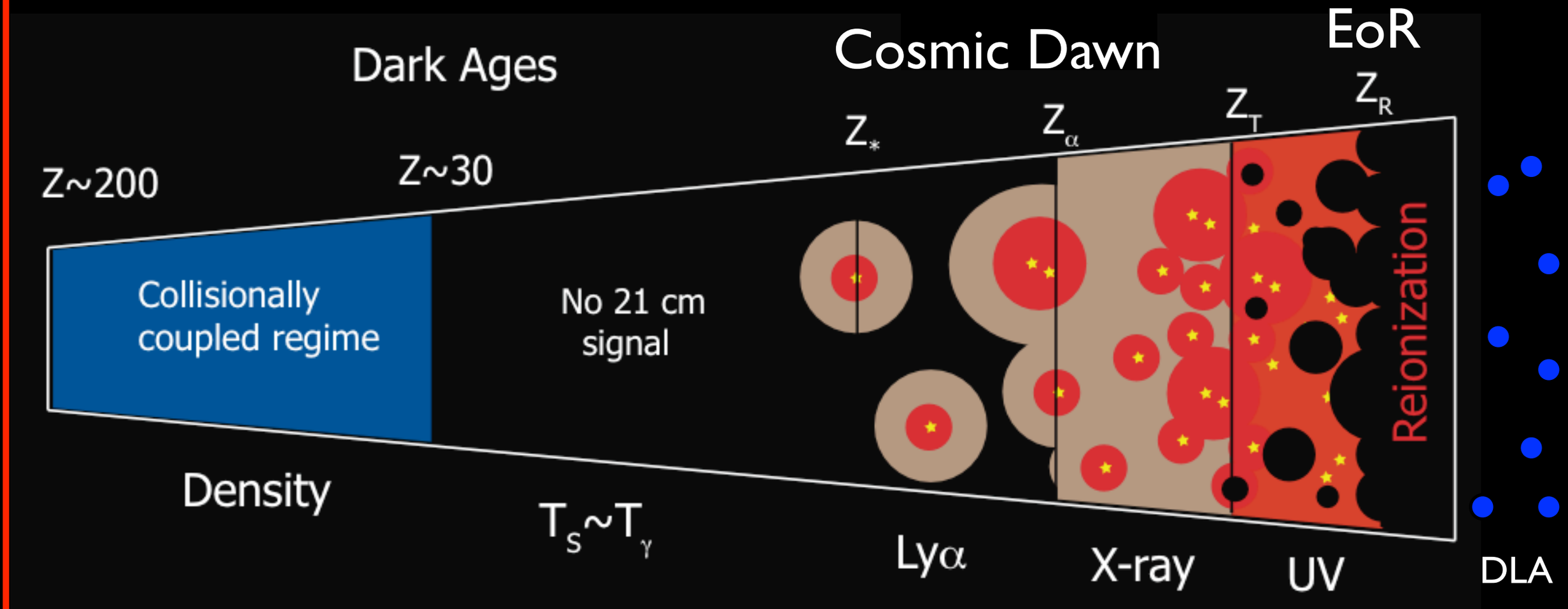
Neutral hydrogen

spin temperature

Brightness Fluctuations

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

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



Getting past astrophysics to cosmology

Three main options for getting at cosmology power spectrum:

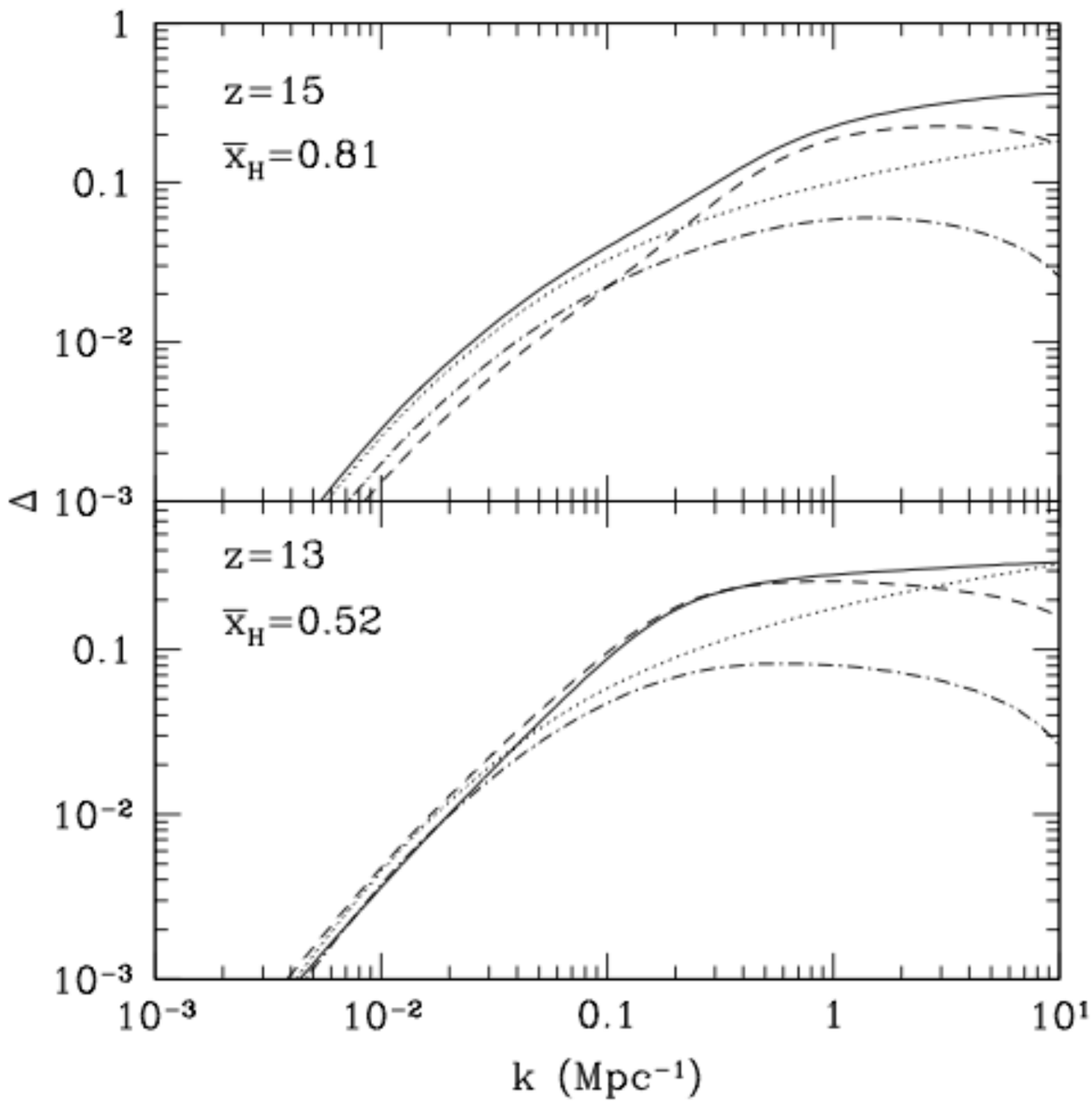
1) Modelling: Understand astrophysics and model it out

2) Avoidance: Go to high redshifts for pristine signal

3) Exploit 3D: Redshift space distortions (+imaging)

Modeling the astrophysics

- Reionization contribution relatively well understood on large scales



Furlanetto+ 2004

- Model and marginalise

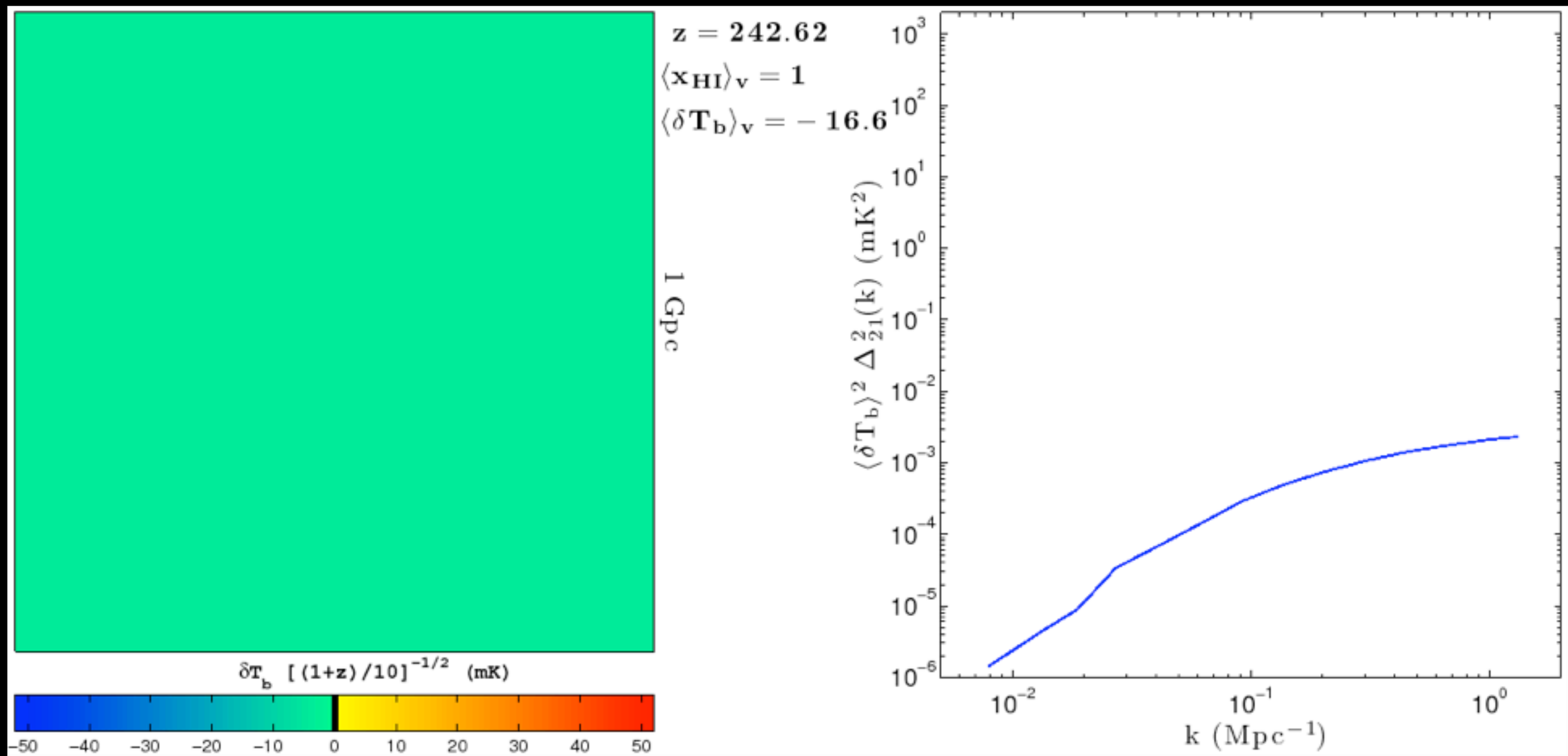
$$\mathcal{P}_{xx}(k) = b_{xx}^2 \left[1 + \alpha_{xx}(k\,R_{xx}) + (k\,R_{xx})^2\right]^{-\frac{\gamma_{xx}}{2}} \mathcal{P}_{\delta\delta}\,,$$
$$\mathcal{P}_{x\delta}(k) = b_{x\delta}^2 \exp\left[-\alpha_{x\delta}(k\,R_{x\delta}) - (k\,R_{x\delta})^2\right] \mathcal{P}_{\delta\delta}\,,$$

Mao+ 2008

- Could hope to do the same for other fluctuations

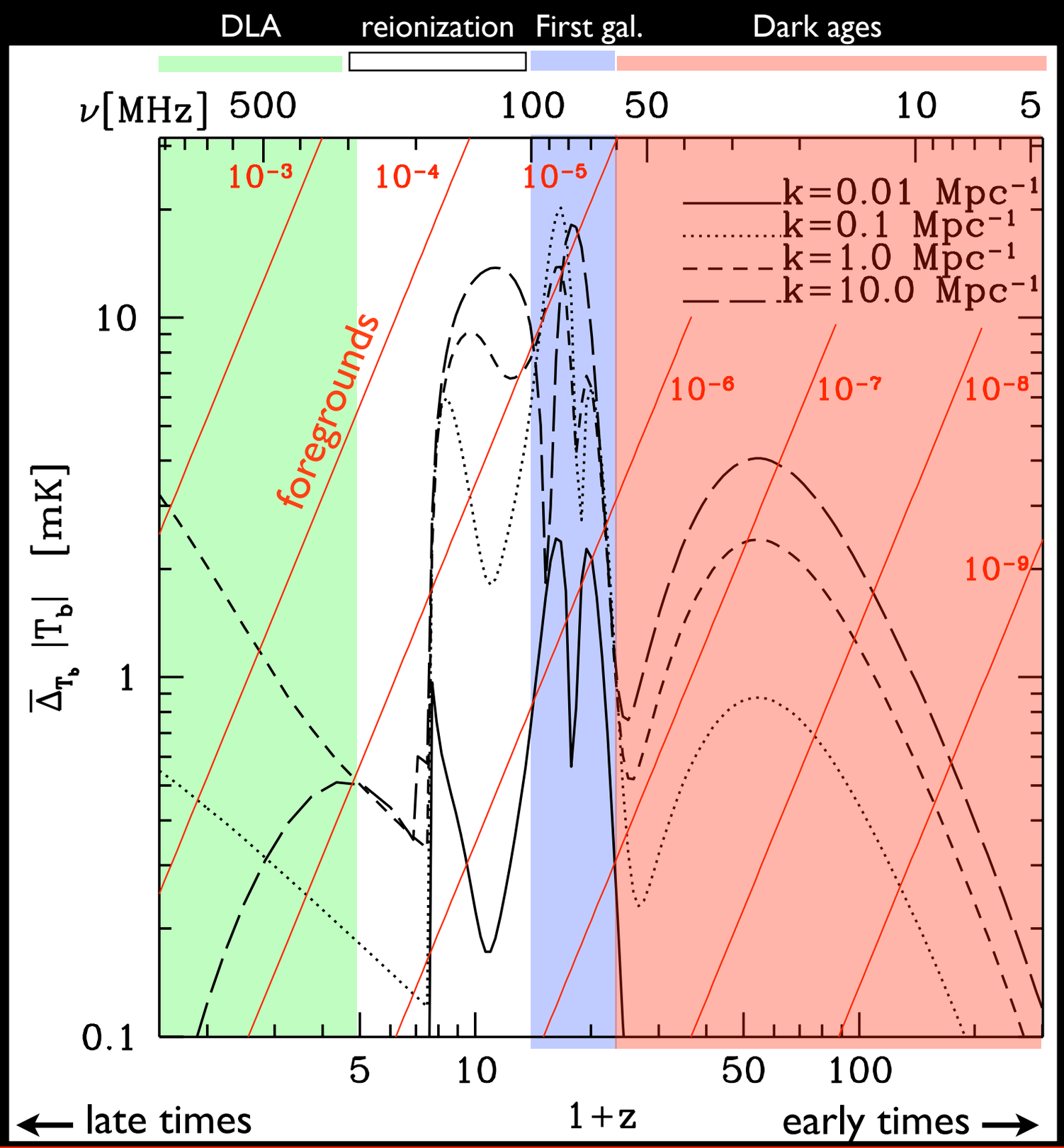
Modelling of the power spectrum

Mesinger+ 2010



Modelling + redshift evolution
can constrain astrophysics

Accessing the dark ages



Evolution of signal means that detecting signal at z=20 not necessarily more difficult than at z=10

Intensity mapping at z<4 similar

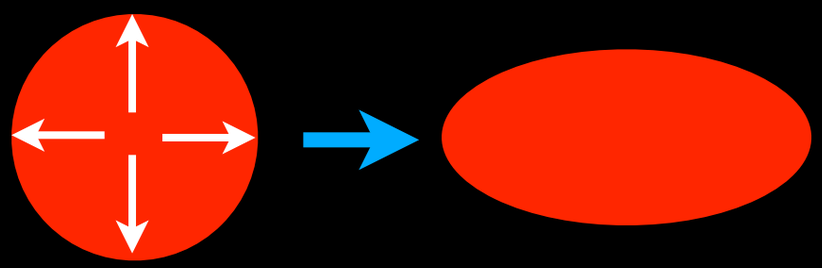
z=30-50 range much harder!

Distinguish different contributions via shape and redshift evolution

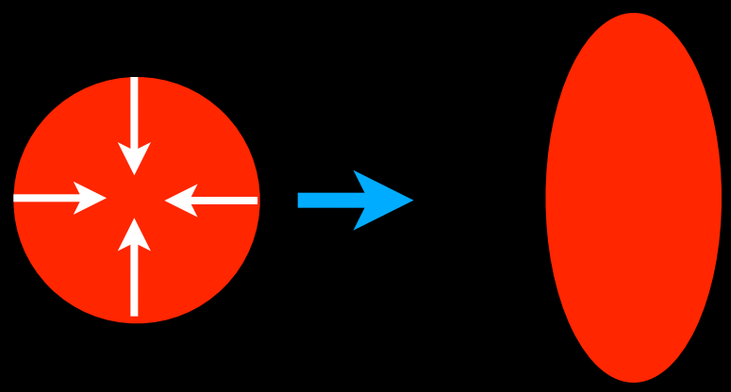
Pritchard & Loeb 2008

Redshift distortions

Underdensity



Overdensity



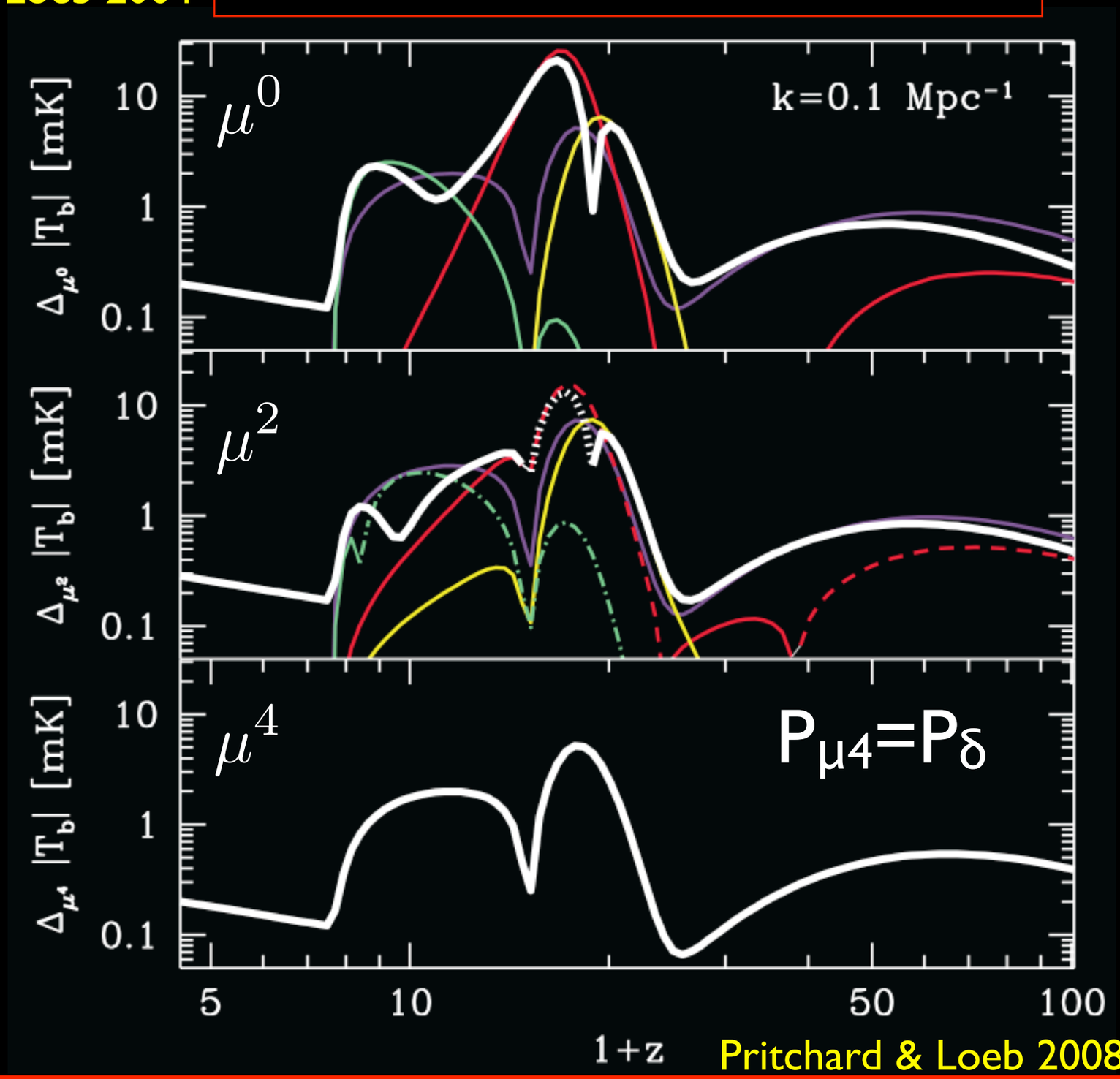
Real space

redshift space

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

Barkana & Loeb 2004

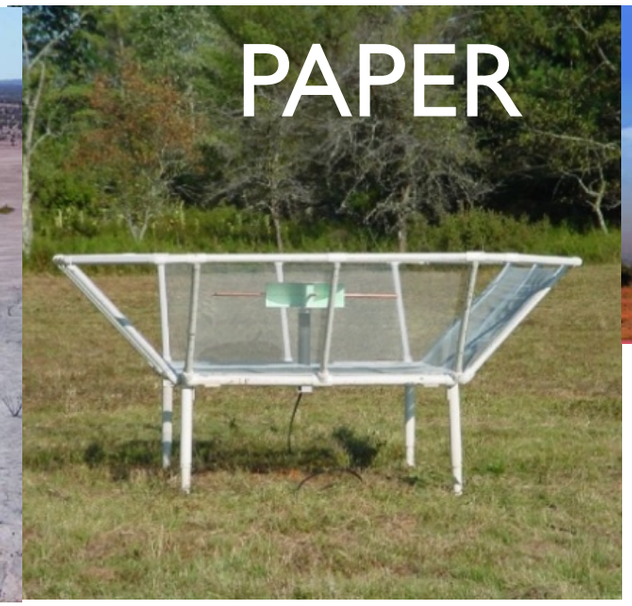
$$P_{T_b}(\mathbf{k}) = \mu^4 P_{\mu^4} + \mu^2 P_{\mu^2} + P_{\mu^0}$$



Pritchard & Loeb 2008

21 cm experiments

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



Lunar arrays concepts for dark ages (z>30)

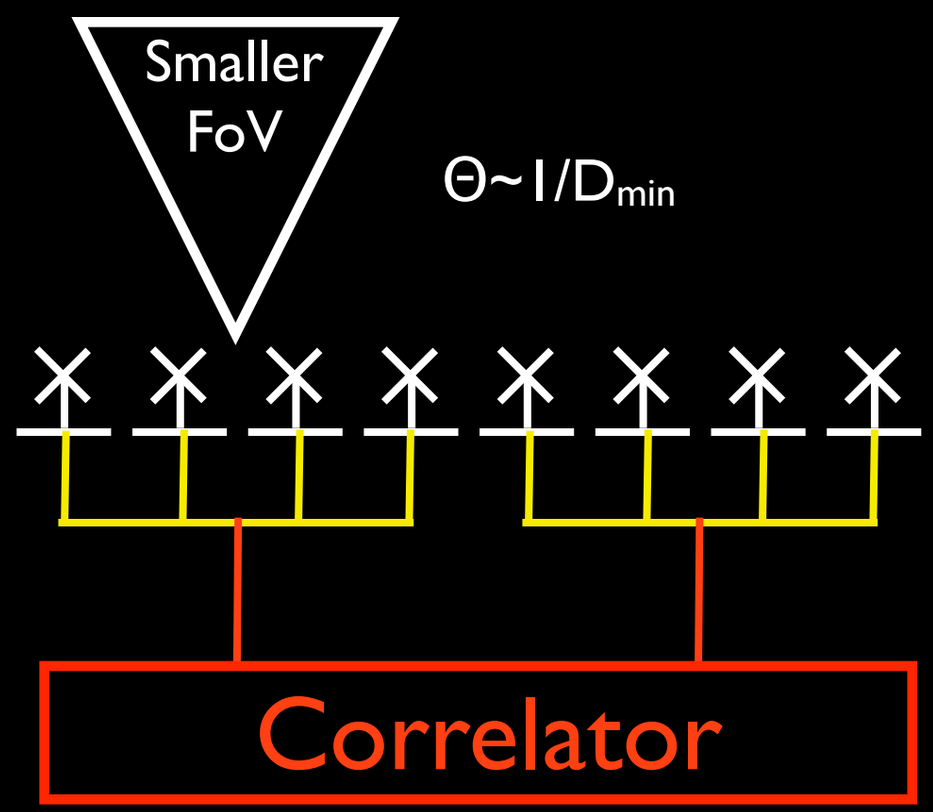
Next generation required for probing fluctuations from the first galaxies (z>12)
e.g.
Square Kilometer Array
FFTT

Future arrays

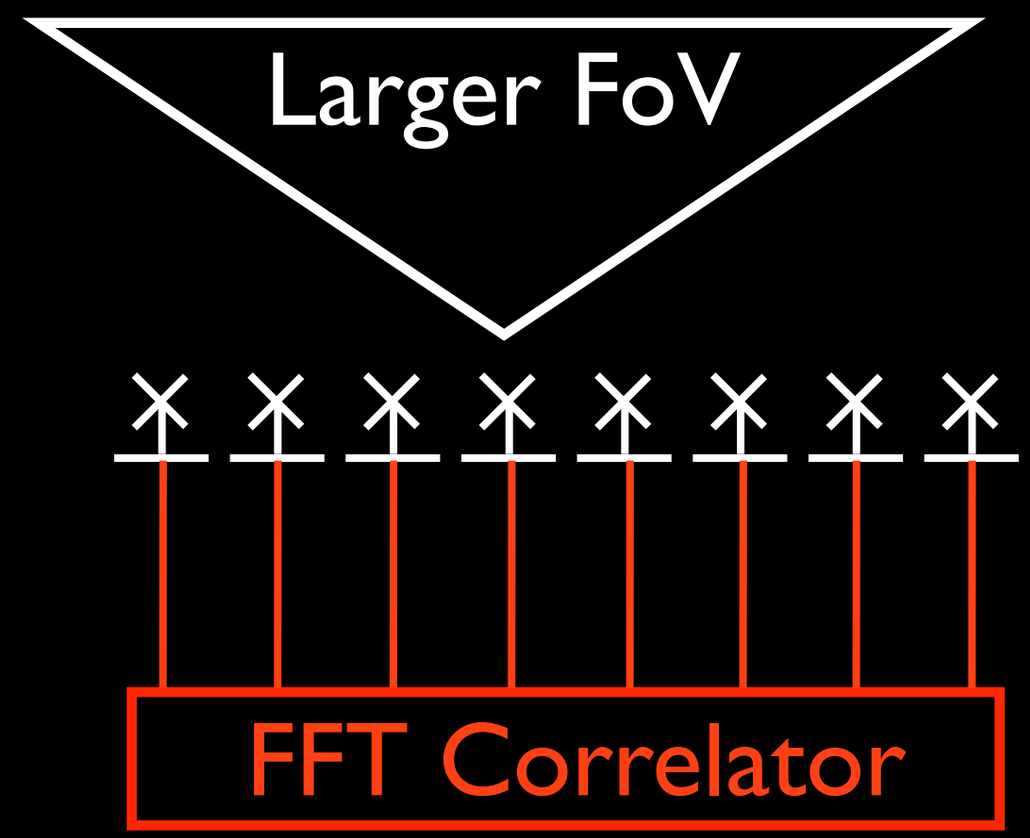
Computational limitions:
number of correlations ~O(N^2)
=> collect dipoles into tiles
=> smaller N for fixed Atot

FFTT based techniques help ~O(N log N)
=> correlate all elements
=> huge sensitivity boost!

Tegmark & Zaldarriaga 2009



MWA



FFTT

Power spectrum sensitivity depends on number of elements

Errors ~$1/(N_{element} \sqrt{V_{survey}})$

Power spectrum sensitivity

Mao+ 2008	n_s	running	Mnu (eV)
Planck	0.0033	0.0026	0.23
+SKA (opt)	0.00039	0.00027	0.010
+SKA (model)	0.0025	0.0022	0.056
+FFTT (opt)	0.00009	0.000054	0.0018
+FFTT (model)	0.00033	0.00017	0.0066
+FFTT (peculiar only)	0.0033	0.0024	0.11

Need to model astrophysics will degrade constraints

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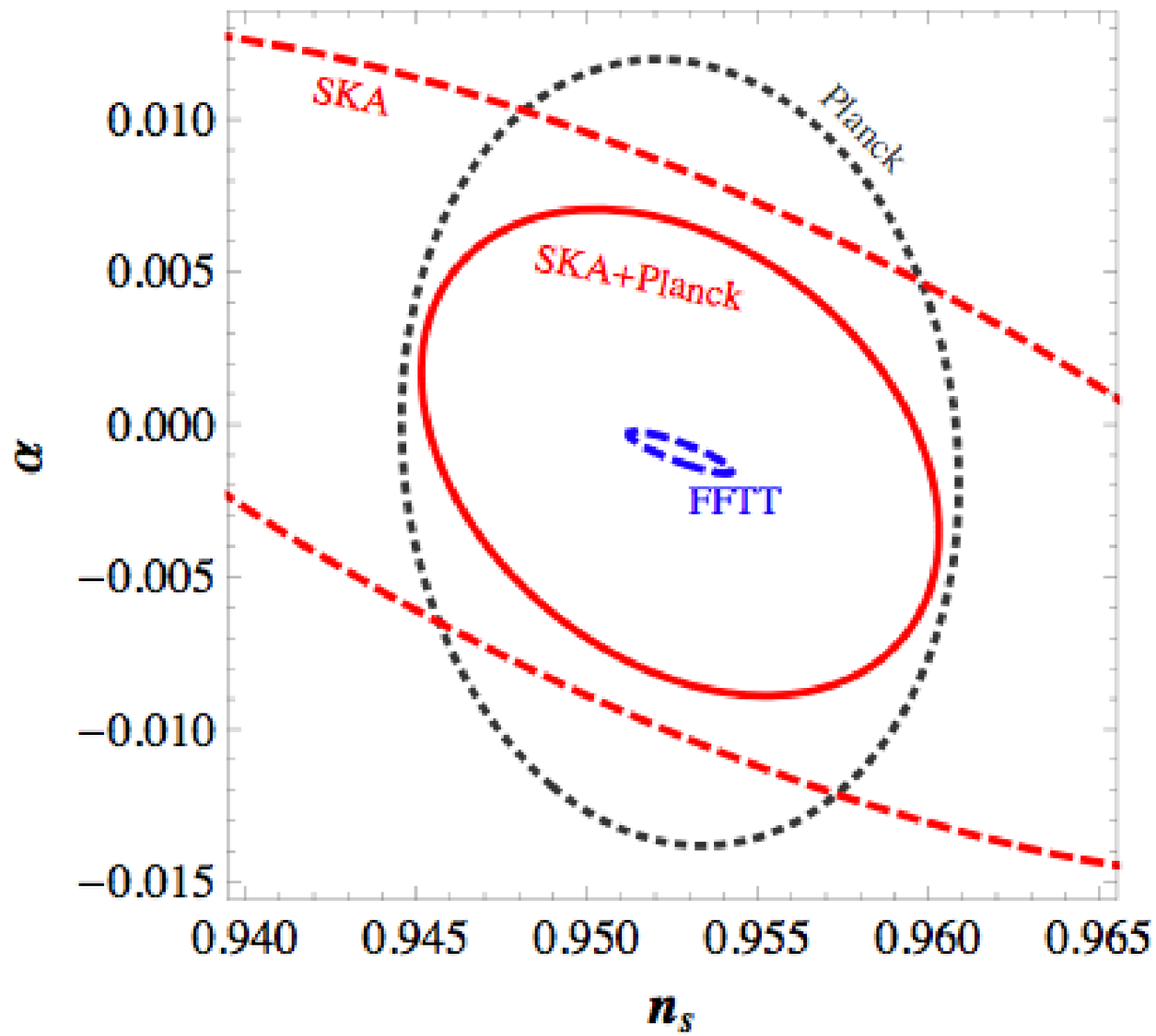
Need to model astrophysics will degrade constraints

Inflationary tilt and running

Mao+ 2008

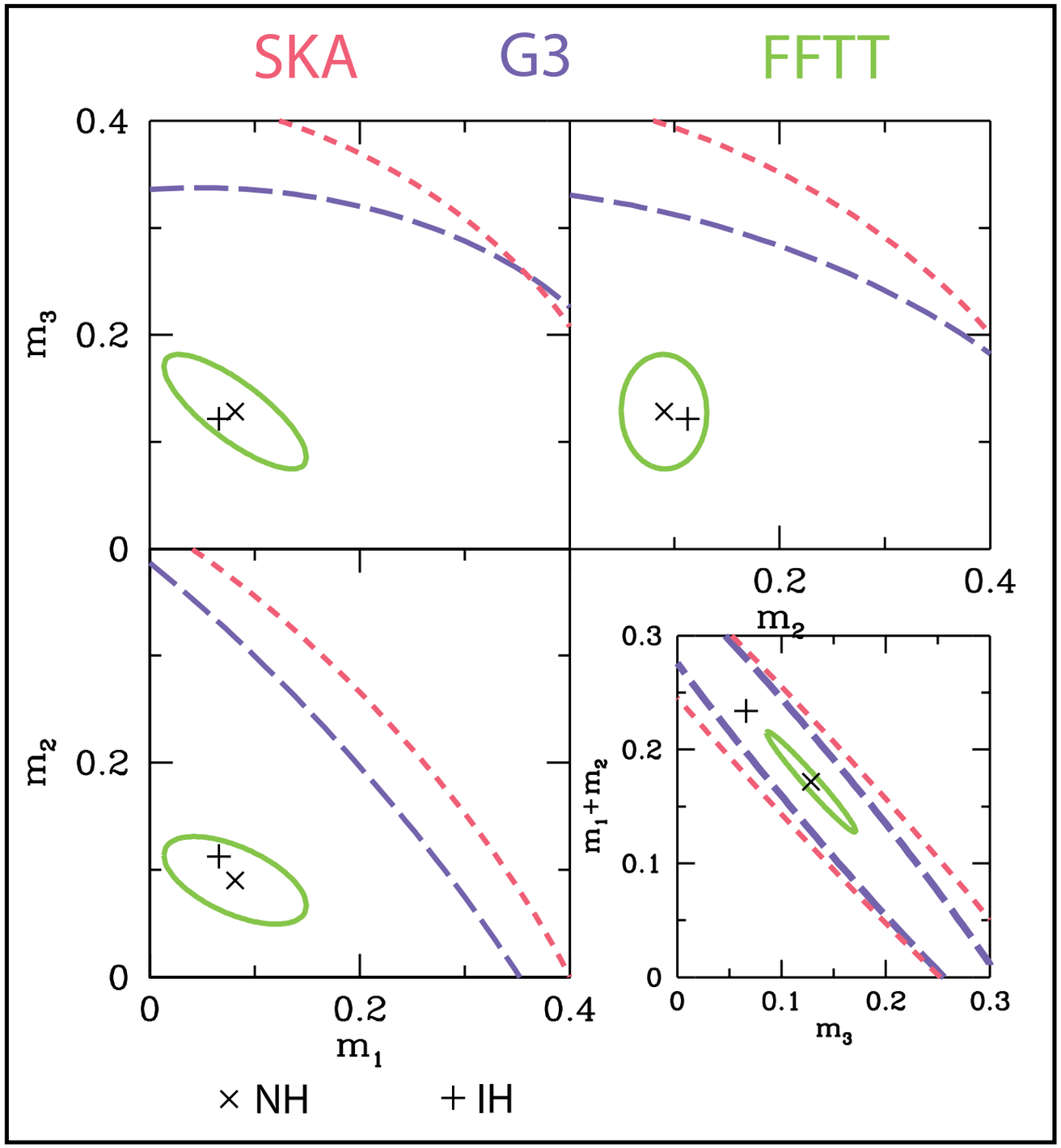
Barger, Gao, Mao & Marfatia 2008



SKA+Planck	$\delta n_s = 0.0031,\ \delta\alpha = 0.0032$
FFTT+Planck	$(\delta n_s = 6 \times 10^{-4},\ \delta\alpha = 2.7 \times 10^{-4})$

measure running at slow roll level: alpha~$(1-n_s)^2$

Individual neutrino masses

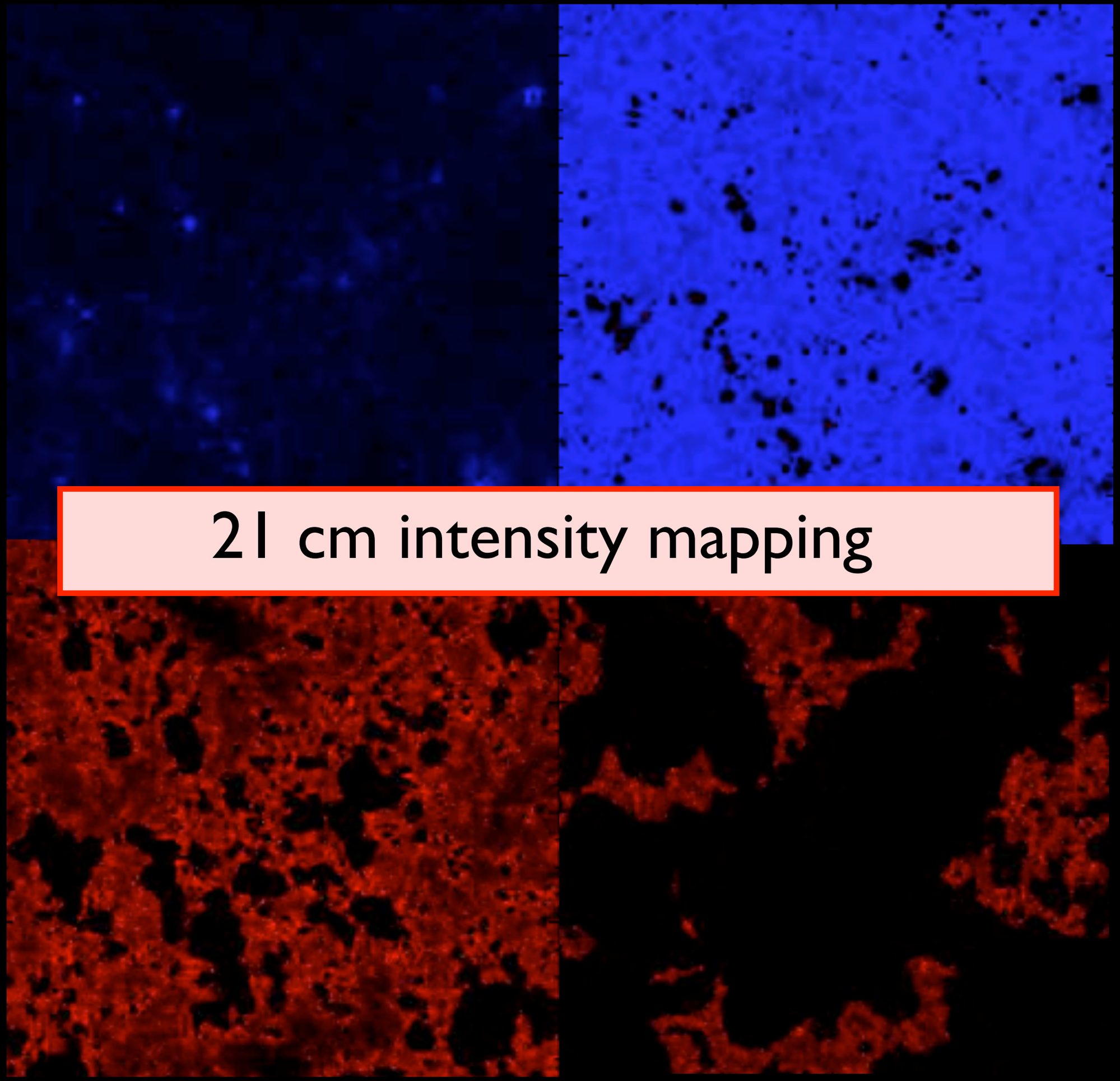


fiducial:
M_ν=0.3eV

68% conf. contours

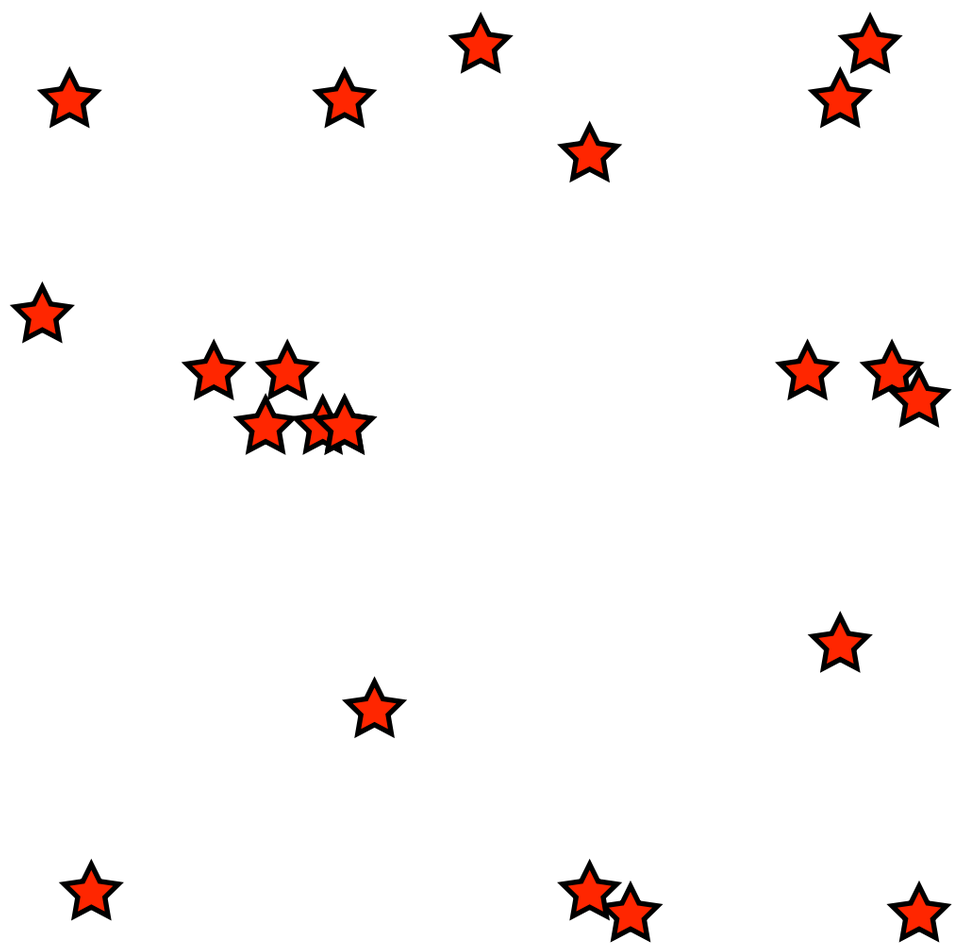
convention:
$m_1<m_2<m_3$

Pritchard & Pierpaoli 2008



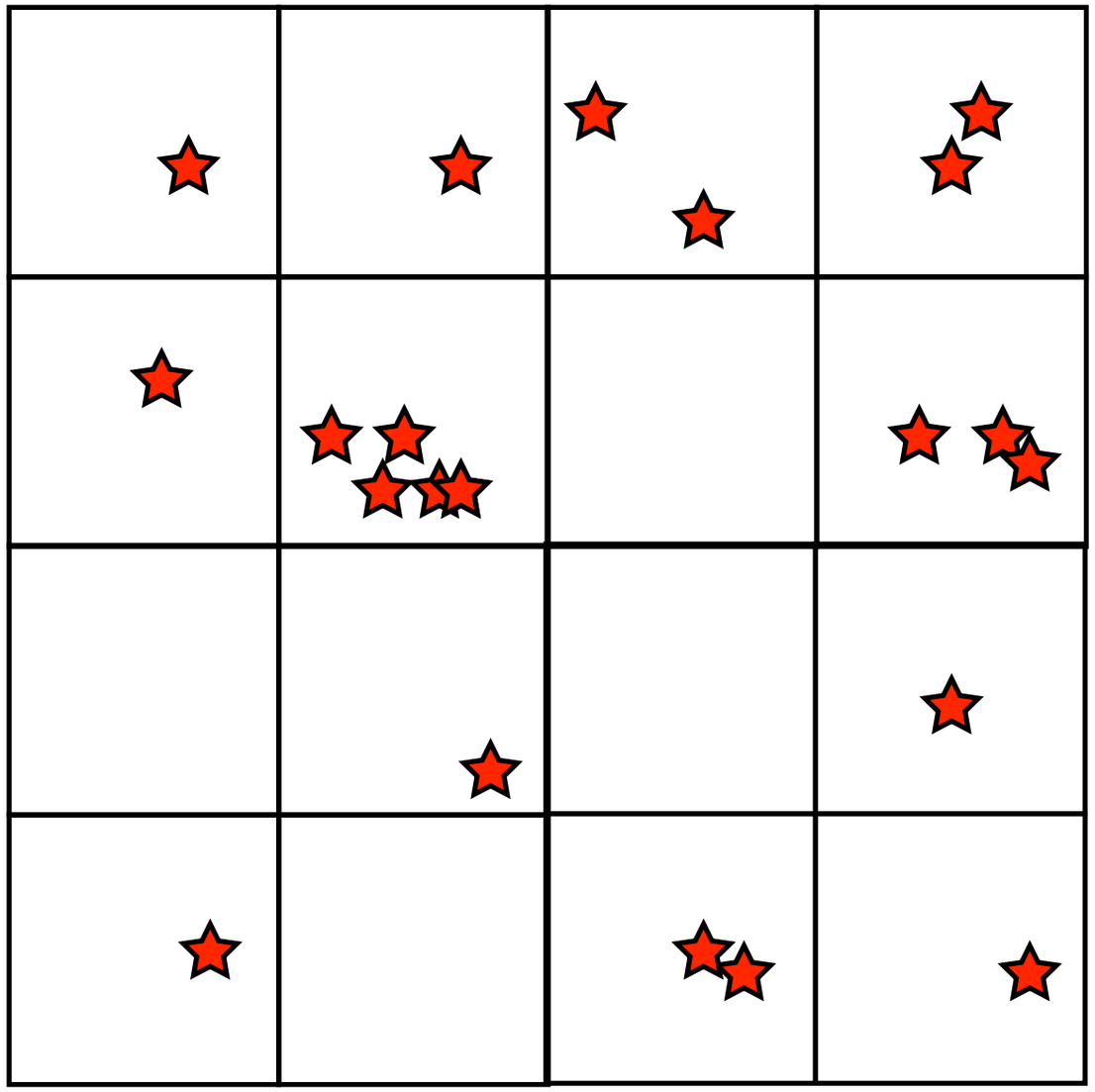
21 cm intensity mapping

Intensity mapping in outline



Traditional galaxy survey identifies individual galaxies

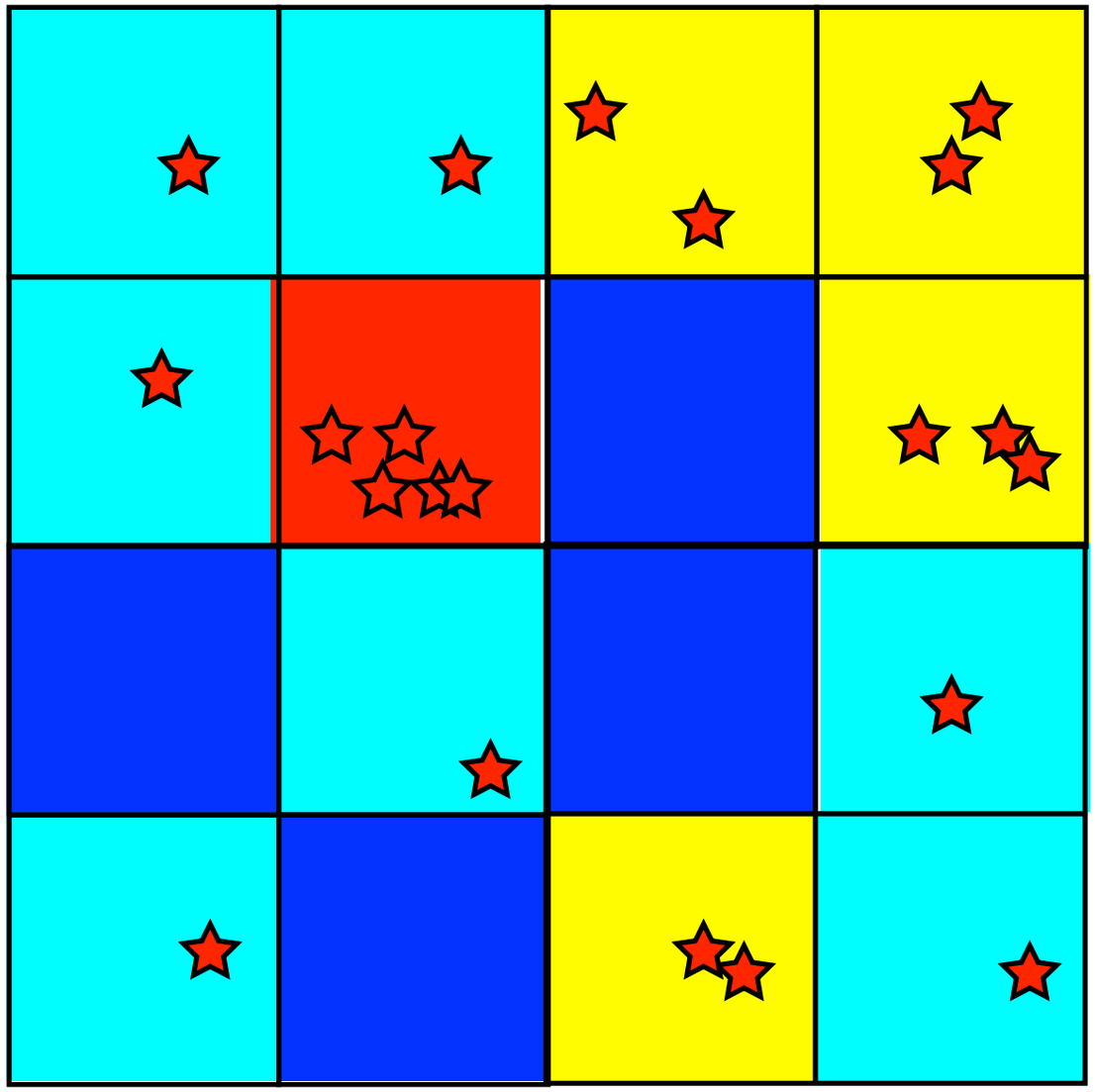
Intensity mapping in outline



Traditional galaxy survey identifies individual galaxies

Bin galaxies to estimate density field

Intensity mapping in outline



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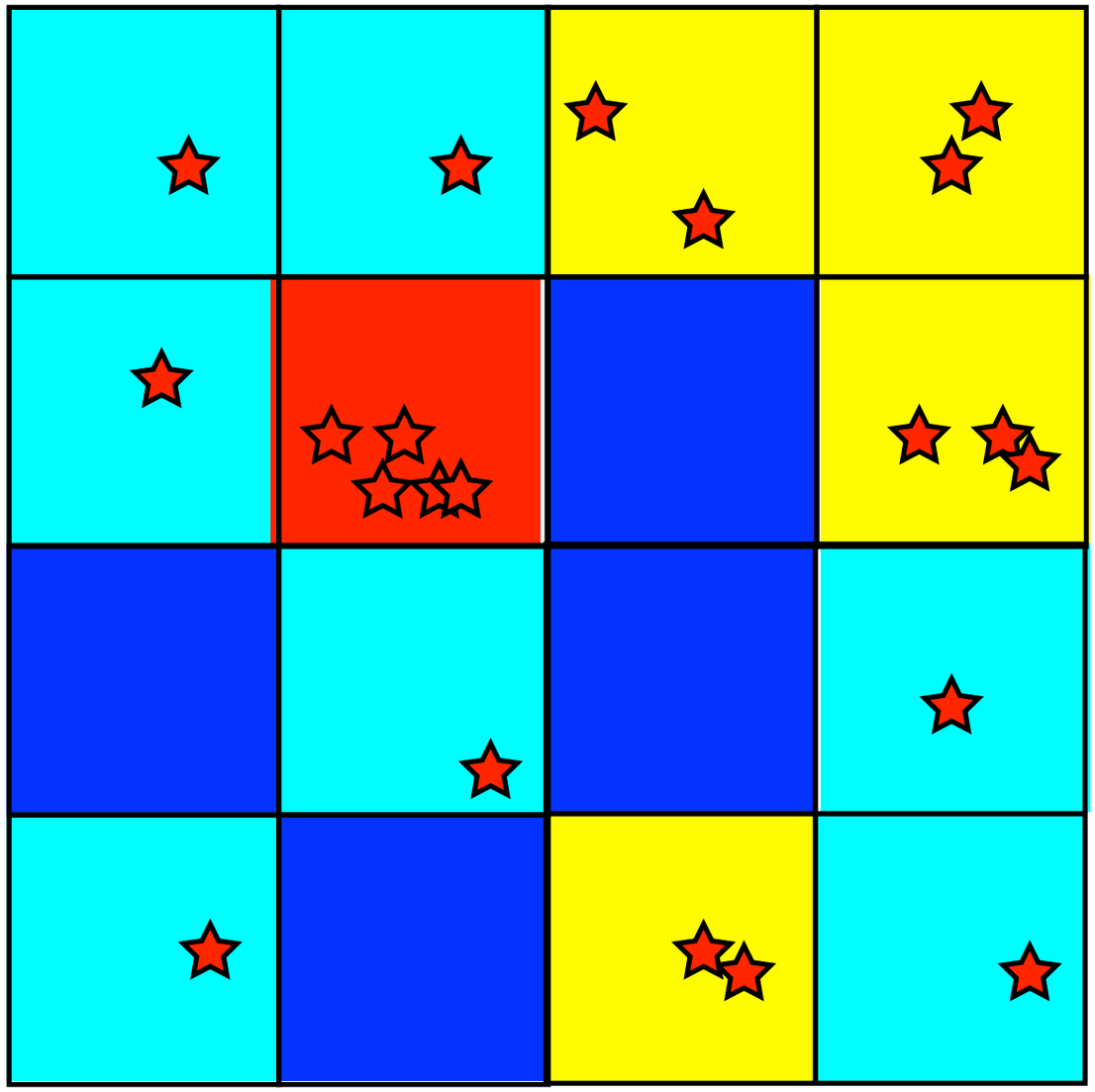
Bin galaxies to estimate density field

Intensity mapping integrates flux from all galaxies

Intensity mapping in outline



Traditional galaxy survey identifies individual galaxies

Bin galaxies to estimate density field

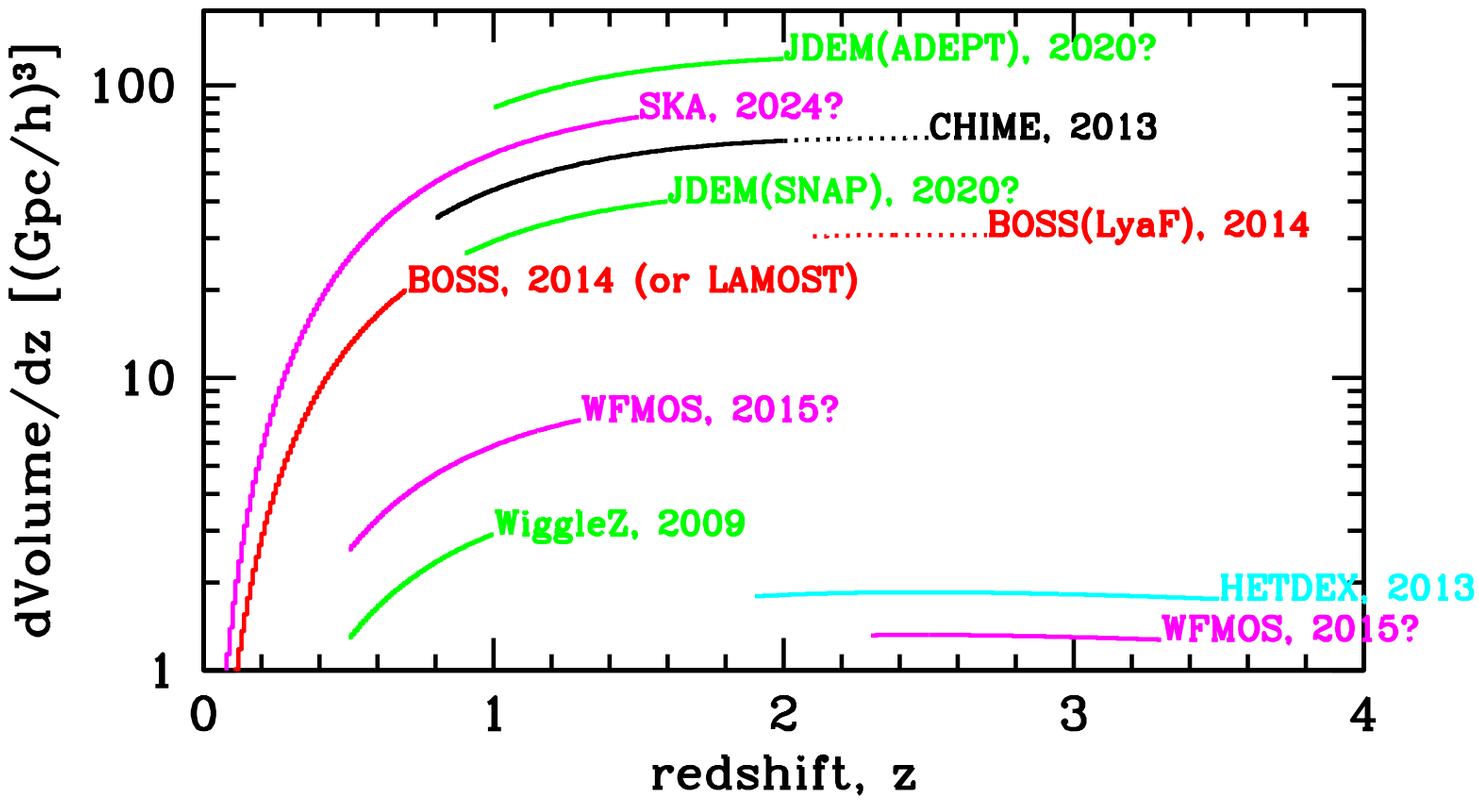
Intensity mapping integrates flux from all galaxies

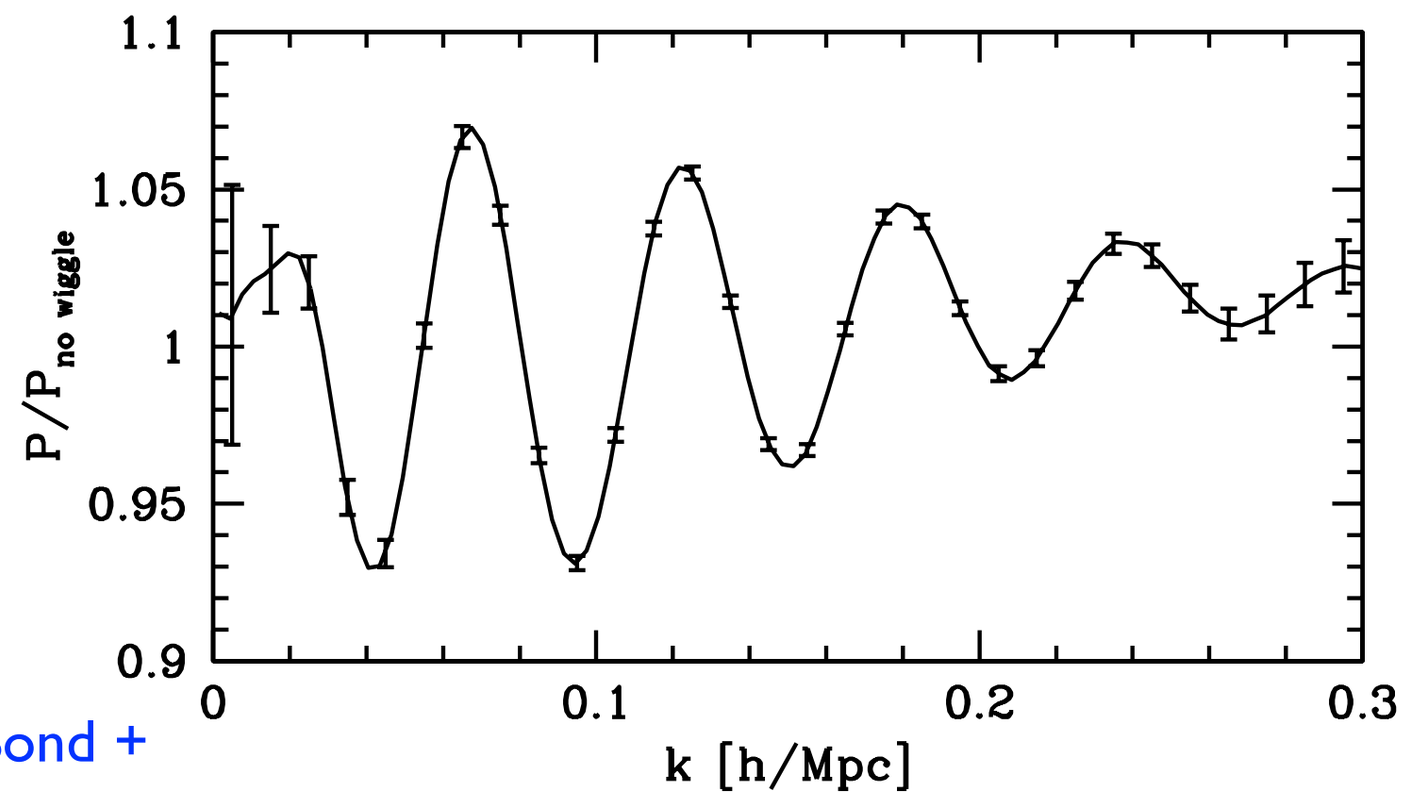
Requires experiments similar to 21 cm tomography only at higher frequencies
=> target neutral hydrogen in galaxies at z~1-3

Chang, Pen, Peterson, McDonald 2008 Loeb & Wyithe 2008

Intensity mapping in other lines possible: CO, CII, ...

BAO and dark energy





Bond +

Cylinder telescope provides for 1D FFTT

CHIME

5 100m X 20 m cylinders

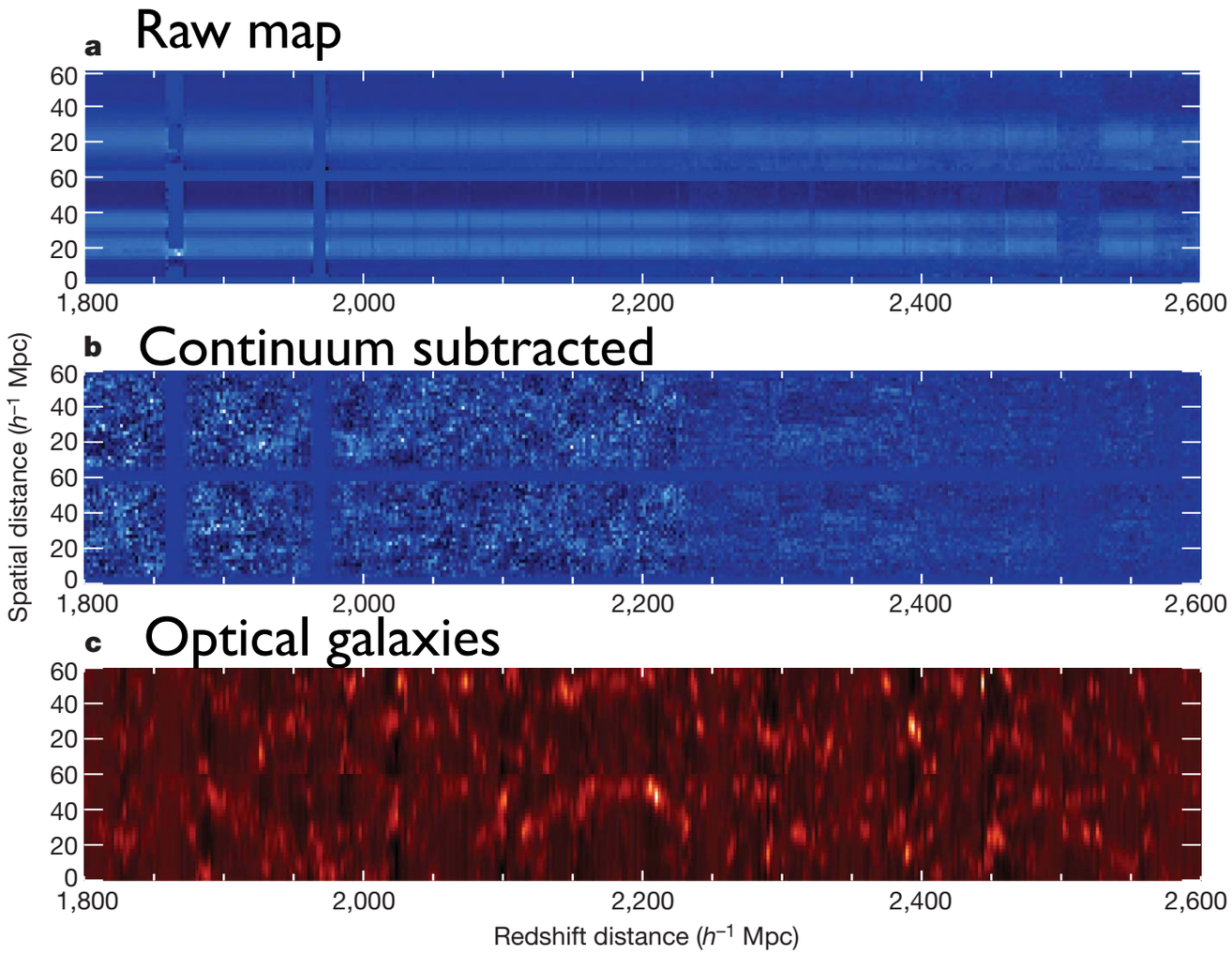
400-800MHz 0.8<z<2.5

fsky~1/4-1/2

2 year survey

Potentially competitive dark energy probe

21cm intensity mapping results



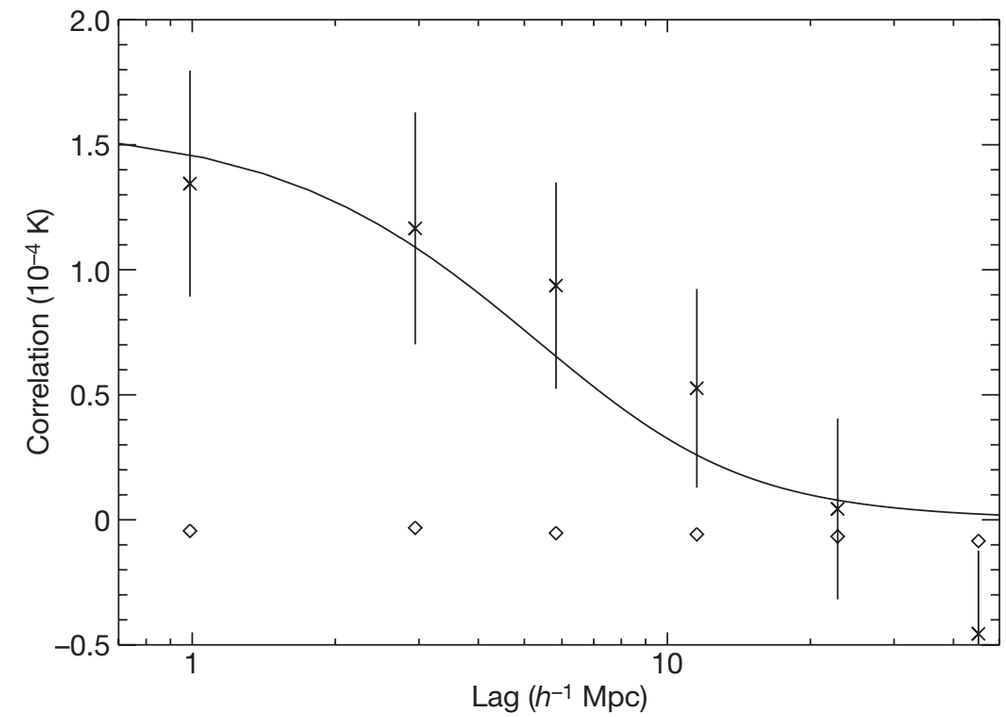


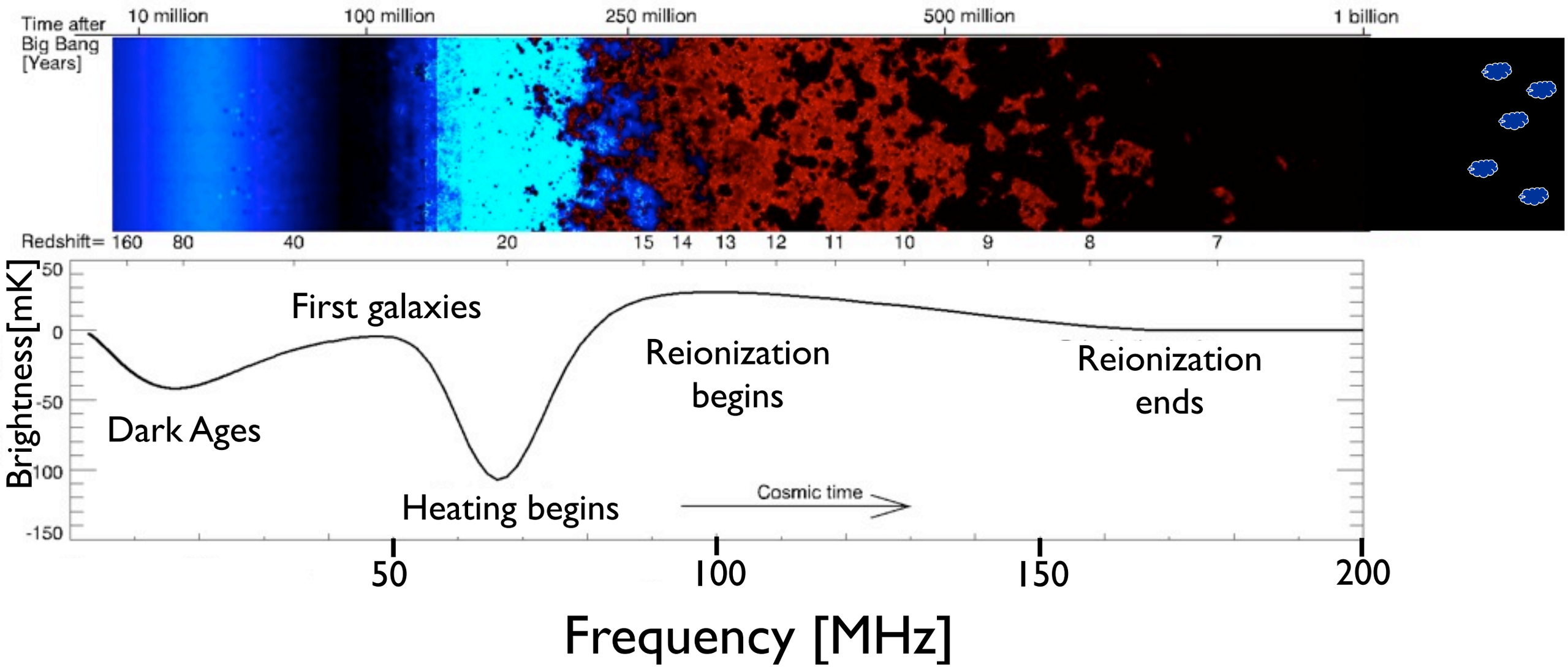
Figure 2 | The cross-correlation between the DEEP2 density field and GBT H I brightness temperature. Crosses, measured cross-correlation temperature. Error bars, 1σ bootstrap errors generated using randomized optical data. Diamonds, mean null-test values over 1,000 randomizations as described in Supplementary Information. The same bootstrap procedure performed on randomized radio data returns very similar null-test values and error bars. Solid line, a DEEP2 galaxy correlation model, which assumes a power law correlation and includes the GBT telescope beam pattern as well as velocity distortions, and uses the best-fit value of the cross-correlation amplitude.

cross-correlation between DEEP2 optical galaxies and GBT 21cm intensity map at z~1

Chang, Pen, Bandura & Peterson 2010

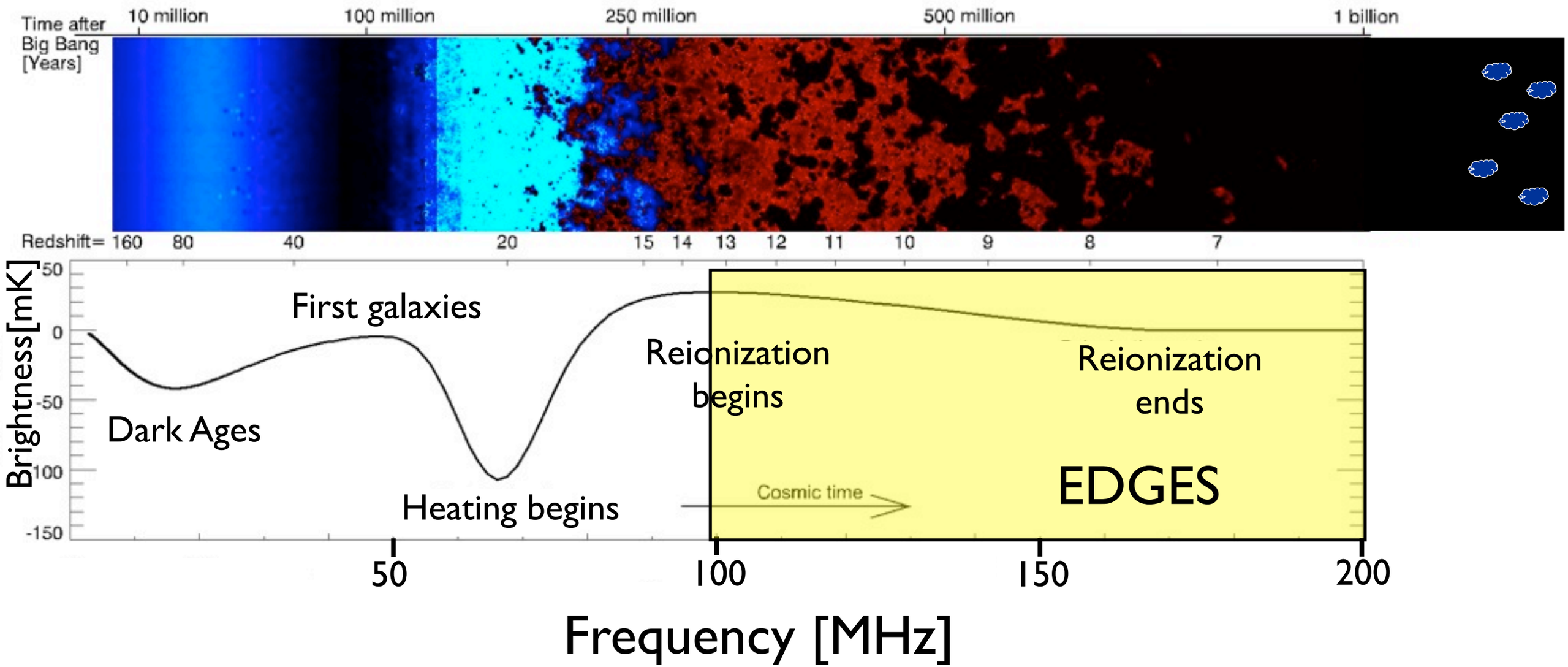
21 cm summary

Pritchard & Loeb 2010



21 cm summary

Pritchard & Loeb 2010



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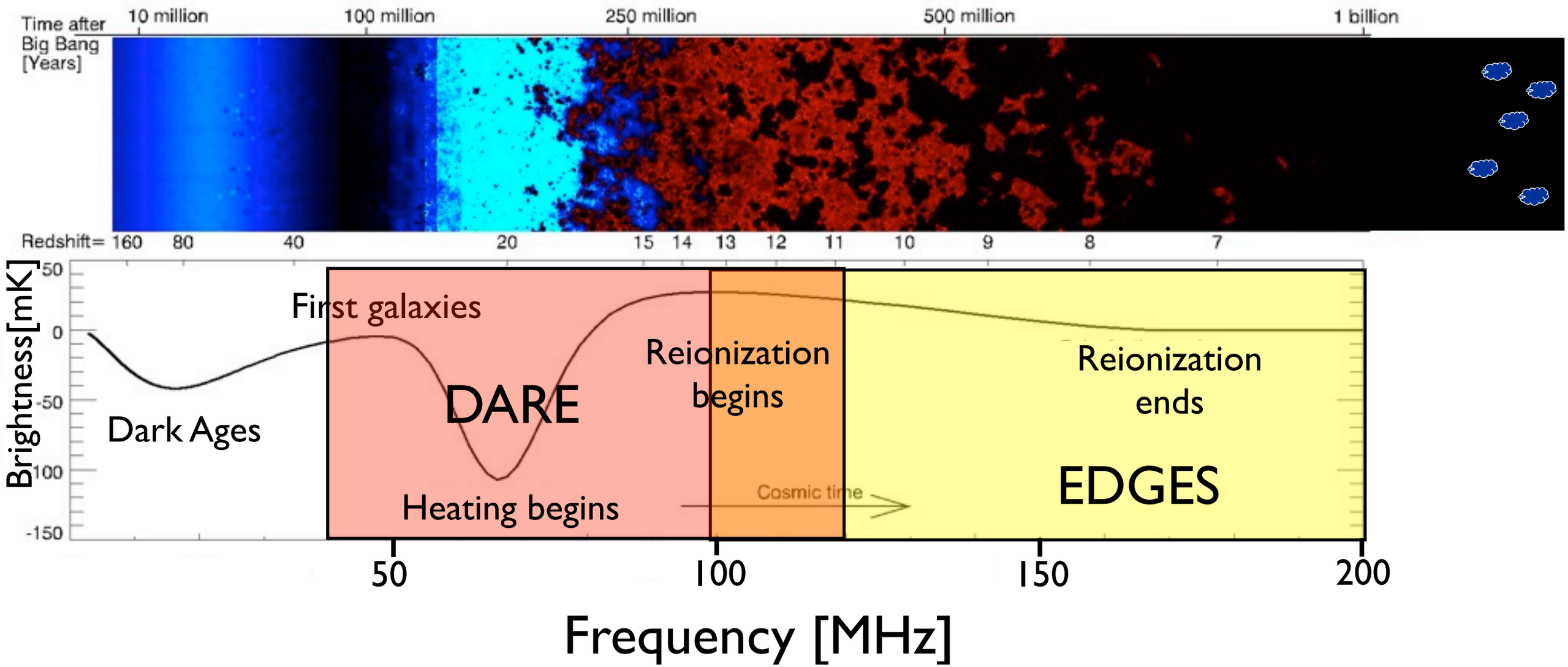

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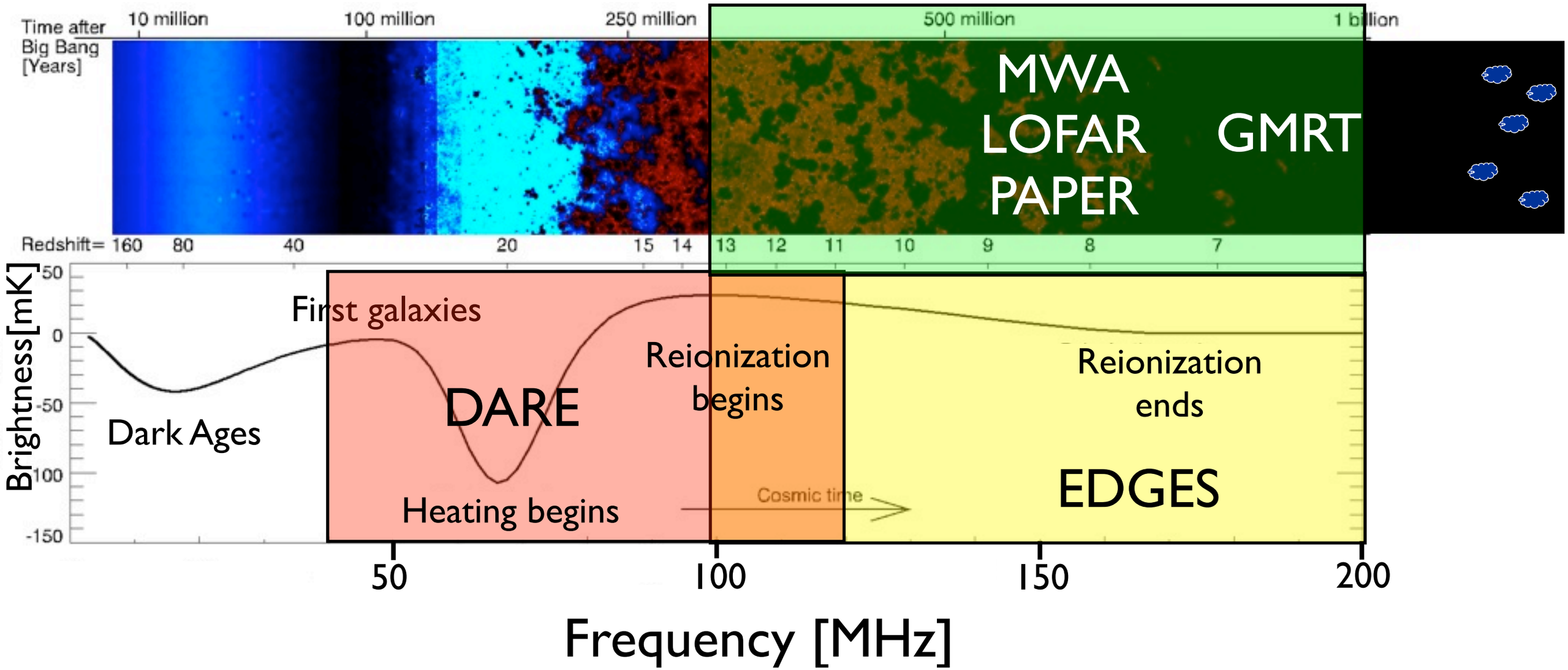
Pritchard & Loeb 2010



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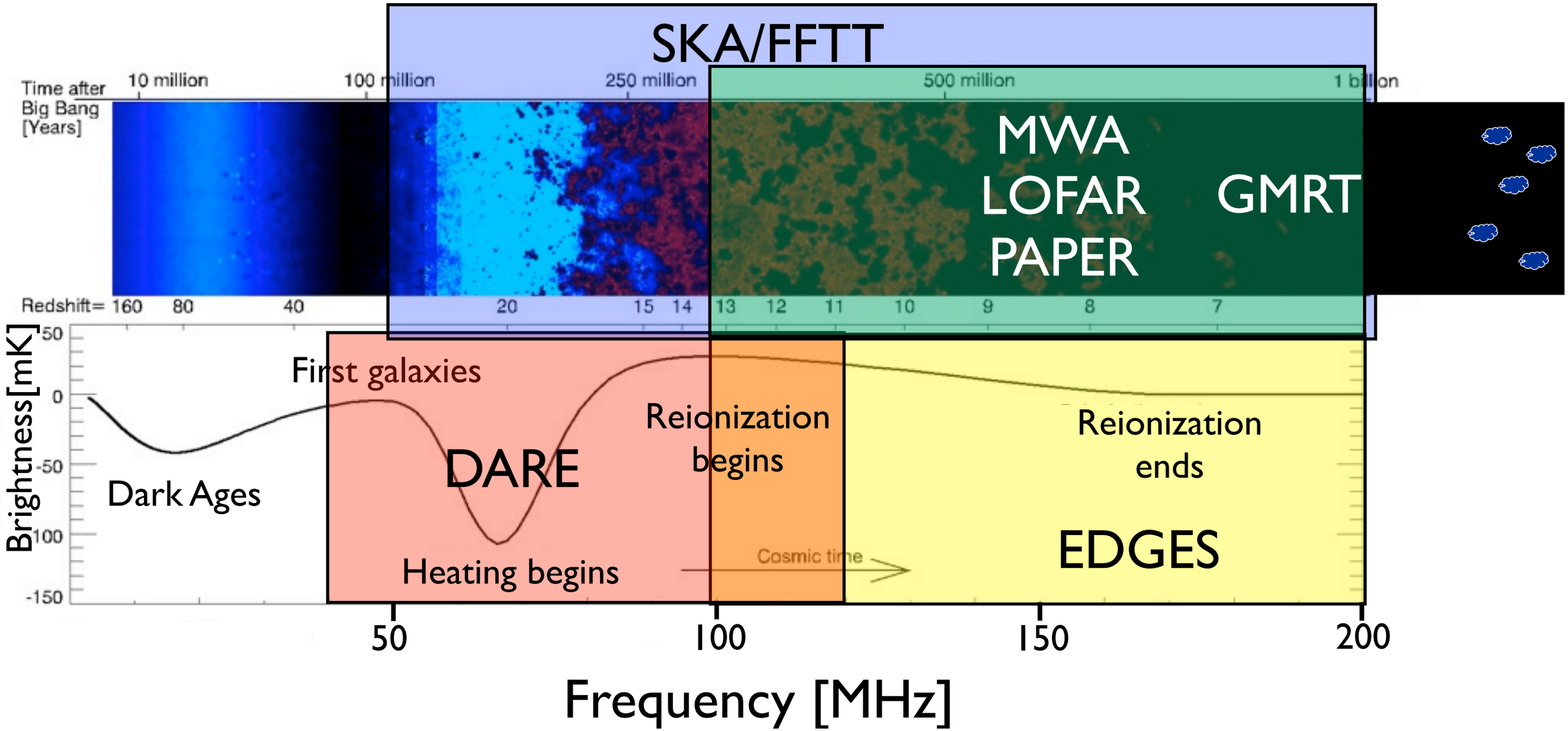
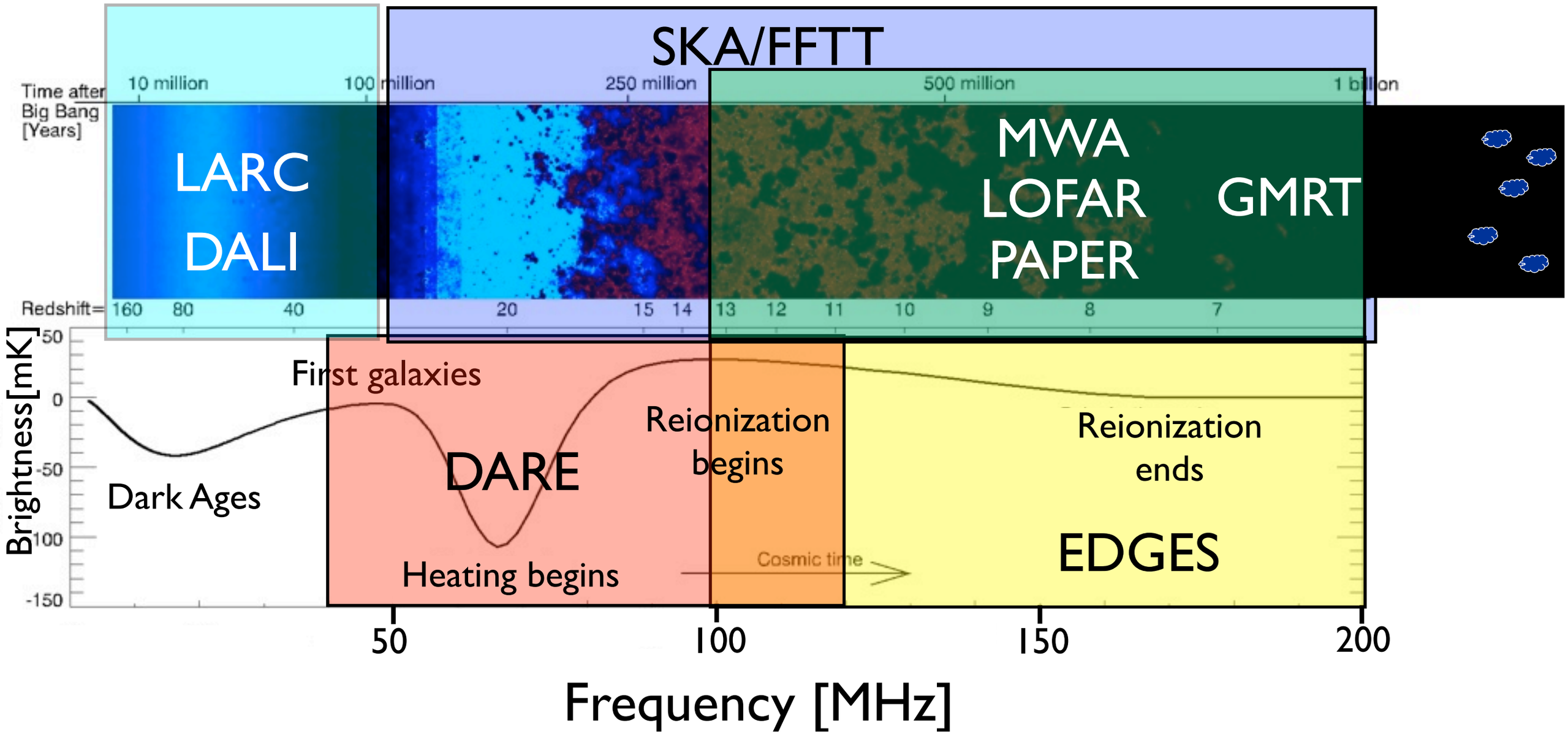


21 cm summary

Pritchard & Loeb 2010



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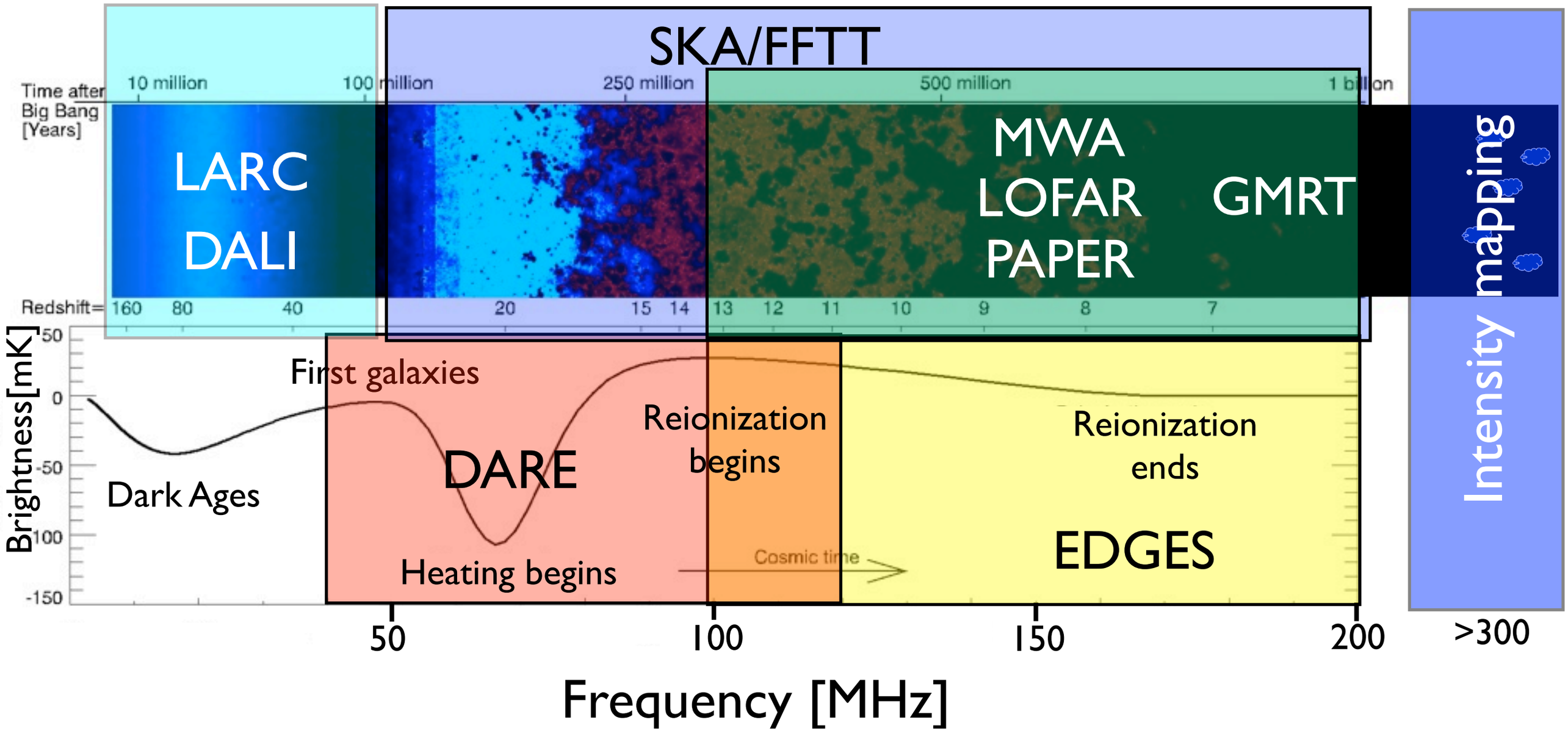
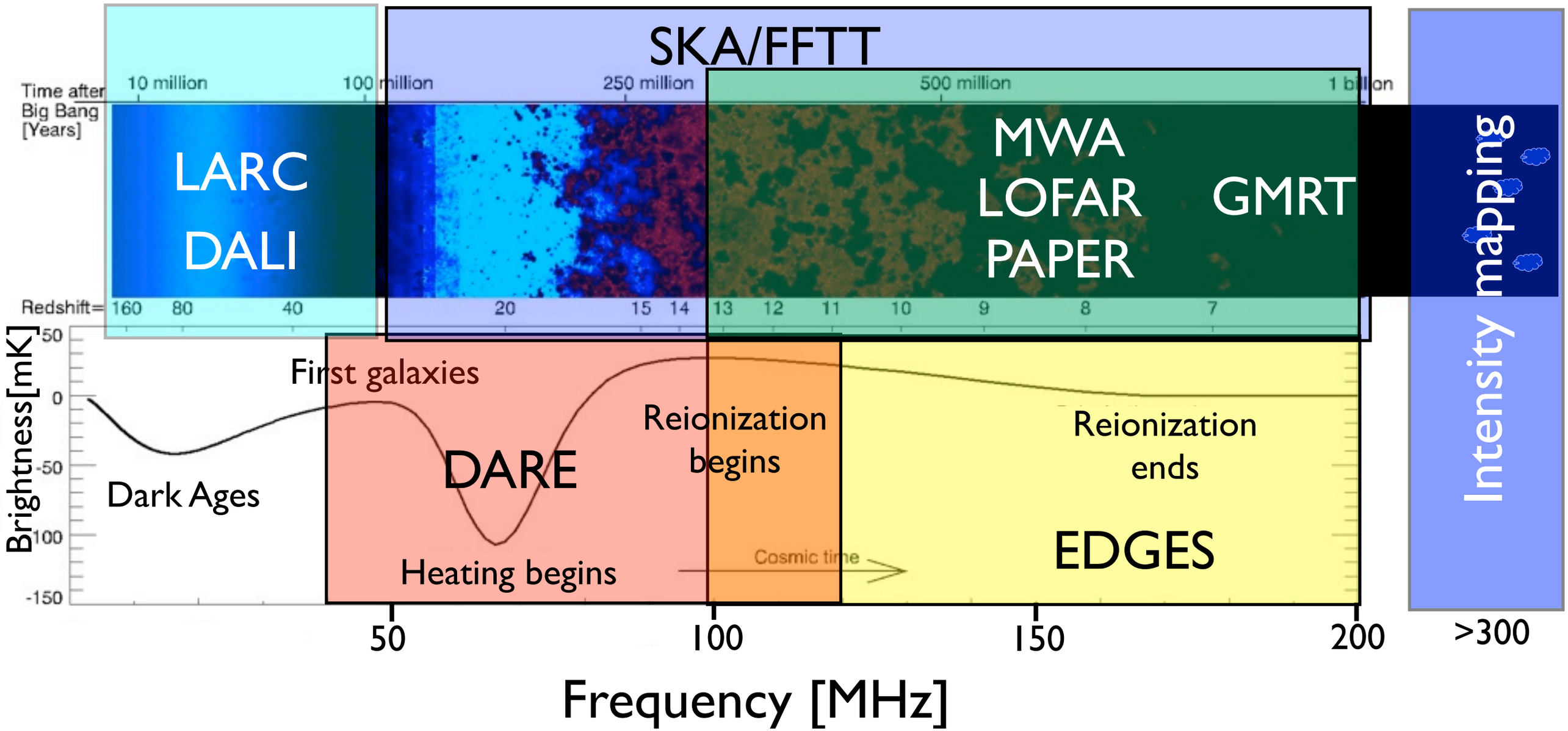
Pritchard & Loeb 2010



21 cm summary

Pritchard & Loeb 2010



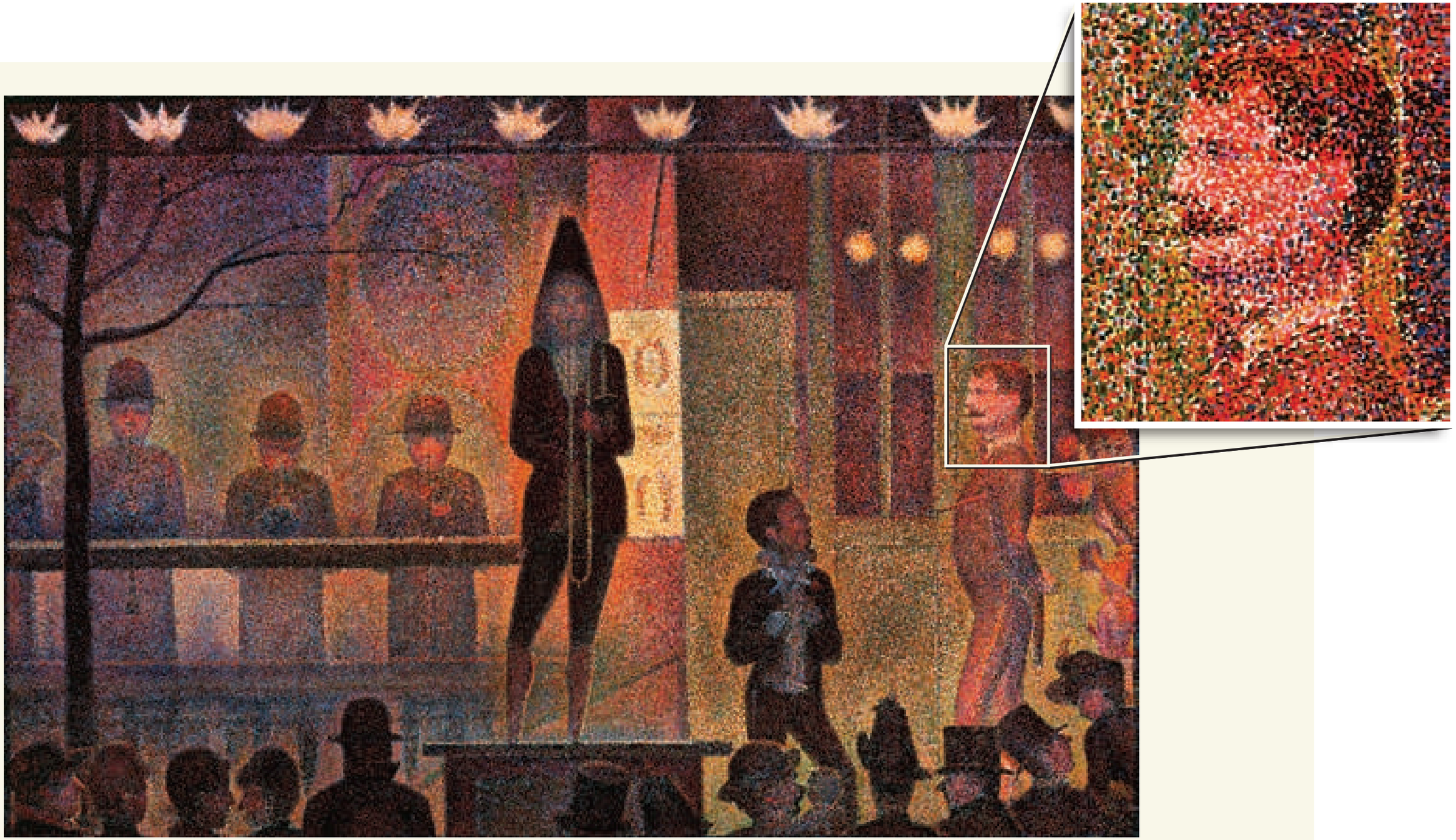
Systematic path to probing different epochs

Conclusions

- Future of cosmology requires pushing frontiers of precision, redshift, and scale
- 21 cm global signal can open window on early exotic heating
- Three windows for 21 cm fluctuations:
  - 21 cm tomography during dark ages z>30: pristine cosmology, larger foregrounds
  - 21 cm tomography during EoR 6<z<30: cosmology once astrophysics understood
  - Intensity mapping at z<3: probe of dark energy & growth of structure
- Need to overcome astrophysics to do cosmology (but worth trying!)
  Modelling, avoidance, 3D information (+ non-Gaussianity, imaging,...)
- Early days, but field moving fast with data finally coming in!

Bonus material

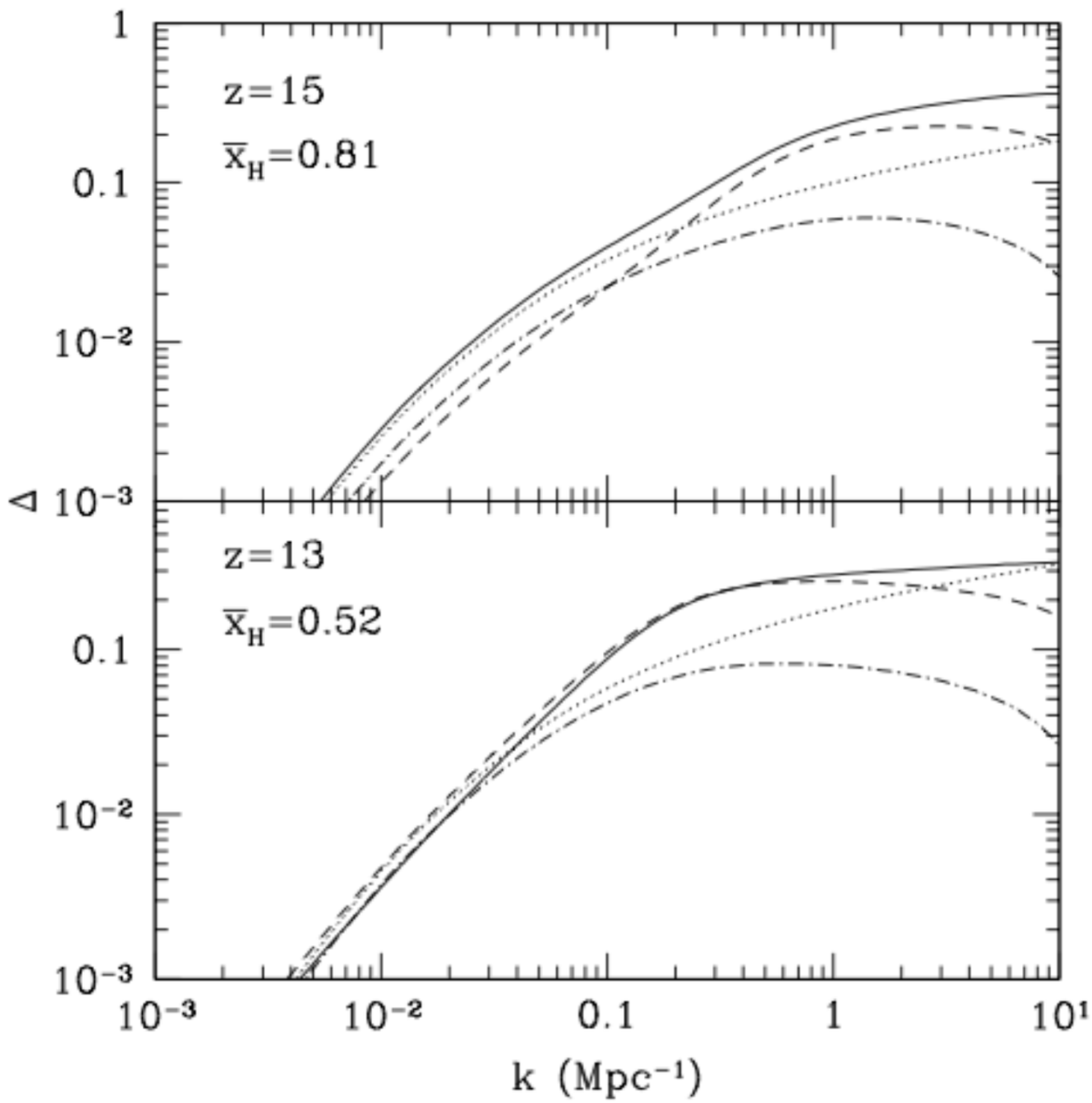
Holistic alternative to pointillism



Carilli 2010

Modeling the astrophysics

- Reionization contribution relatively well understood on large scales



Furlanetto+ 2004

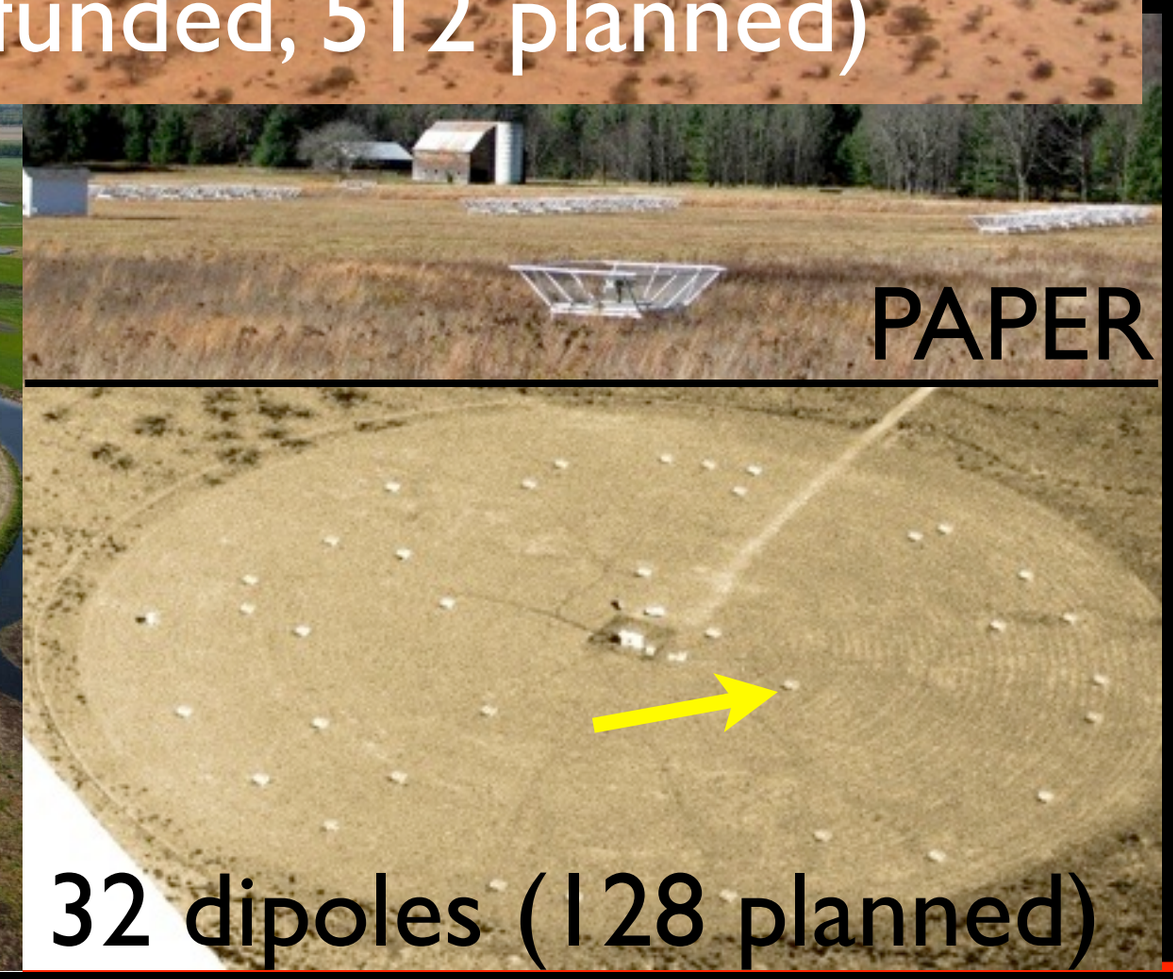
- Model and marginalise

$$\mathcal{P}_{xx}(k) = b_{xx}^2 \left[1 + \alpha_{xx}(k\,R_{xx}) + (k\,R_{xx})^2\right]^{-\frac{\gamma_{xx}}{2}} \mathcal{P}_{\delta\delta}\,,$$
$$\mathcal{P}_{x\delta}(k) = b_{x\delta}^2 \exp\left[-\alpha_{x\delta}(k\,R_{x\delta}) - (k\,R_{x\delta})^2\right] \mathcal{P}_{\delta\delta}\,,$$

Mao+ 2008

- Could hope to do the same for other fluctuations

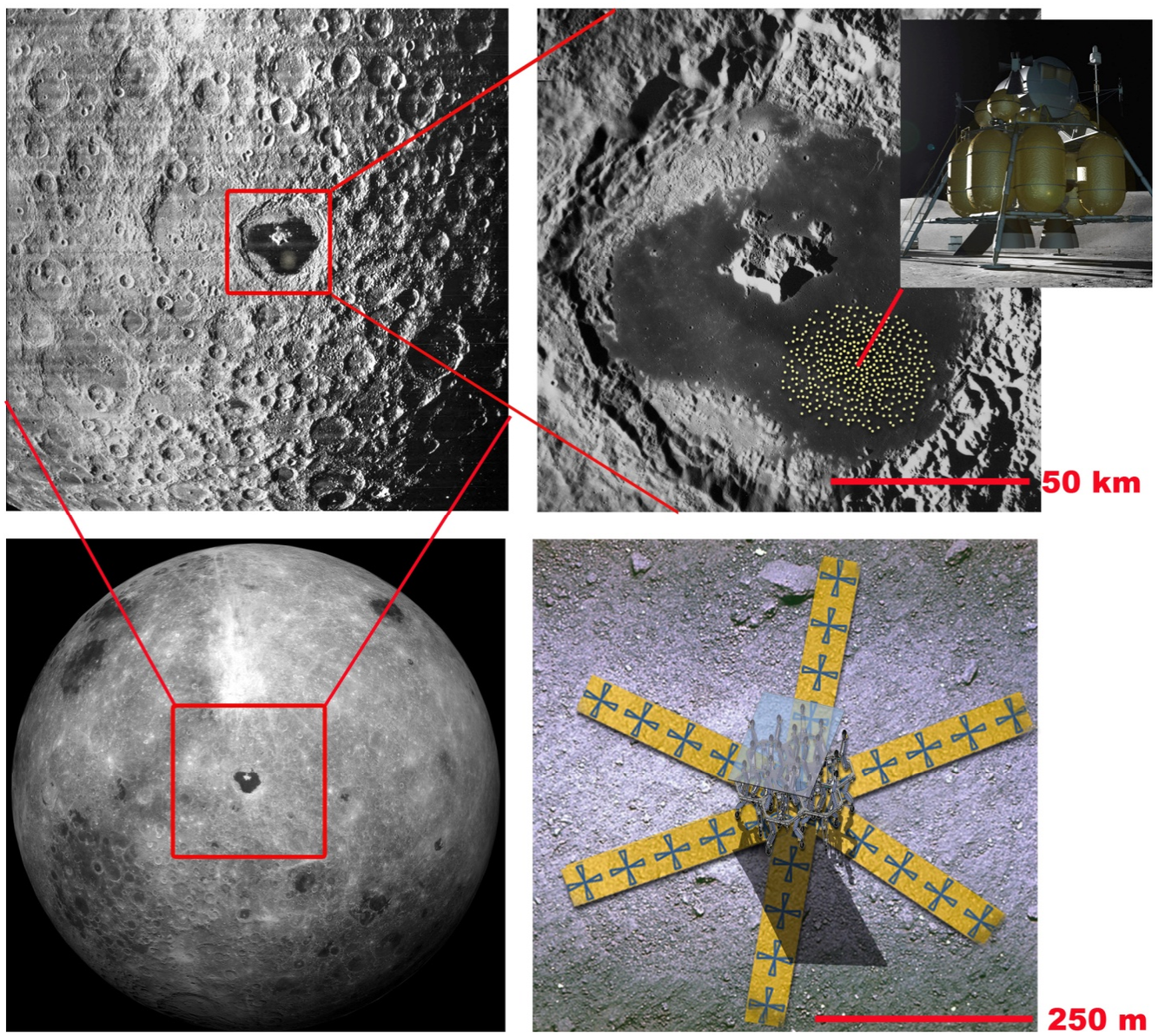
Under construction...



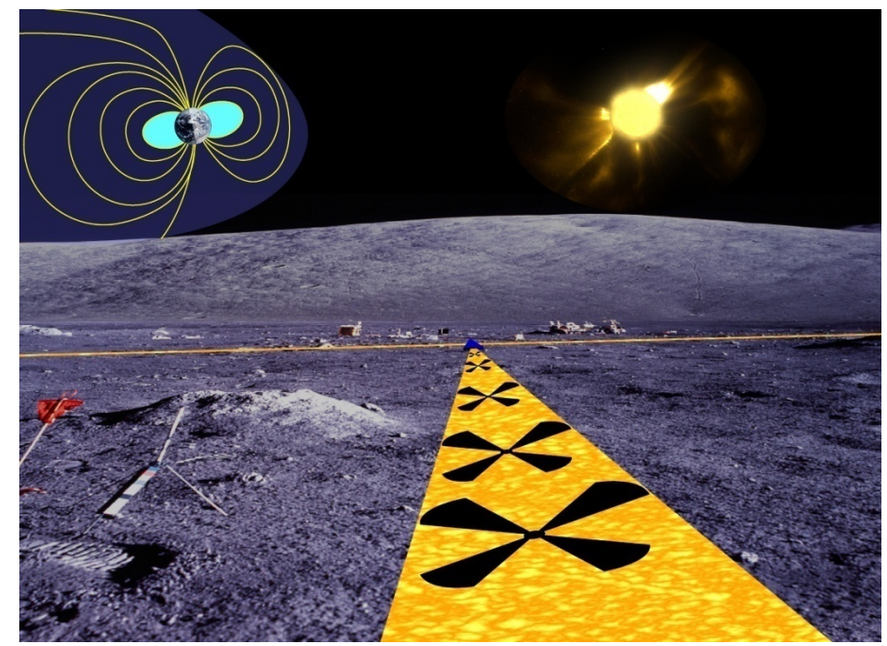
Radio arrays on the moon

- basic elements are robust and light weight
  1 Ares V payload ~ 0.5 km^2 reasonable

DALI/LARC

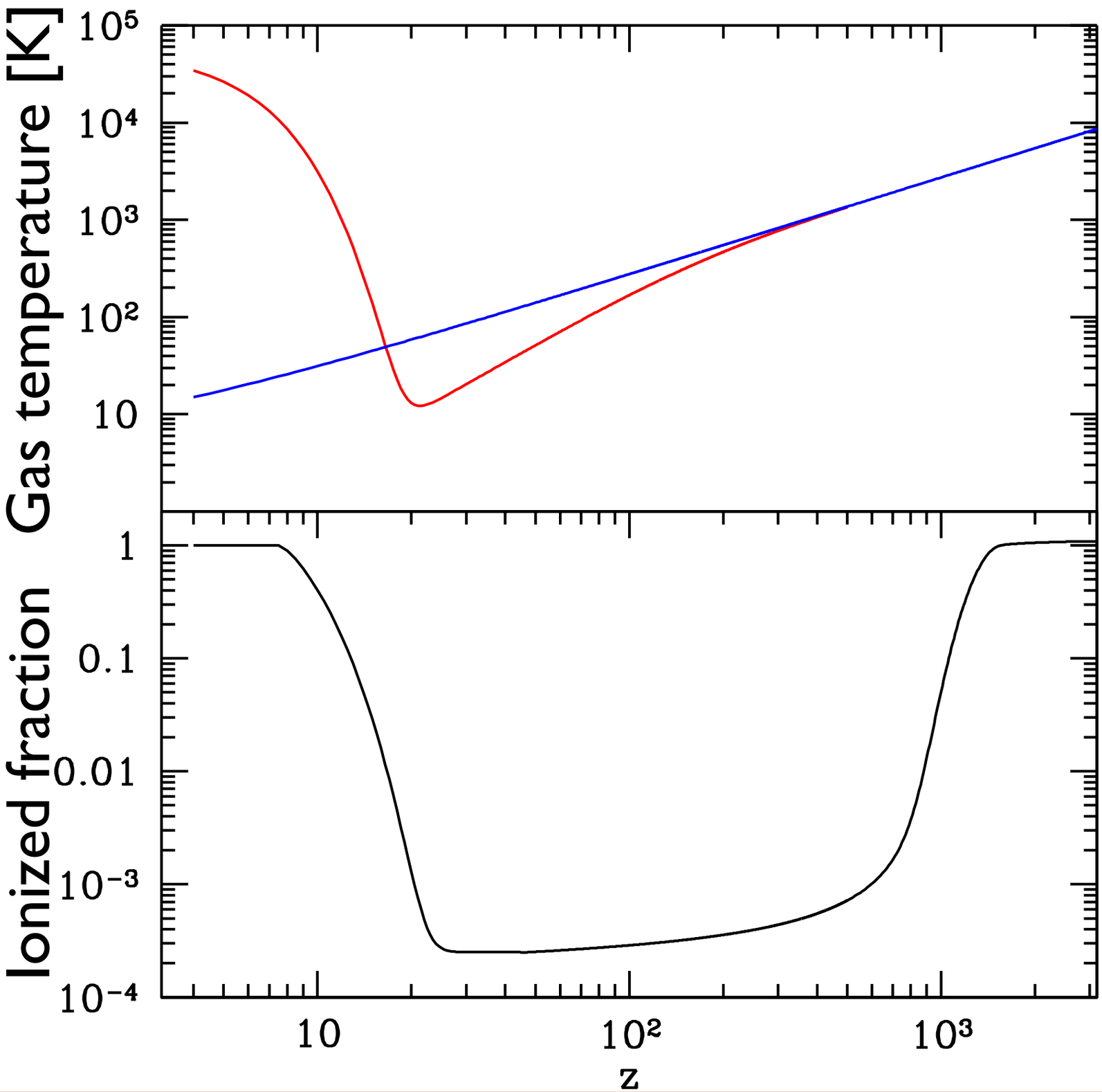


ROLSS

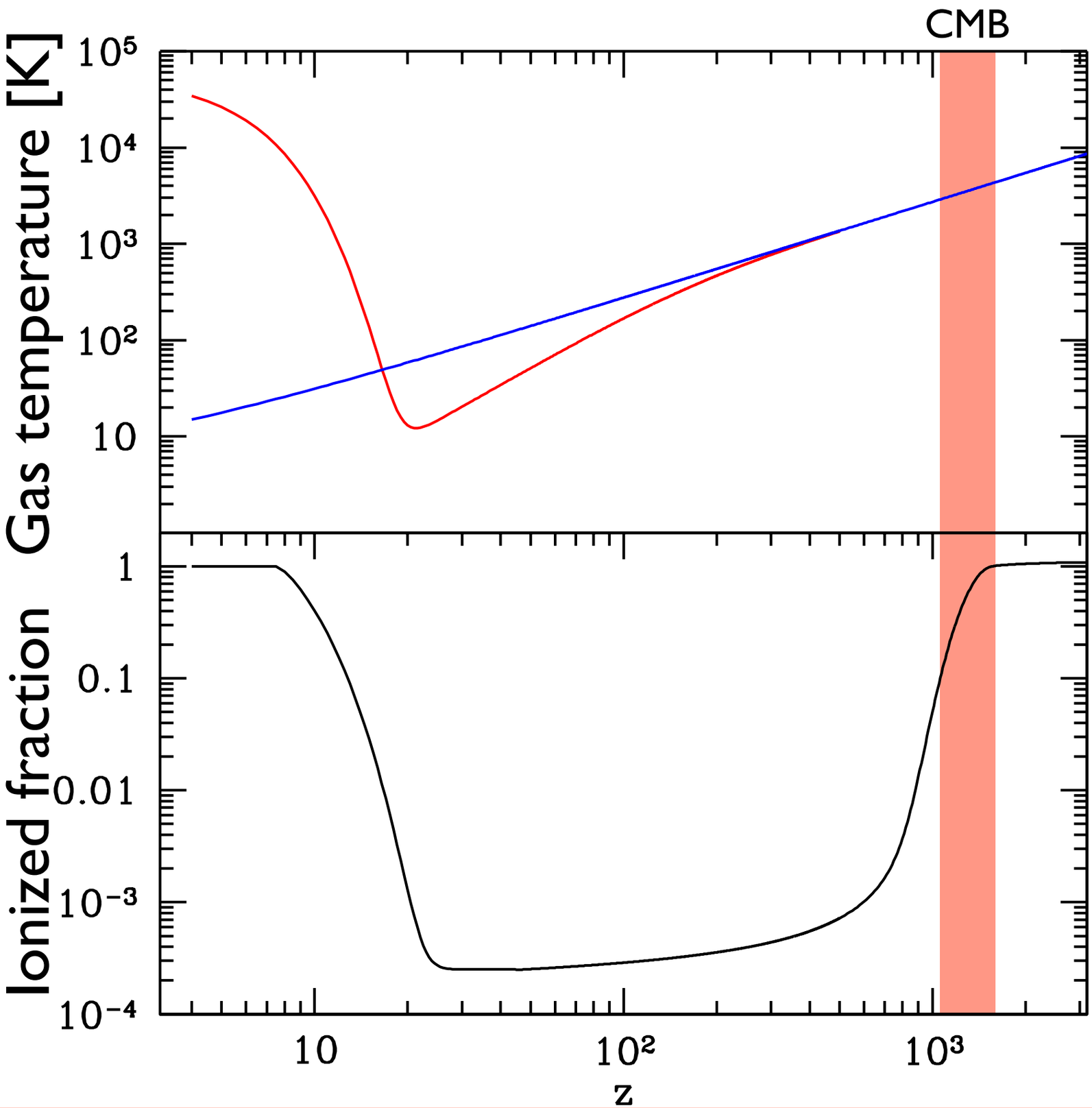


Need something like Ares V launcher

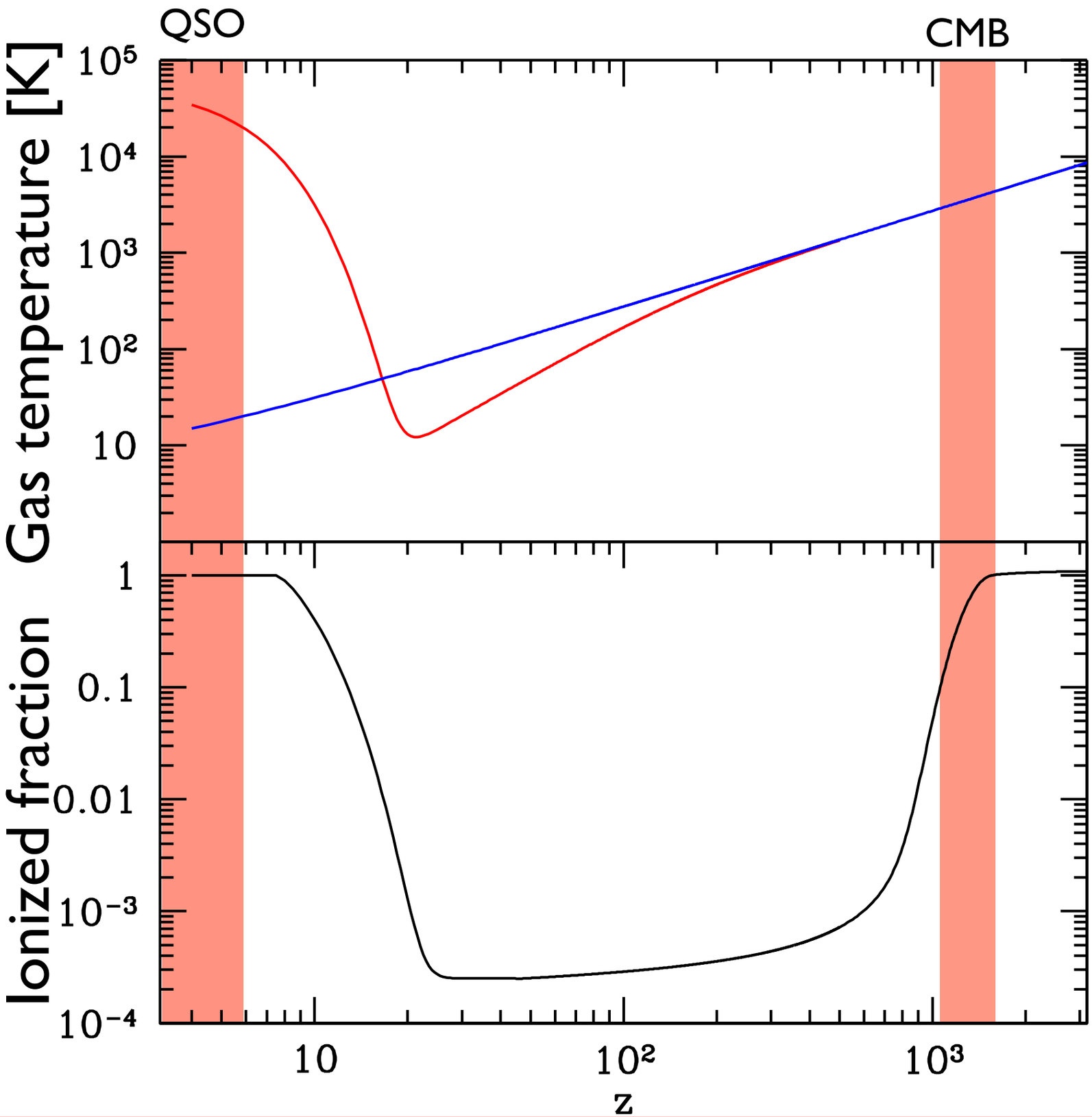
The story of H



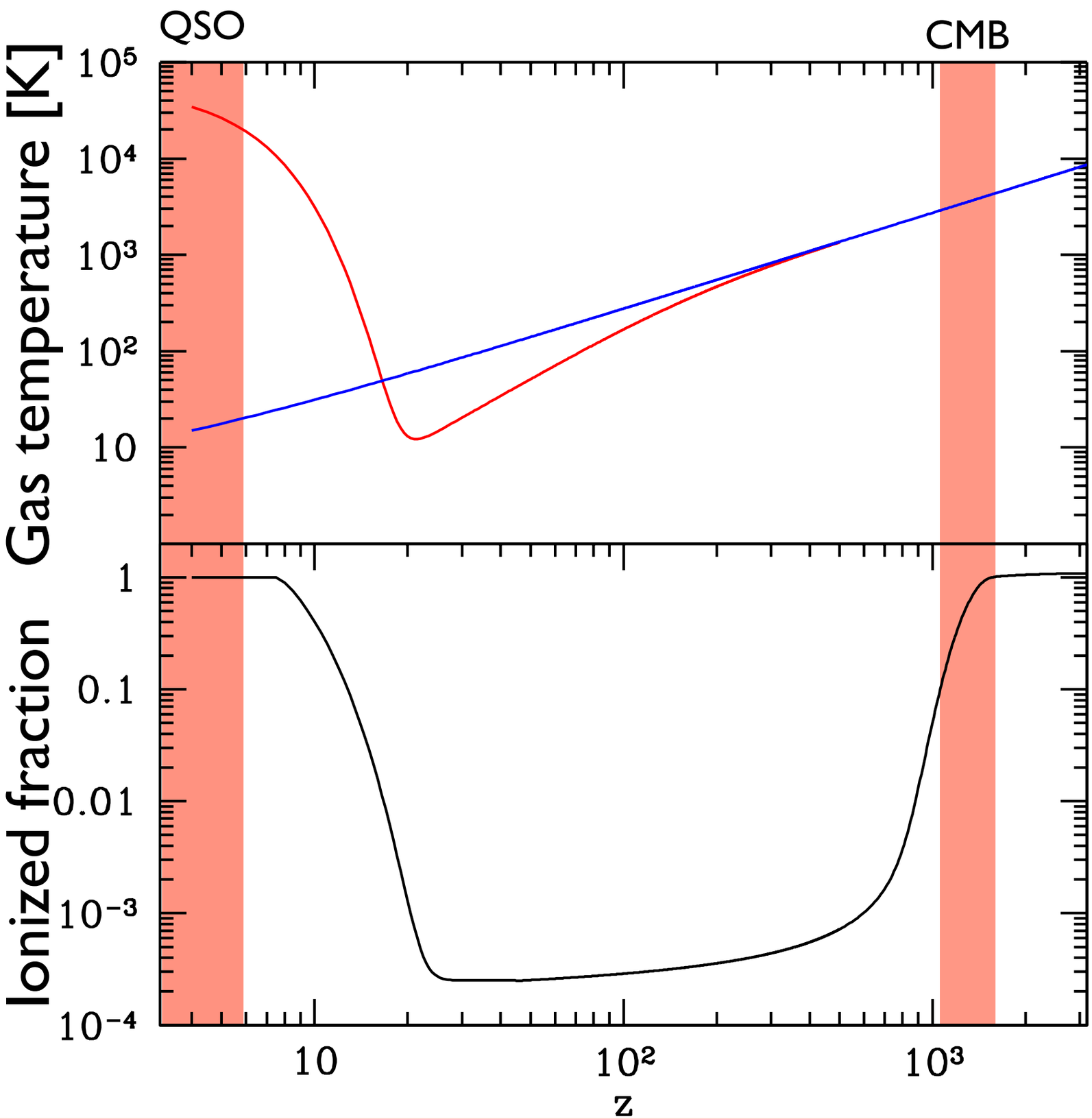
The story of H



The story of H



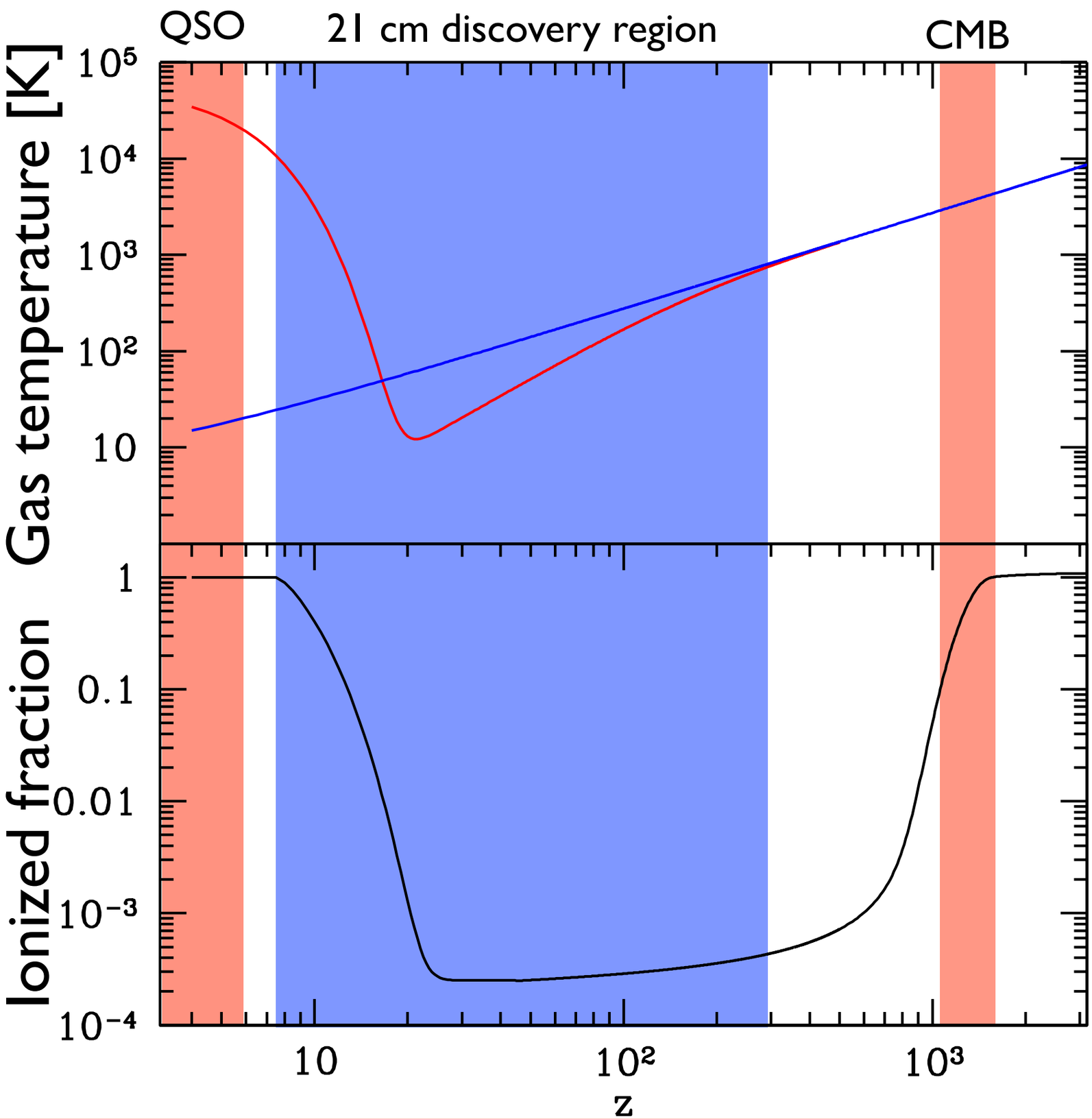
The story of H



We know nothing concrete about the thermal history of the Universe between z=1100 and z=6

Room for surprises if new physics is relevant

The story of H



We know nothing concrete about the thermal history of the Universe between z=1100 and z=6

Room for surprises if new physics is relevant

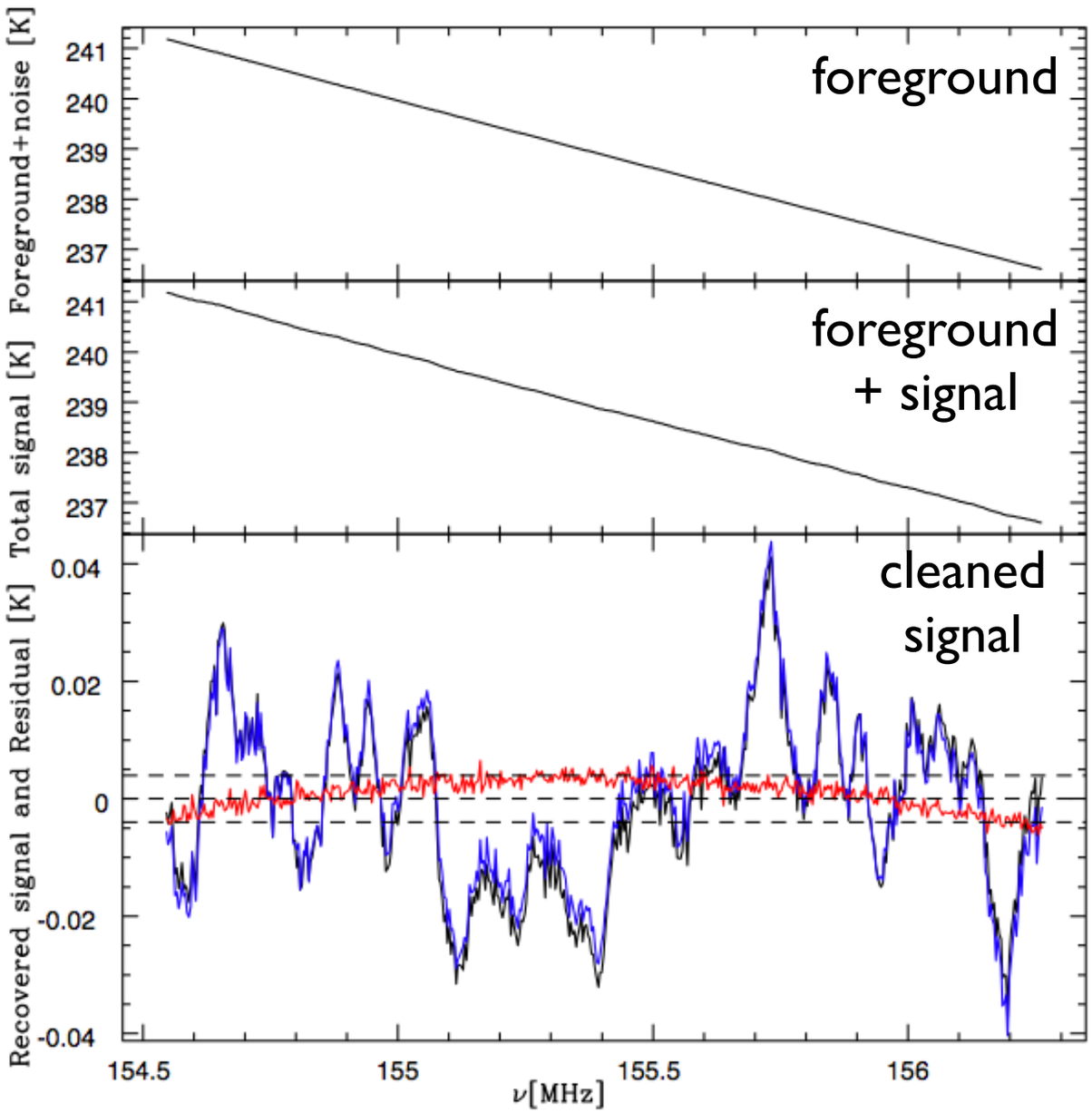
Astrophysical foregrounds

- Foregrounds dwarf signal: 100s K vs 10s mK
  - Terrestrial RFI
  - Galactic synchrotron
  - Extragalactic radio point sources
  - Radio recombination
- Exploit foreground smoothness
- Point source "peeling"

  localisation & removal errors

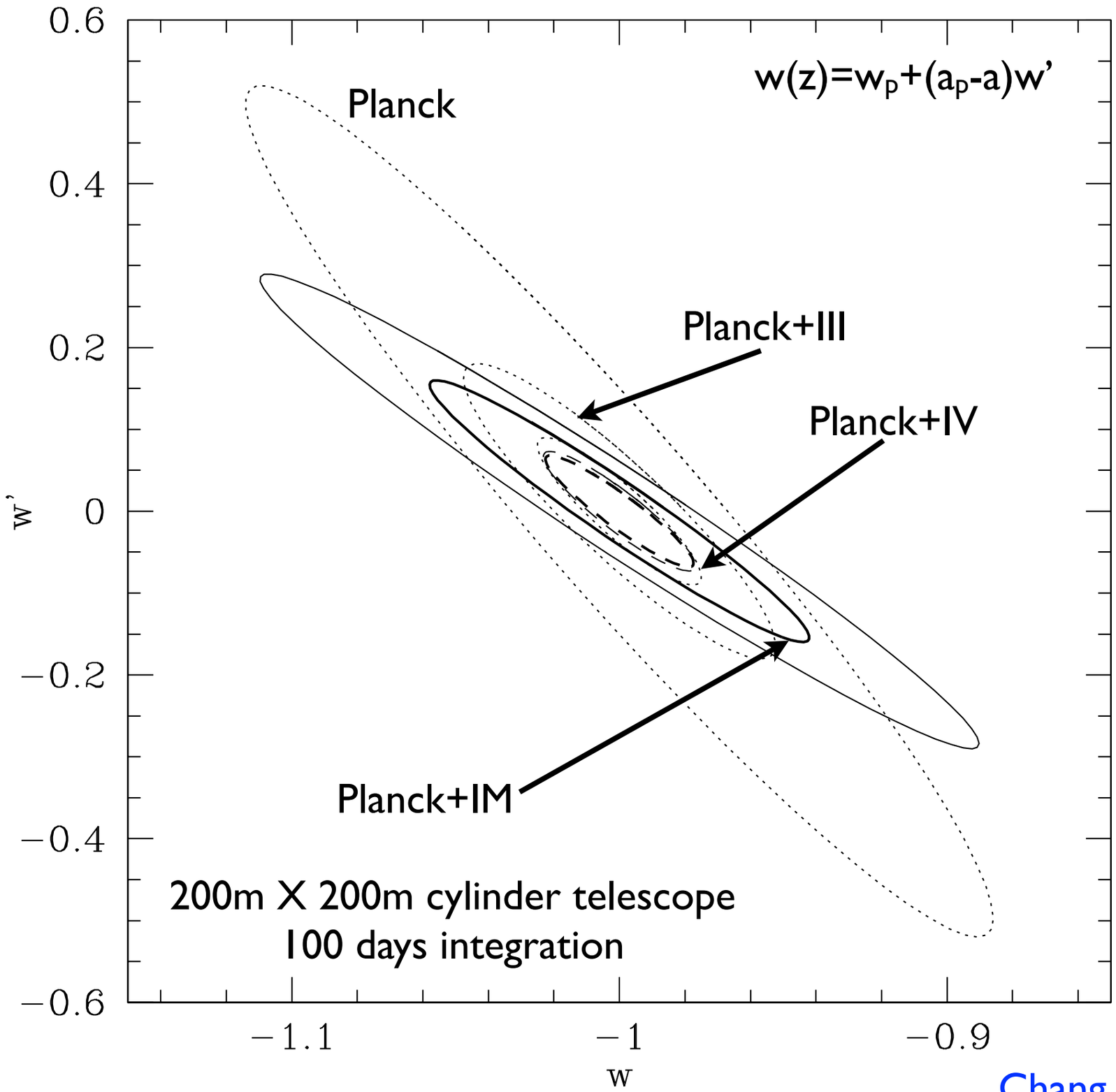
  => residuals with distinctive shape

Datta+ 2010



Wang, Tegmark, Santos, Knox 2005

Dark energy constraints



Intensity mapping can provide an effective dark energy probe at z~1-3

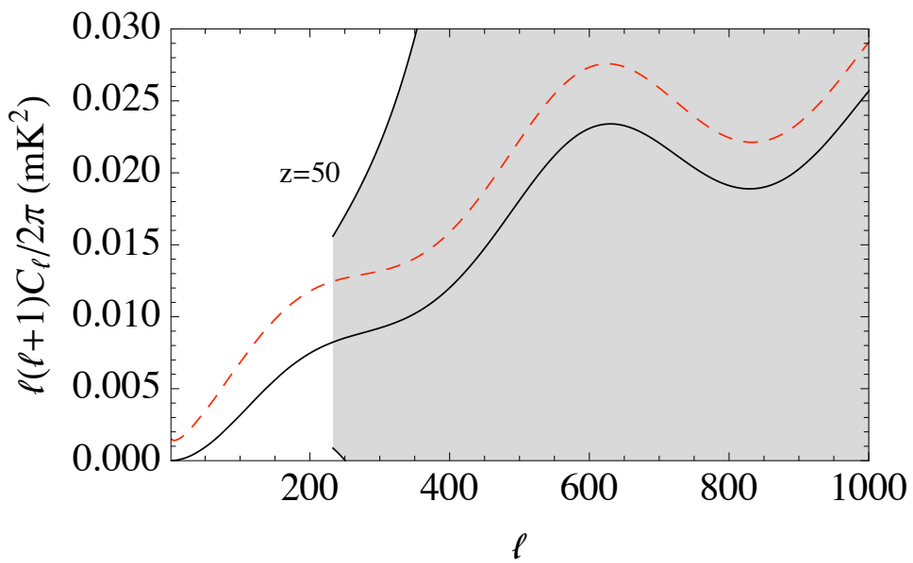
Growth of structure

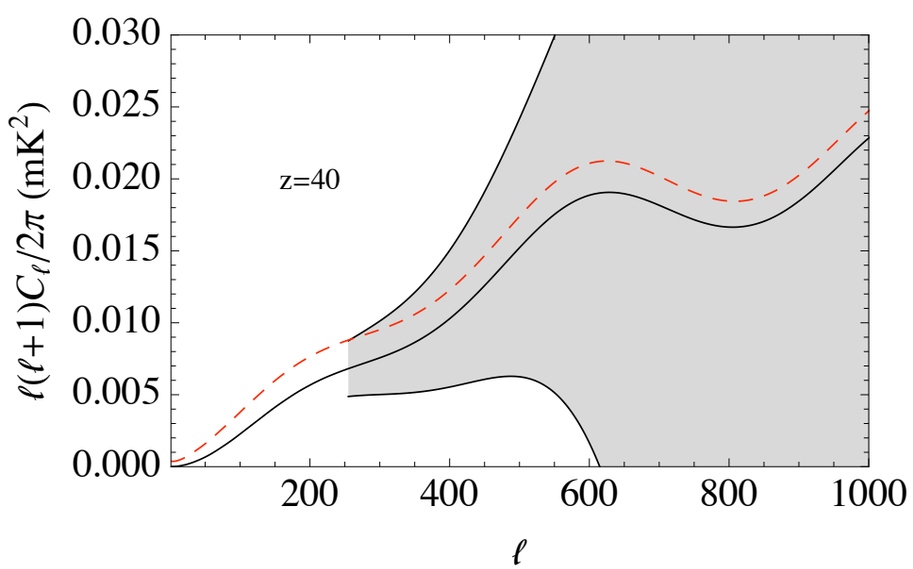
Chang, Pen, Bandura & Peterson 2010

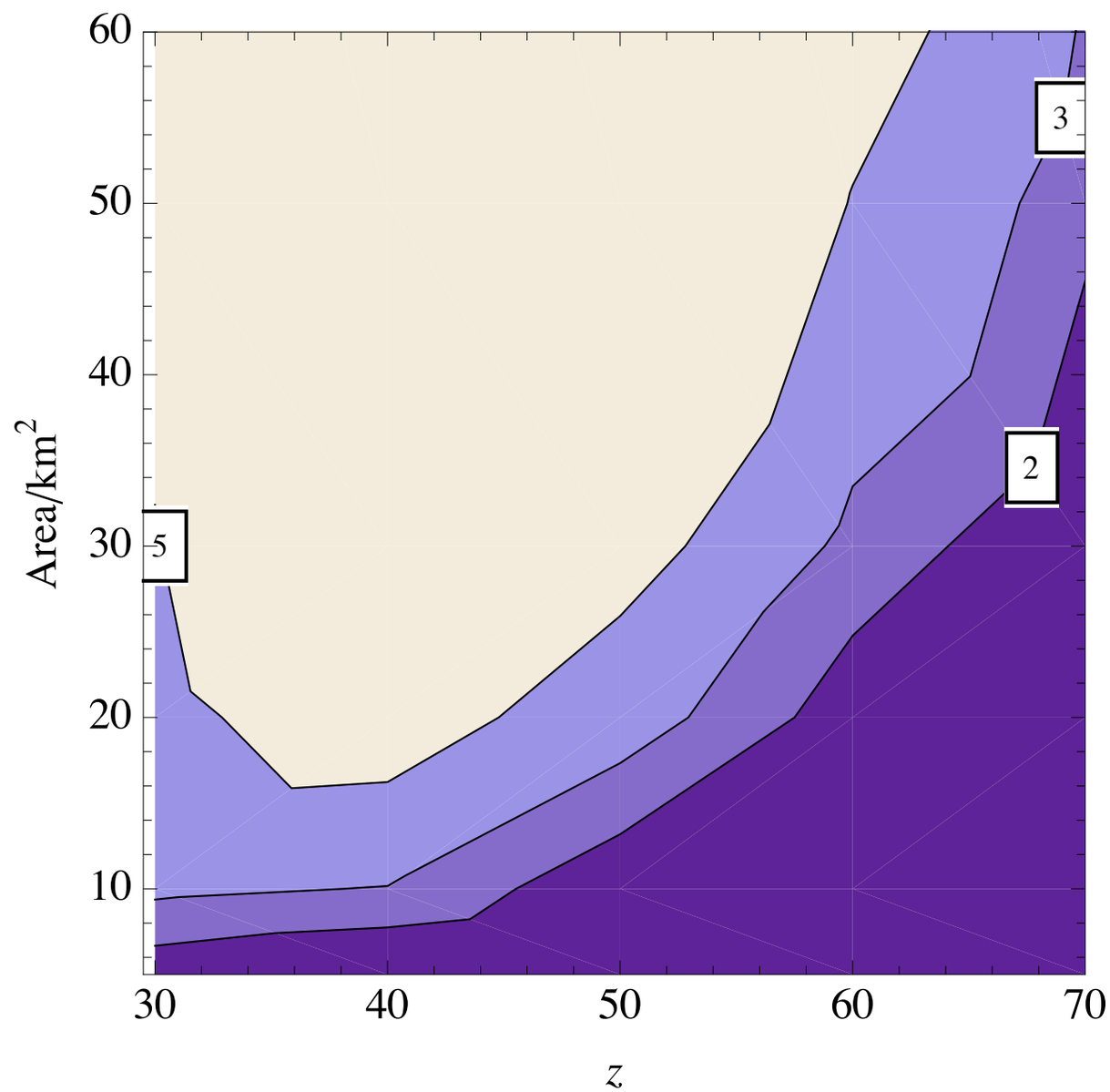
Compensated Isocurvature Modes

Example of physics that can be done with 21cm

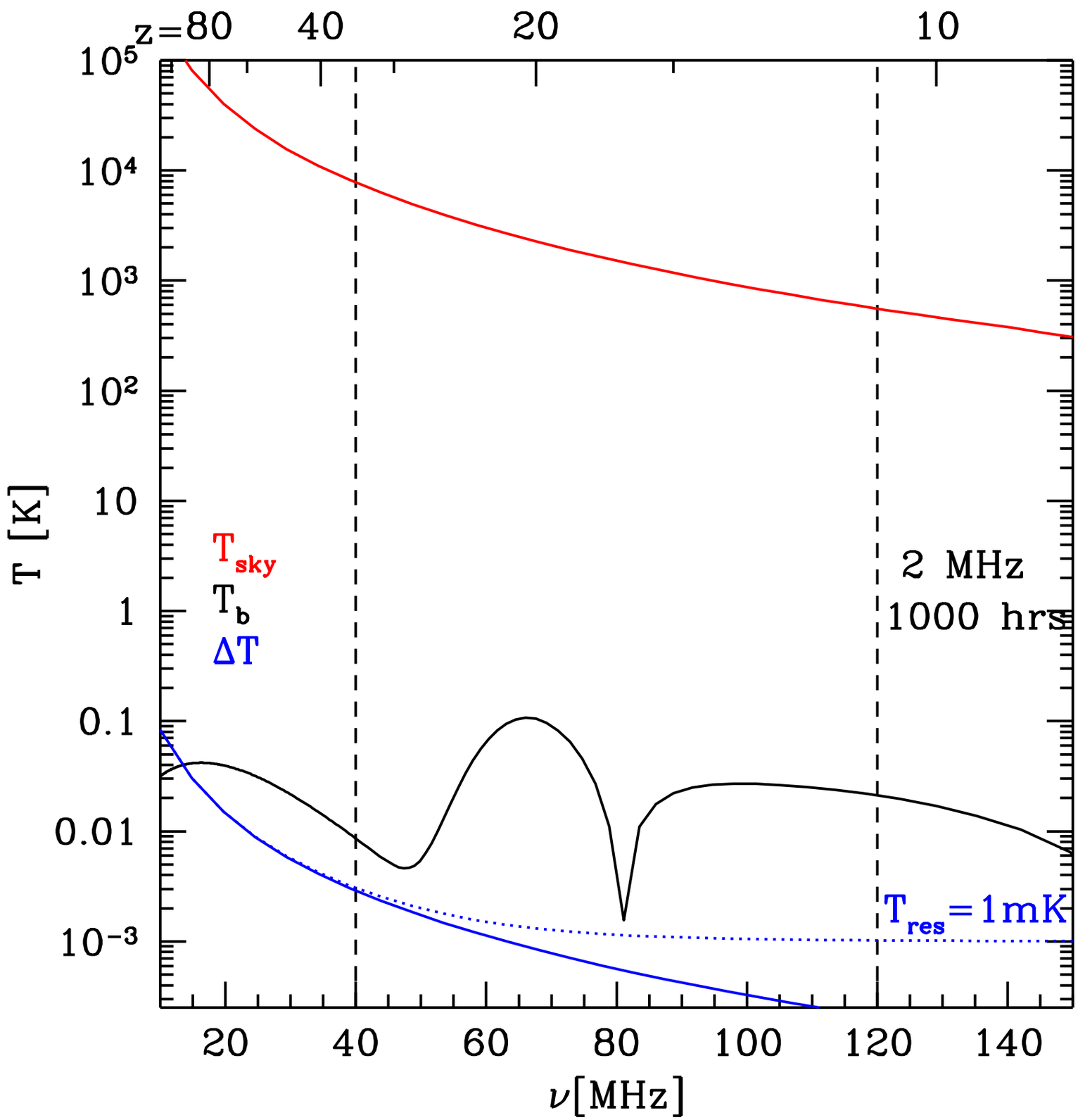
Effect on large scales only at high-z







Foregrounds vs Signal

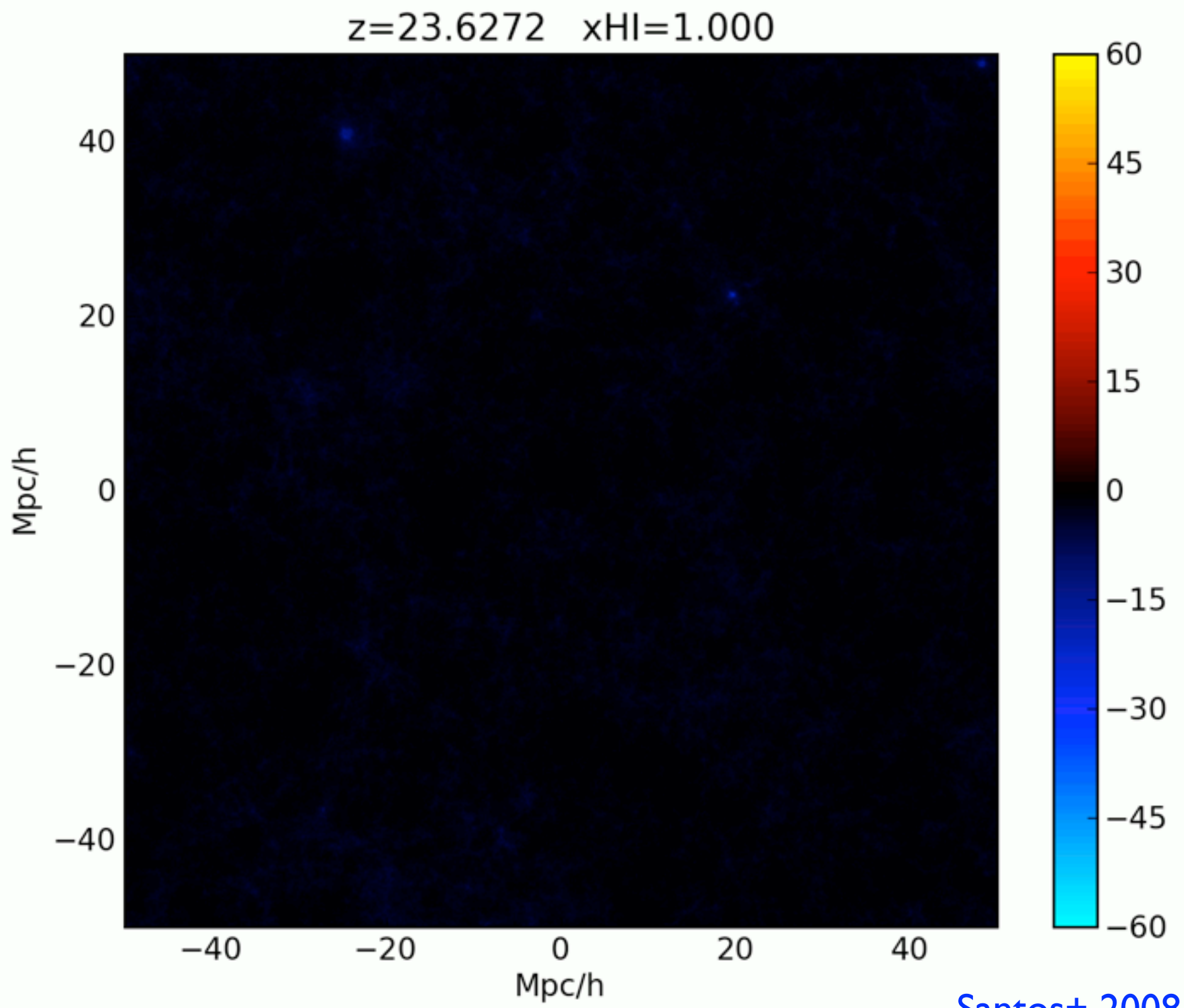


Foregrounds smooth
Signal has structure
Separation possible...

Dynamic range >10^5 needed

$$\Delta T = \frac{T_{\rm sky}}{\sqrt{\Delta\nu t_{\rm obs}}}$$

Numerical simulation



Santos+ 2008

Wouthysen-Field Effect

Hyperfine structure of HI

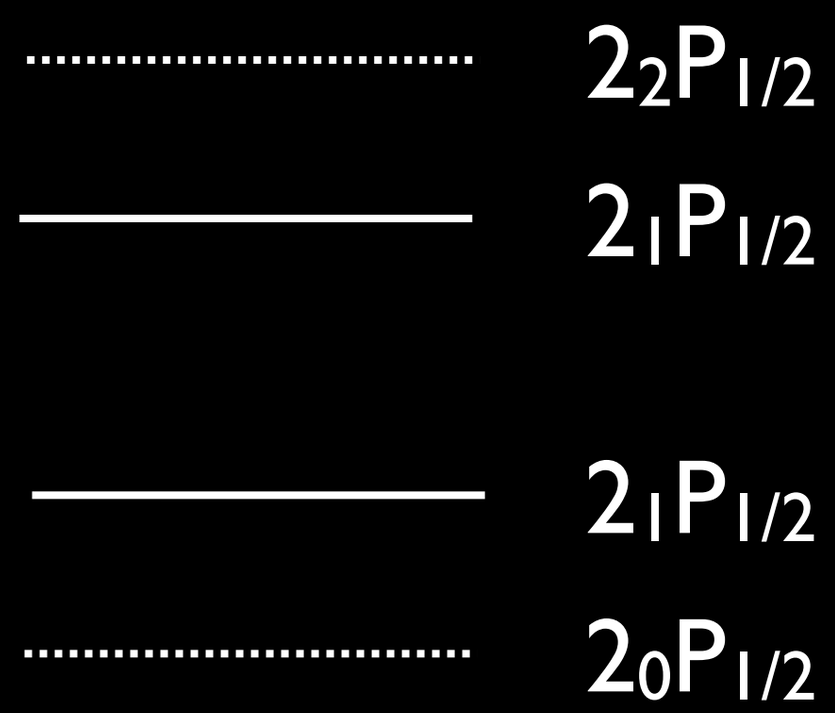
Resonant Lyman α scattering couples ground state hyperfine levels

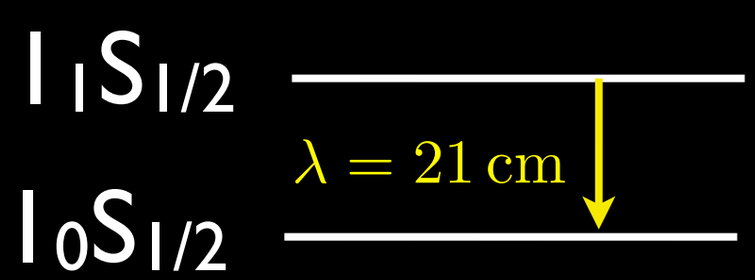
Coupling ∝ Lyα flux

spin colour gas

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

W-F recoils





Wouthysen 1959

Field 1959

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Coupling ∝ Lyα flux

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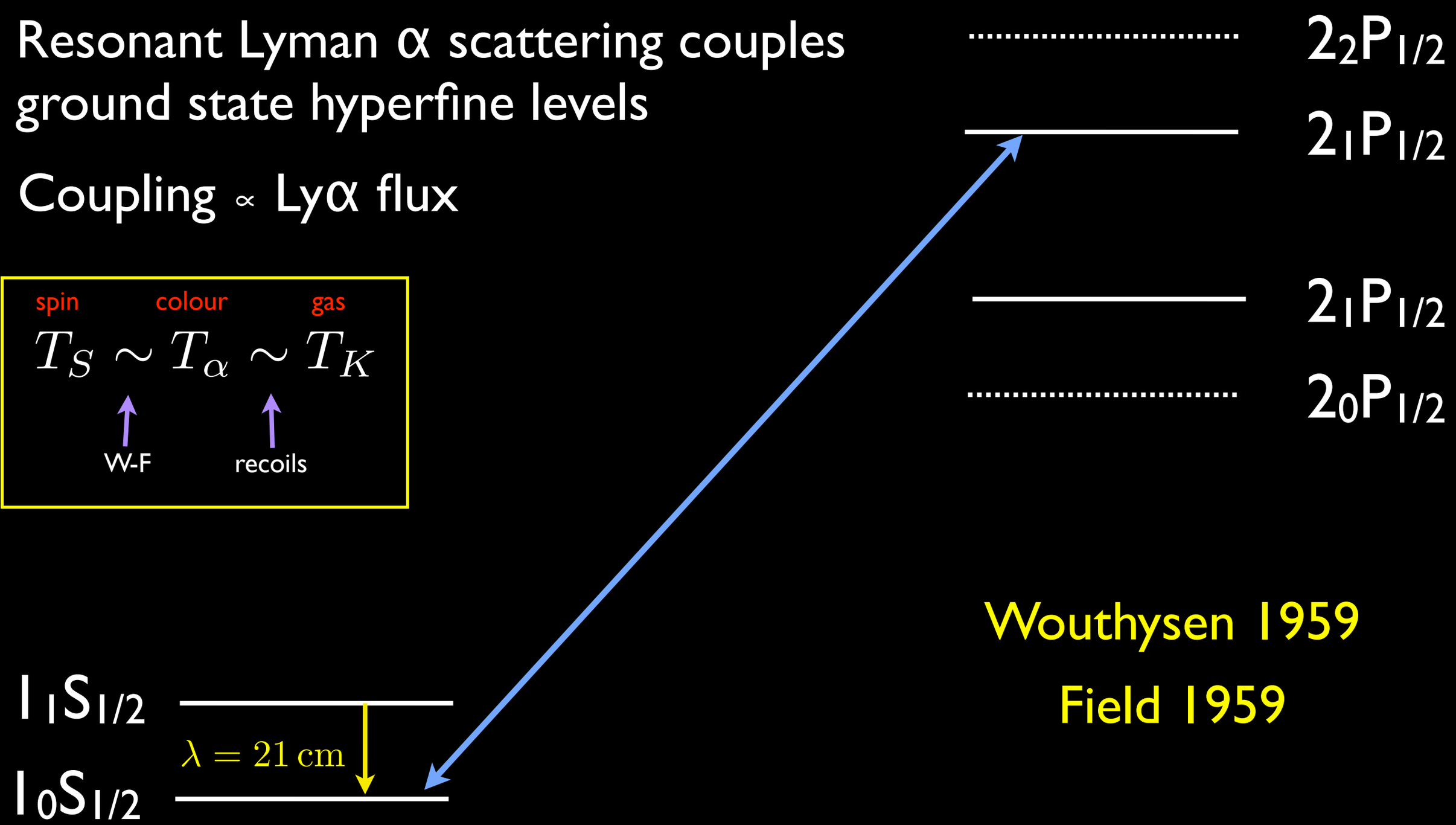

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Hyperfine structure of HI

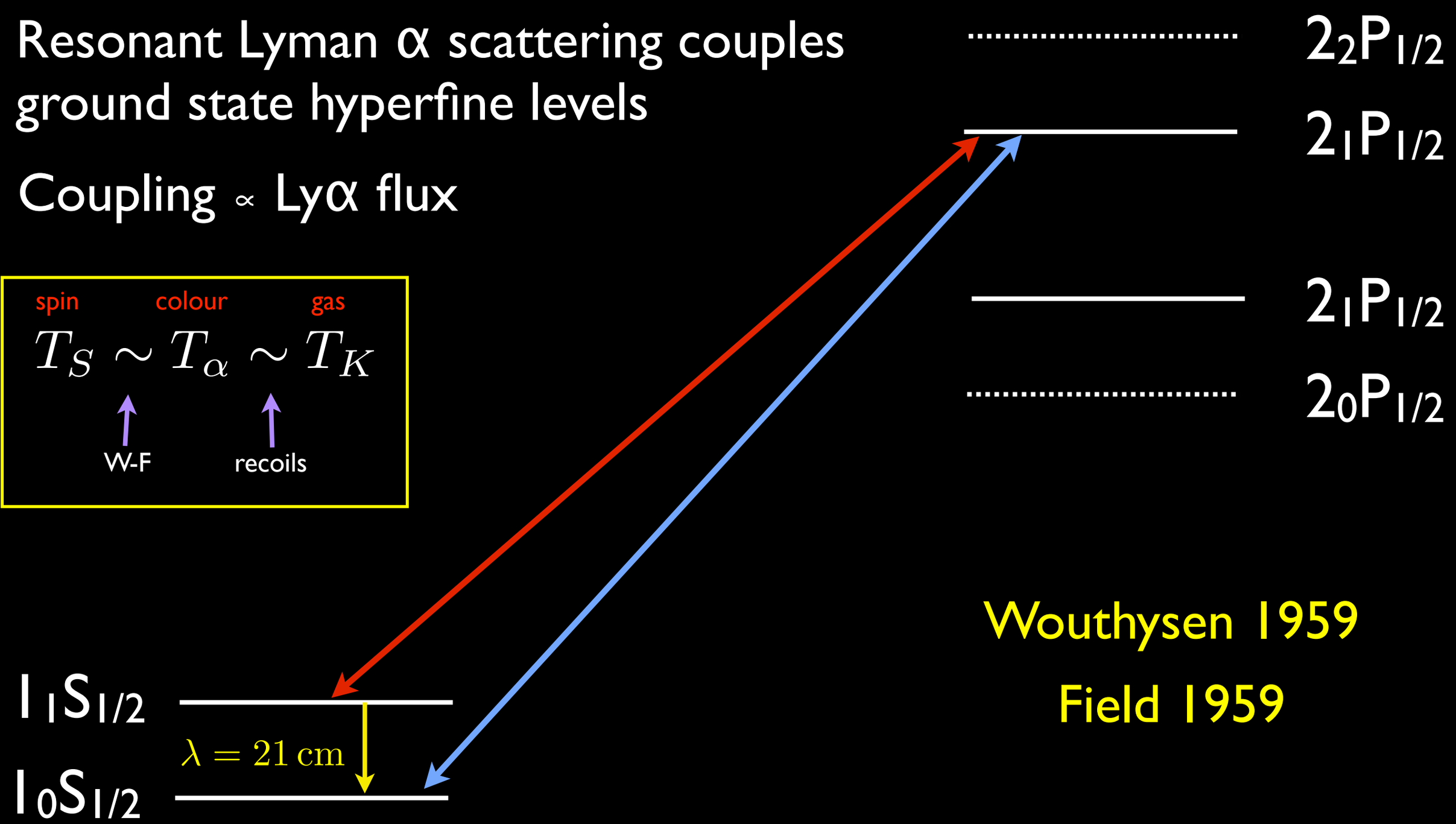
Resonant Lyman α scattering couples ground state hyperfine levels

Coupling ∝ Lyα flux

spin colour gas

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

W-F recoils



Wouthysen 1959

Field 1959

Wouthysen-Field Effect

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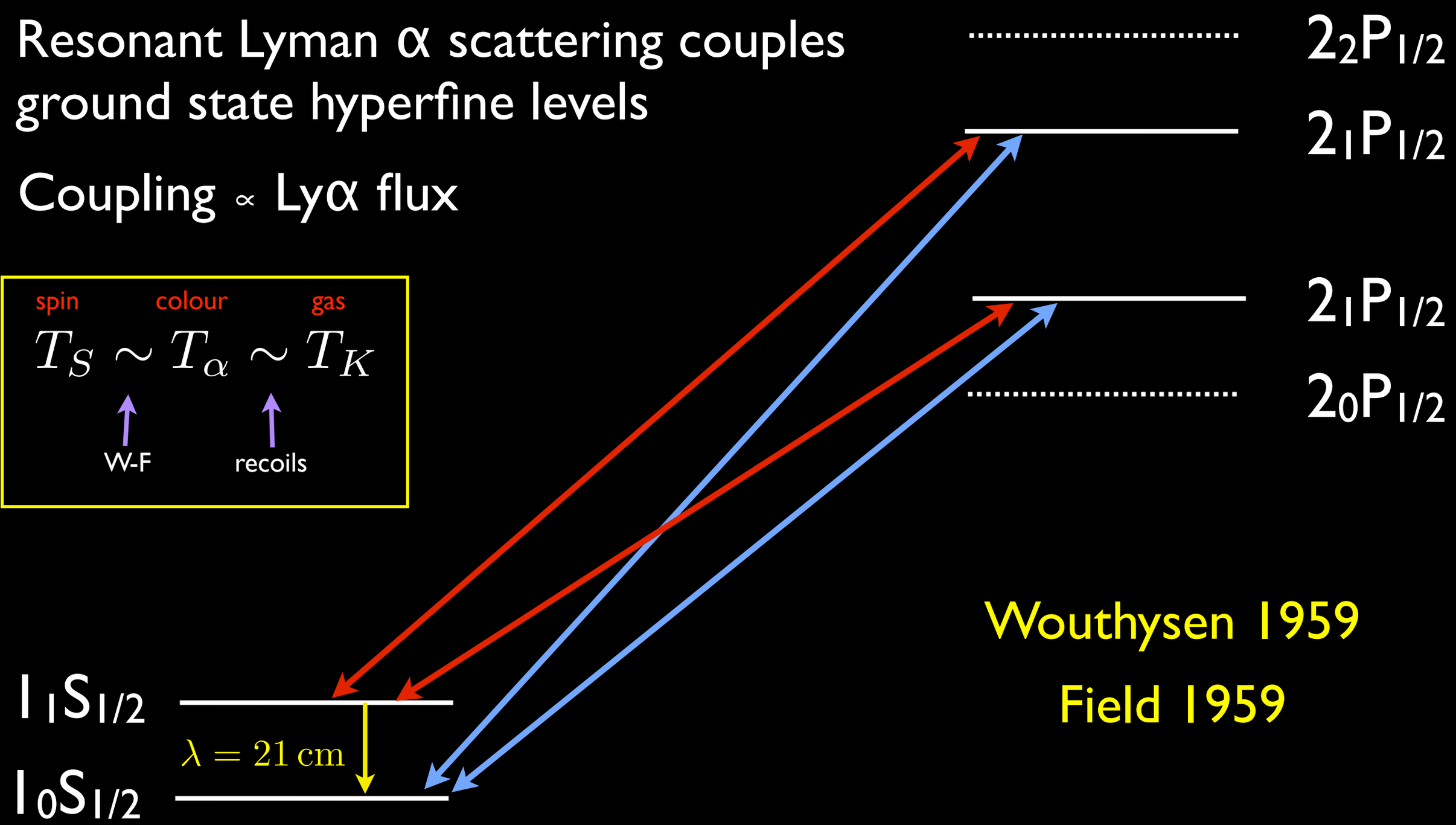
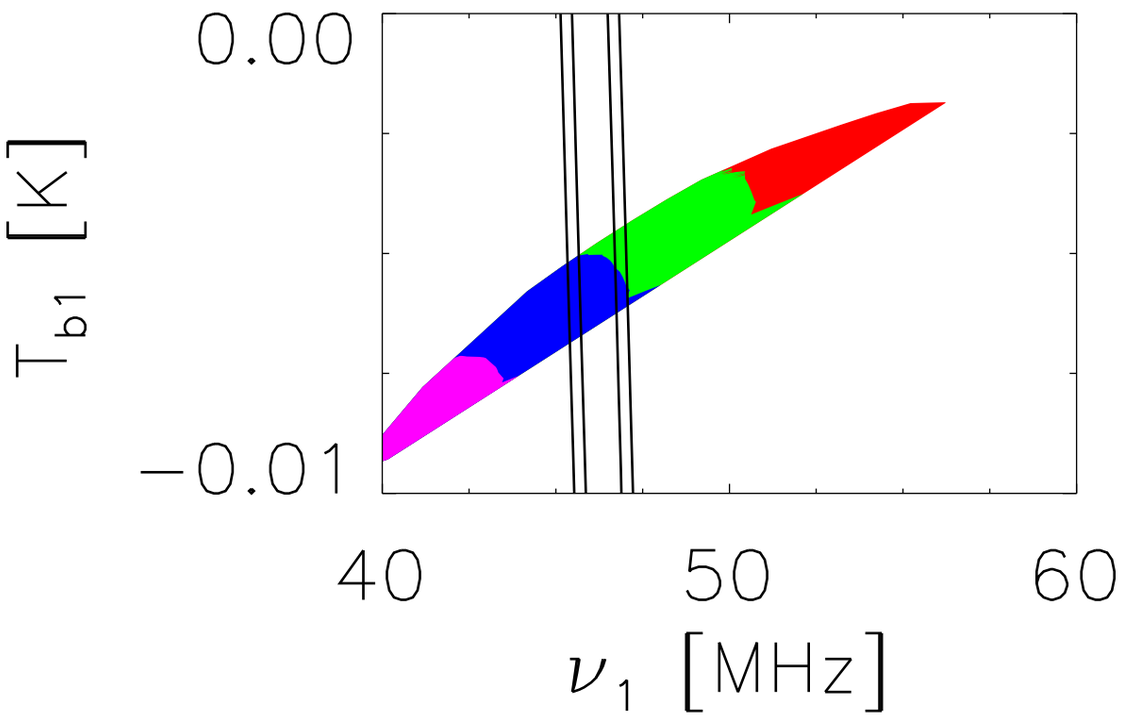


Wouthysen 1959

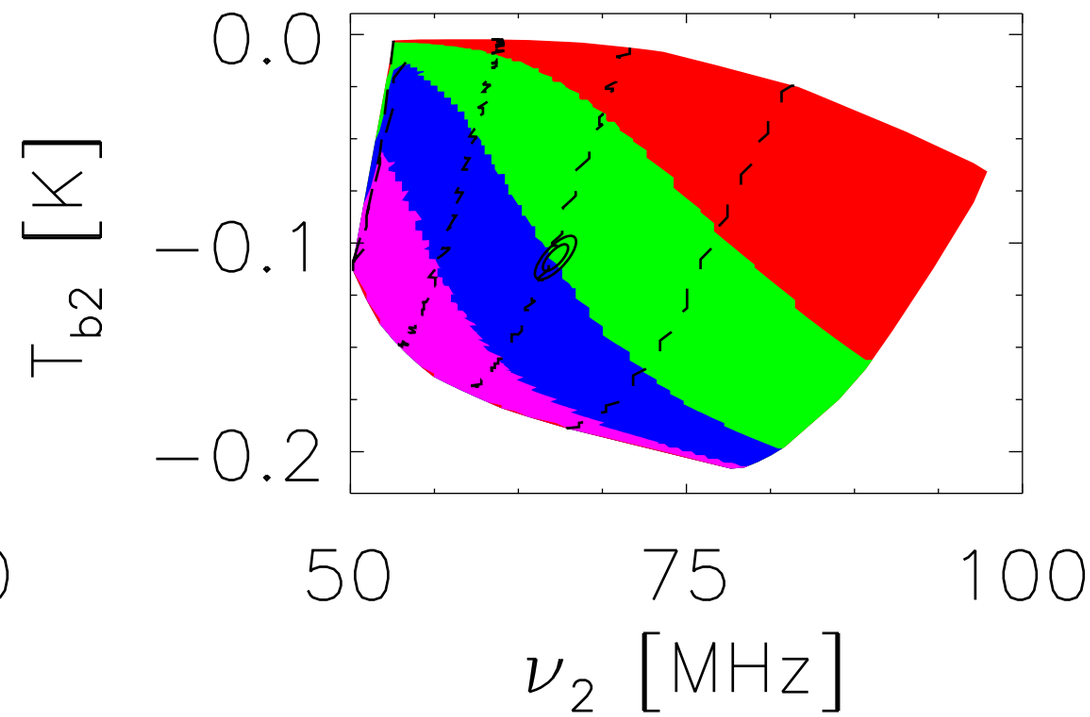
Field 1959

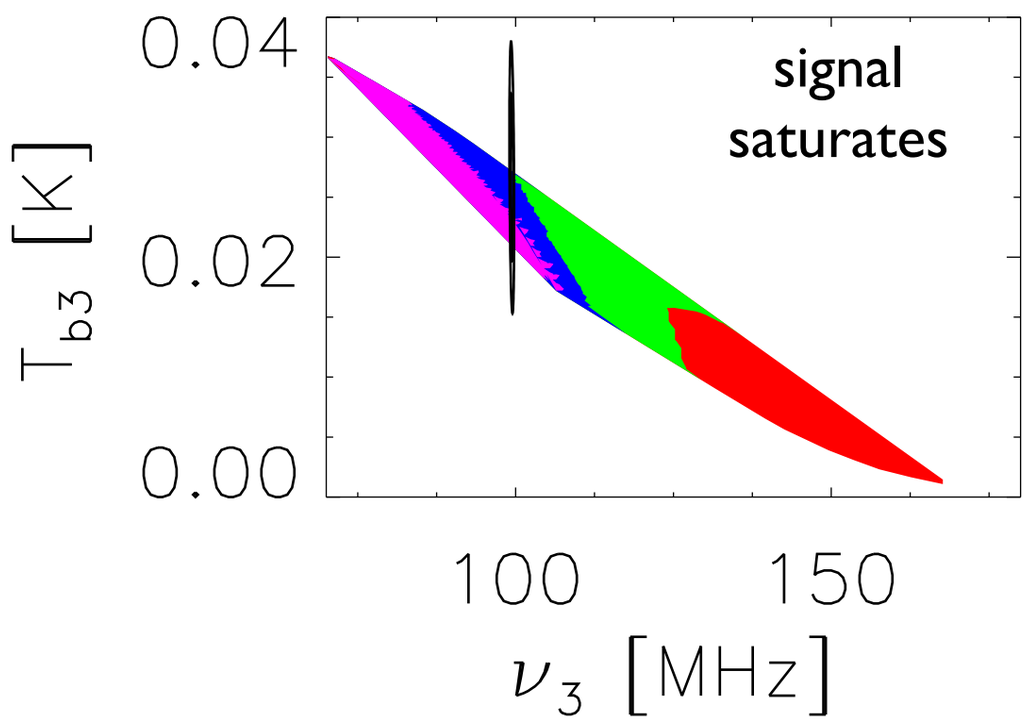
Constraining turning points

Lya coupling begins



heating begins

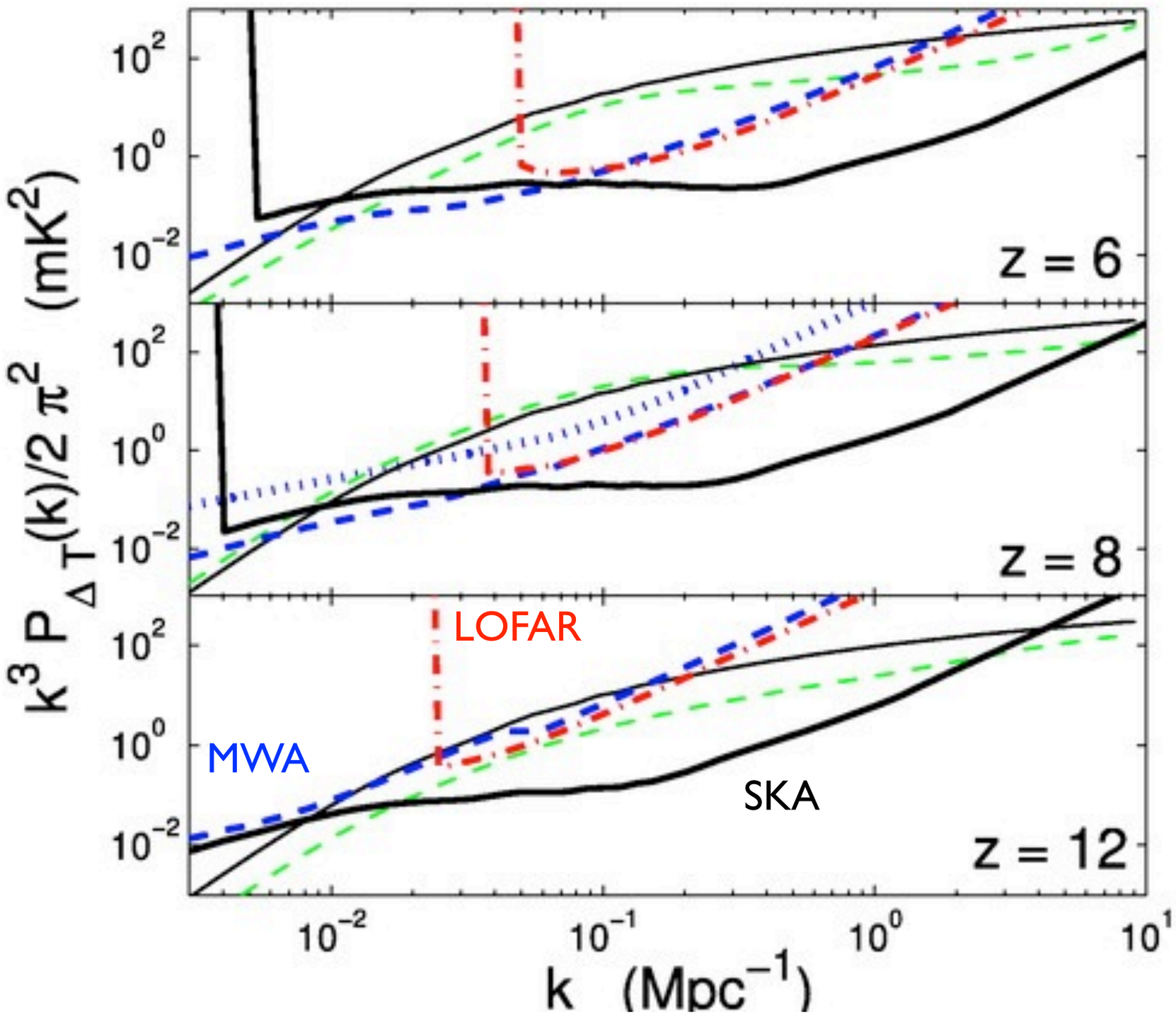




Npoly=3
tint= 500hrs,
50 channels spanning
40-140 MHz

Similar sensitivity as for reionization constrains deep absorption feature

Power spectrum sensitivity



Pathfinder instruments sensitive to about a decade in wavenumber

=> evolution of tilt and amplitude of power spectrum

Lidz+ 2008

SKA can measure shape of power spectrum

McQuinn+ 2006