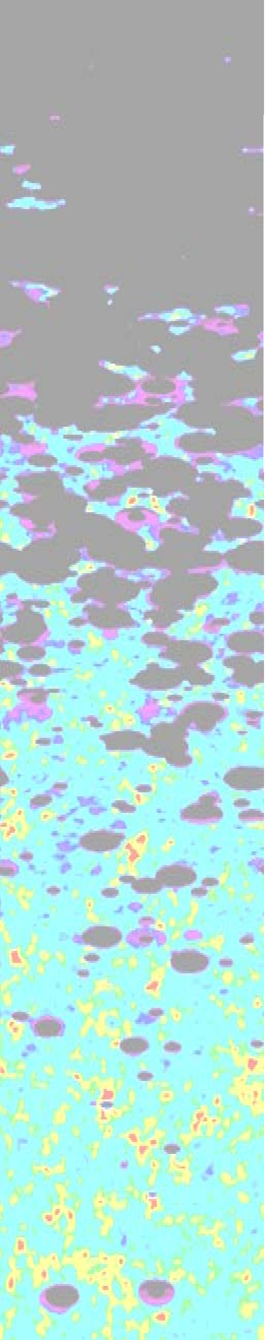

Cosmological Reionization Simulations for LOFAR

Rajat Mani Thomas

LOFAR

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People involved:
The LOFAR-EoR Core

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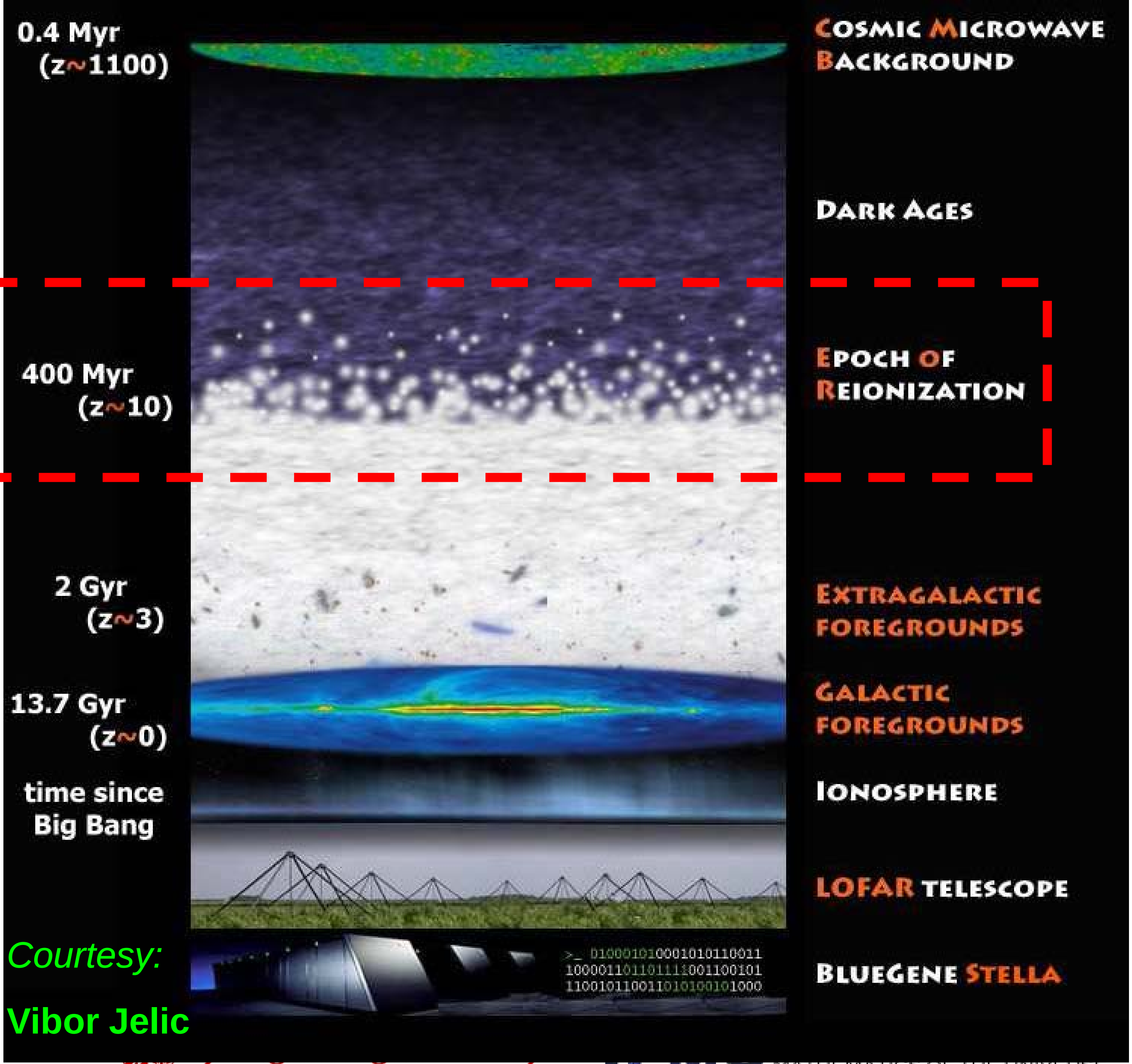
Outline

- Introduction
  - Glossary of the relevant physics and the astrophysics
- “The goal”
- Implementation & Results
- What comes next?

Glossary

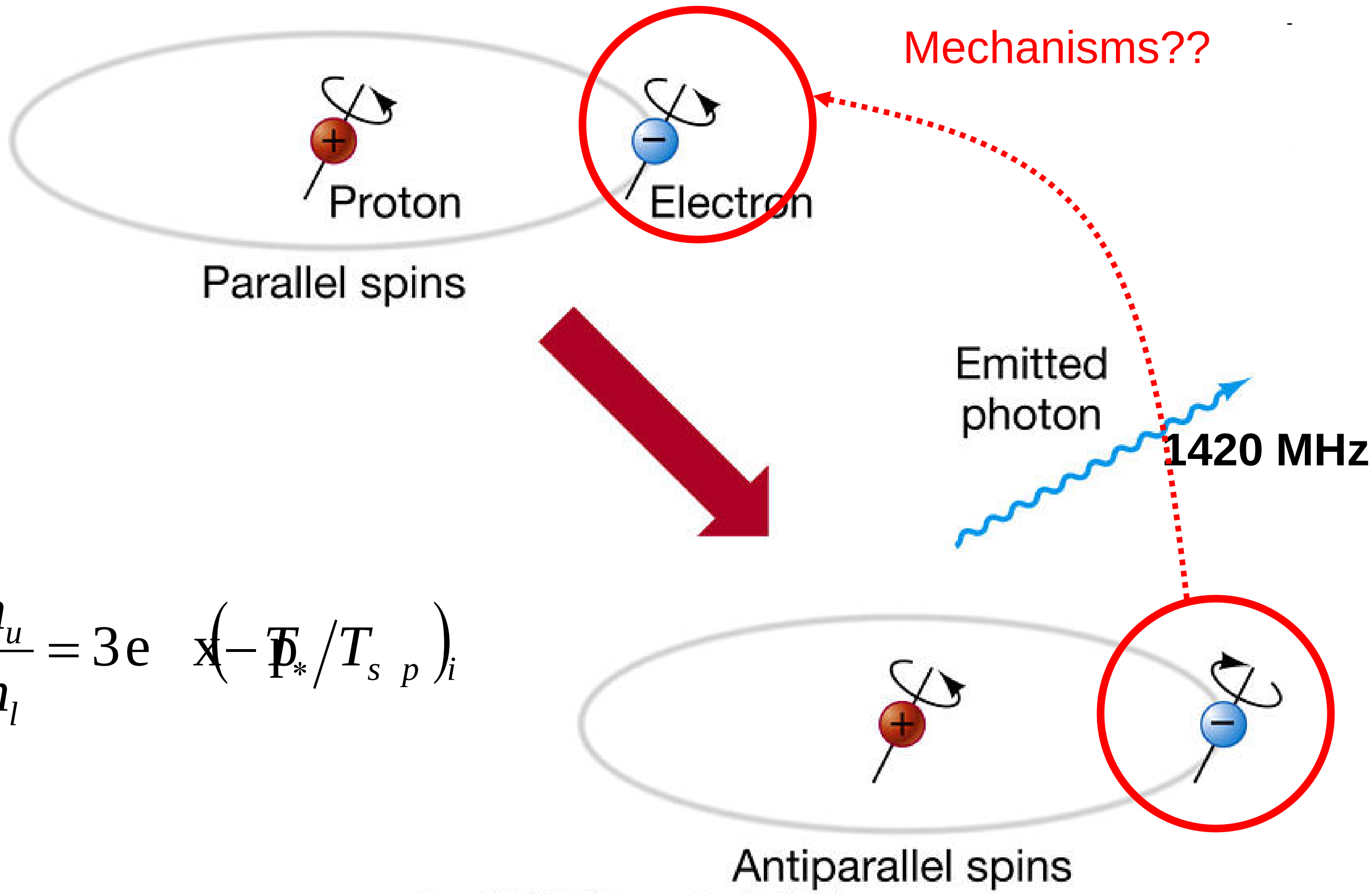
- Brief history of the Universe
- Observable: 21-cm spin-flip transition
- Brightness temperature
- Radiative transfer basics



Courtesy:

Vibor Jelic

21-cm Physics



$$\frac{n_u}{n_l} = 3\exp\left(-T_*/T_{sp}\right)_i$$

21cm Physics: Spin Temp

$$T_s = \frac{T_{CMB} + y_k T_k + y_\alpha T_\alpha}{1 + y_k + y_\alpha}$$

Field: 1958

K → kinetic and α → light

We assume $T_k = T_\alpha$

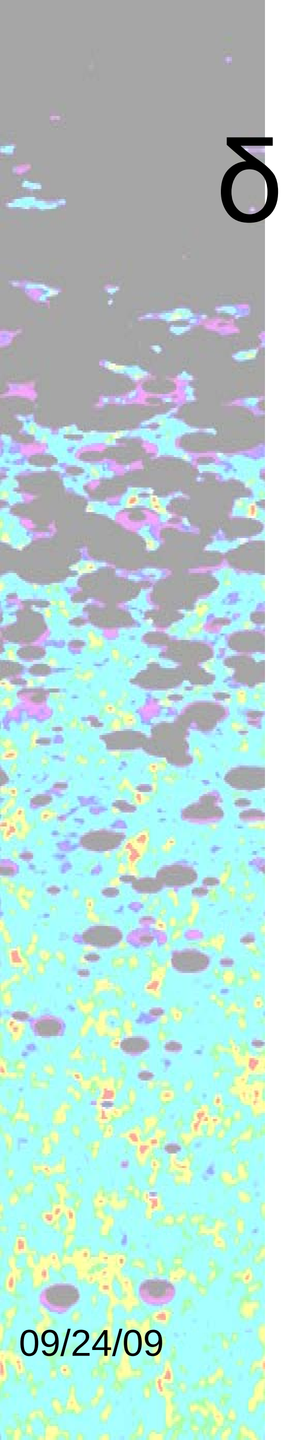
If y_k or $y_\alpha >> 1$ then $T_s = T_k$

If y_k and $y_\alpha << 1$ then $T_s = T_{CMB}$

Remember!!

It is very well possible;

$T_k < T_{CMB}$



δTb: Brightness temperature

$$\delta T_b = (20\,\mathrm{mK})(1+\delta)\left(\frac{X_{HI}}{h}\right)\left(1-\frac{T_{CMB}}{T_{spin}}\right)\left(\frac{\Omega_b h^2}{0.0223}\right)\left[\left(\frac{1+z}{10}\right)\left(\frac{0.24}{\Omega_m}\right)\right]^{1/2}$$

Radiative Transfer

Cosmology

Astrophysics

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The Goal

Develop an efficient ***radiative transfer*** scheme to explore the various plausible reionization scenarios and predict the nature of the redshifted **21-cm signal** from the **Epoch of Reionization** ………specially for the **LOFAR case**.

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Where do we start?

Study the effect of various types of sources on ionization and temperature of their surrounding IGM

Problems studied

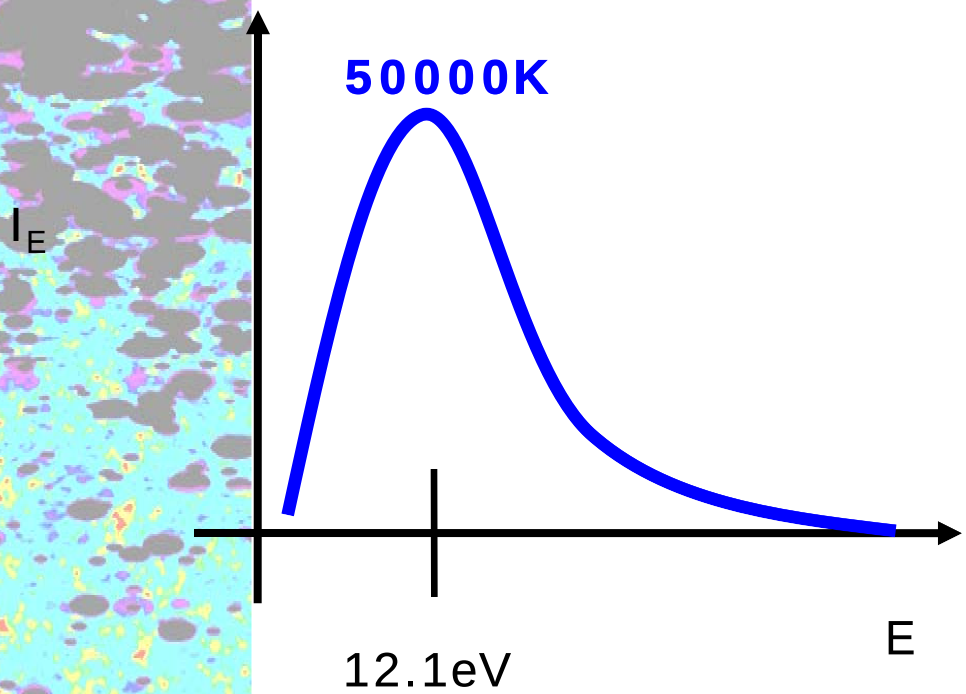
- **(Mini)qsos**:

  Mass range of BH: 1000 – 10^9 $M_\odot$
  SED: $E^{-\alpha}$.
  $E_{low} < E < 10^4$ eV
  E_{low} = 10.4 or 200 eV
  Luminosity : Eddington X Efficiency

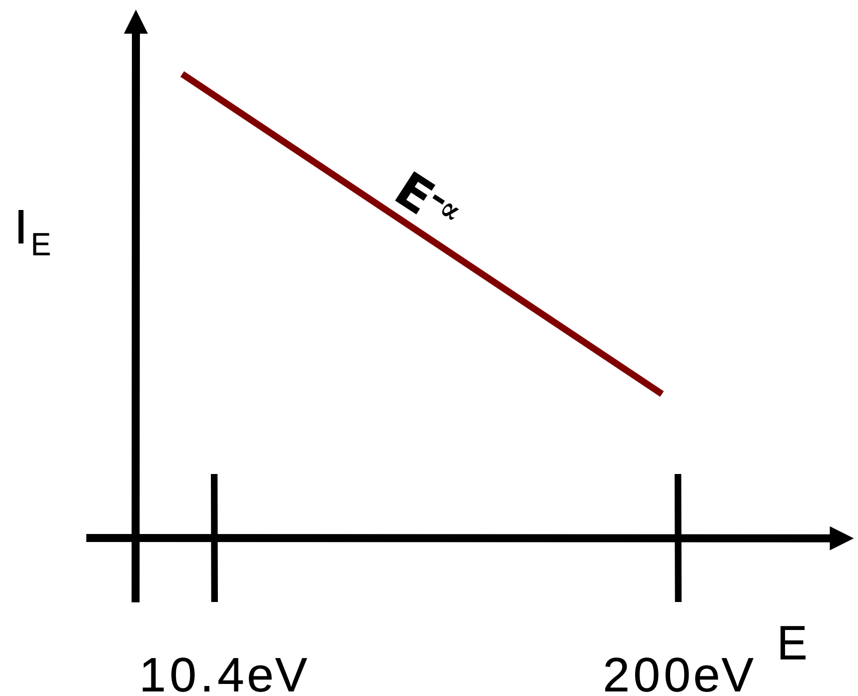
- **Stars:**

  Mass range: 10 – 10^4 $M_\odot$
  SED: Blackbody at 50000 K.
  Luminosity : Schaerer (2004)

Types of “first sources”



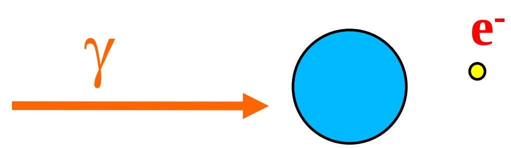
Stars



Power-law source

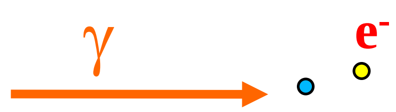
Why X-ray heats

UV photons



Large cross section but ejected electron has low energy

X-ray photons



Low cross section but ejected electron has high energy

RT-Equations

Thomas & Zaroubi, 2008, MNRAS

- Rate equations:

$$\frac{dn_i}{dt} = \Gamma(T) - \alpha(T)$$

$n_i \longrightarrow$ HII , HeII, HeIII

$\Gamma \longrightarrow$ Ionizations

$\alpha \longrightarrow$ Recombinations

- Temperature evolution:

$$\frac{dT}{dt} = H_{P} + H_{Ec} - C_{o\,c\,m} - C_{o\,Hpm} - C_{u\,pe\,b\,l} - C_{eb\,fc\,l}$$

Details : Fukugita & Kawasaki (1994)

Ionization

$$\frac{\mathrm{d}}{\mathrm{d}t}\left[\frac{n(\mathrm{H\,II})}{n_{\mathrm{H}}}\right] = \frac{R_{1c}\, n(\mathrm{H\,I})}{n_{\mathrm{H}}} - \frac{\alpha_{2,\mathrm{H\,II}}\, n_e^2}{n_{\mathrm{H}}}.$$

$$R_{2c} = \gamma_{2c} + \beta_{2,\mathrm{H\,I}}\, n_e + \int_{\varepsilon_{2,\mathrm{H\,I}}} c\,\sigma_{2f,\mathrm{H\,I}}\, n_\gamma(\varepsilon_\gamma)\,\mathrm{d}\varepsilon_\gamma,$$

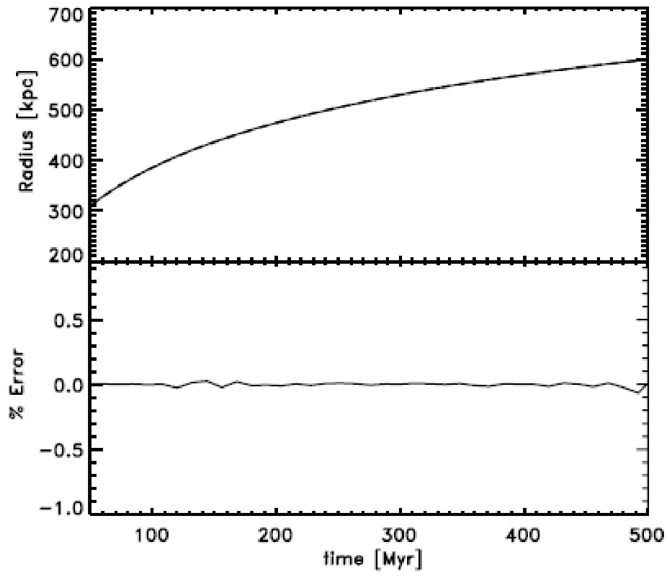
$$\frac{\mathrm{d}}{\mathrm{d}t}\left[\frac{n(\mathrm{He\,II})}{n_{\mathrm{He}}}\right] = \frac{n(\mathrm{He\,I})}{n_{\mathrm{He}}}\int_{\varepsilon_{\mathrm{He\,I}}} \mathrm{d}\varepsilon_\gamma\, \sigma_{\mathrm{bf,He\,I}}\, c\, n_\gamma(\varepsilon_\gamma)$$
$$+ \beta_{\mathrm{He\,I}}\, n_e \frac{n(\mathrm{He\,I})}{n_{\mathrm{He}}} - \beta_{\mathrm{He\,II}}\, n_e \frac{n(\mathrm{He\,II})}{n_{\mathrm{He}}}$$
$$- \alpha_{\mathrm{He\,II}}\, n_e \frac{n(\mathrm{He\,II})}{n_{\mathrm{He}}} + \alpha_{\mathrm{He\,III}}\, n_e \frac{n(\mathrm{He\,III})}{n_{\mathrm{He}}}$$
$$- \xi_{\mathrm{He\,II}}\, n_e \frac{n(\mathrm{He\,II})}{n_{\mathrm{He}}},$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\left[\frac{n(\mathrm{He\,III})}{n_{\mathrm{He}}}\right] = \frac{n(\mathrm{He\,II})}{n_{\mathrm{He}}}\int_{\varepsilon_{\mathrm{He\,II}}} \mathrm{d}\varepsilon_\gamma\, \sigma_{\mathrm{bf,He\,II}}\, c\, n_\gamma(\varepsilon_\gamma)$$
$$+ \beta_{\mathrm{He\,II}}\, n_e \frac{n(\mathrm{He\,II})}{n_{\mathrm{He}}} - \alpha_{\mathrm{He\,III}}\, n_e \frac{n(\mathrm{He\,III})}{n_{\mathrm{He}}},$$

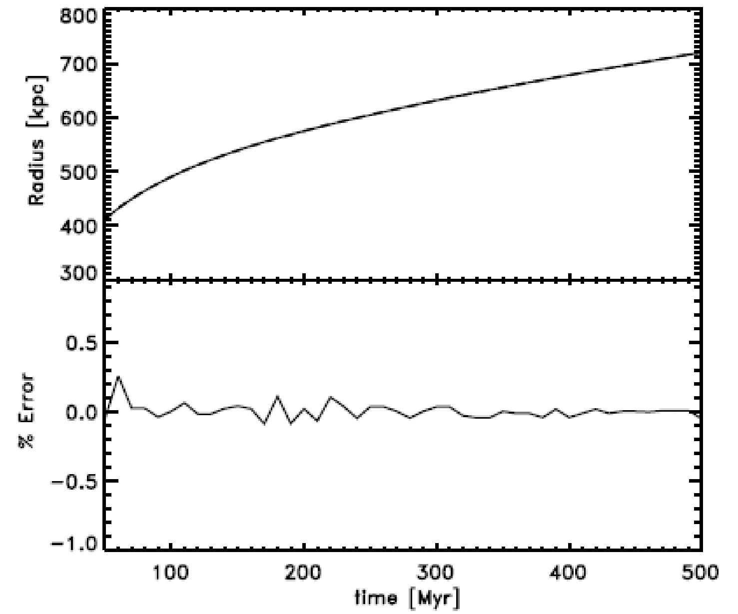
Temperature

$$\frac{3}{2}\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{kT_e n_B}{\mu}\right) = \sum_{i=\mathrm{H\,I,He\,I,He\,II}} n(i)\, c \int (\varepsilon_\gamma - \varepsilon_i)\, n_\gamma\, \sigma_{\mathrm{bf},i}\, \mathrm{d}\varepsilon_\gamma$$
$$- \sum_{i=\mathrm{H\,I,He\,I,He\,II}} \zeta_i\, n_e\, n(i)$$
$$- \sum_{i=\mathrm{H\,II,He\,II,He\,III}} \eta_i\, n_e\, n(i)$$
$$- \omega_{\mathrm{He\,II}}\, n_e\, n(\mathrm{He\,III})$$
$$- \sum_{i=\mathrm{H\,I,He\,I,He\,II}} \psi_i\, n_e\, n(i)$$
$$- \lambda_c$$
$$- \theta_{\mathrm{ff}}[n(\mathrm{H\,II}) + n(\mathrm{He\,II}) + 4n(\mathrm{He\,III})]\, n_e$$
$$- \frac{15}{2}\frac{\dot{a}}{a}\left(\frac{kT_e n_B}{\mu}\right),$$

Benchmarking RT CODE

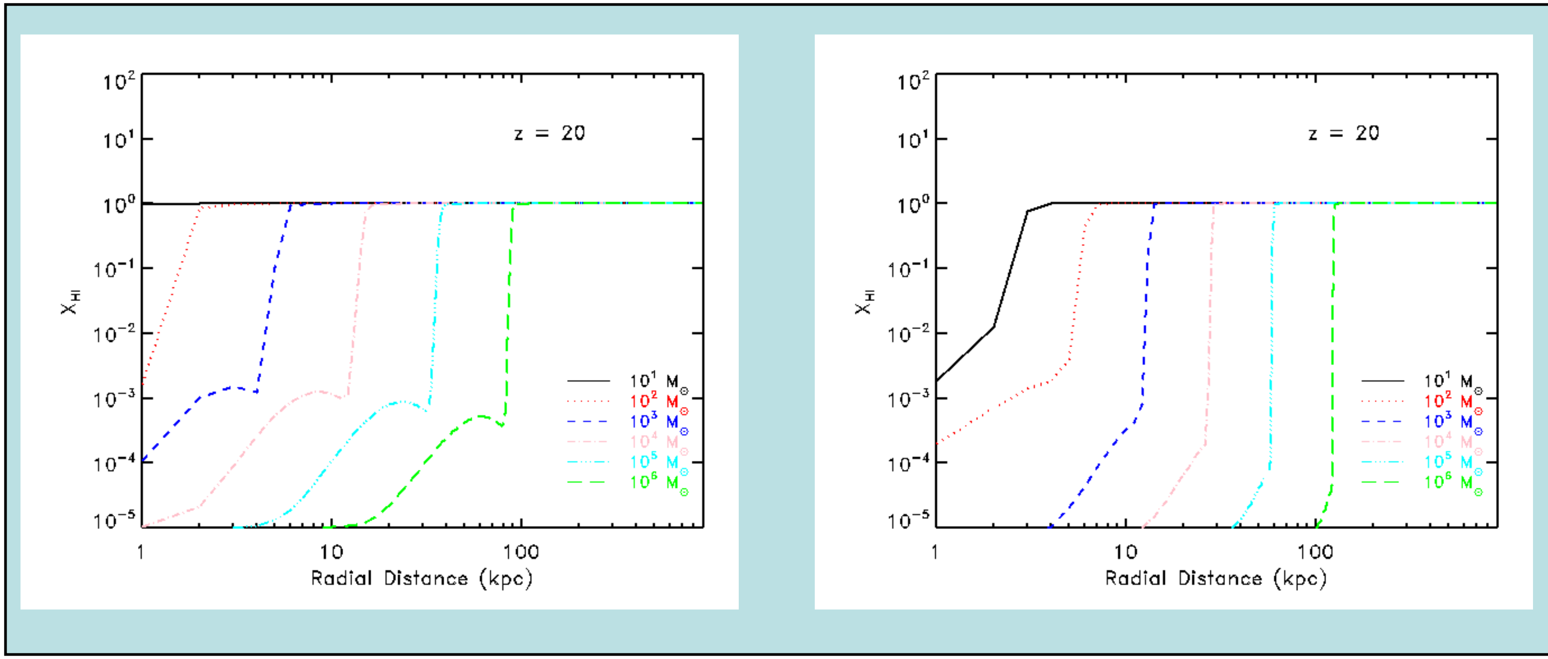


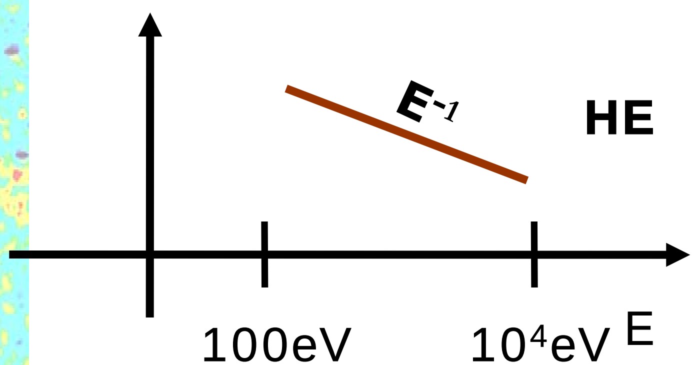
Stromgen sphere

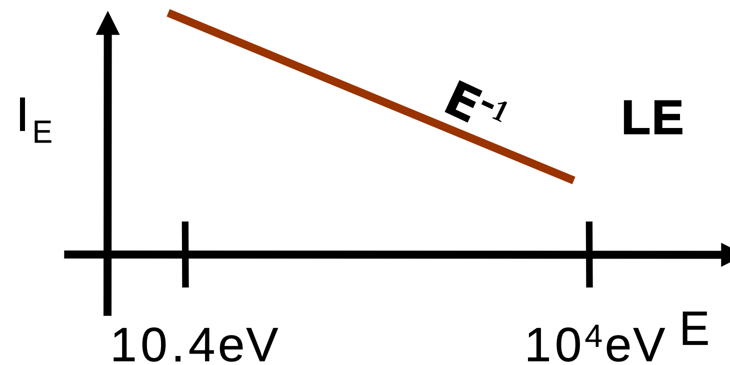


Shapiro & Giroux: expanding Universe

Miniqso: Ionization







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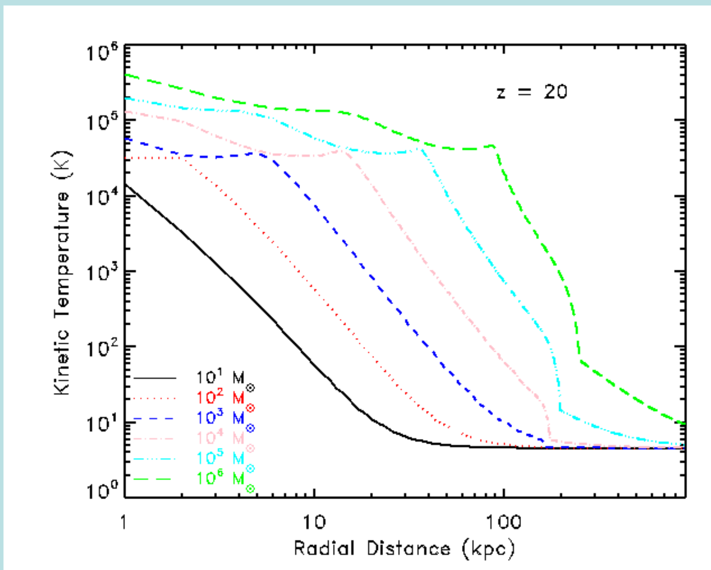
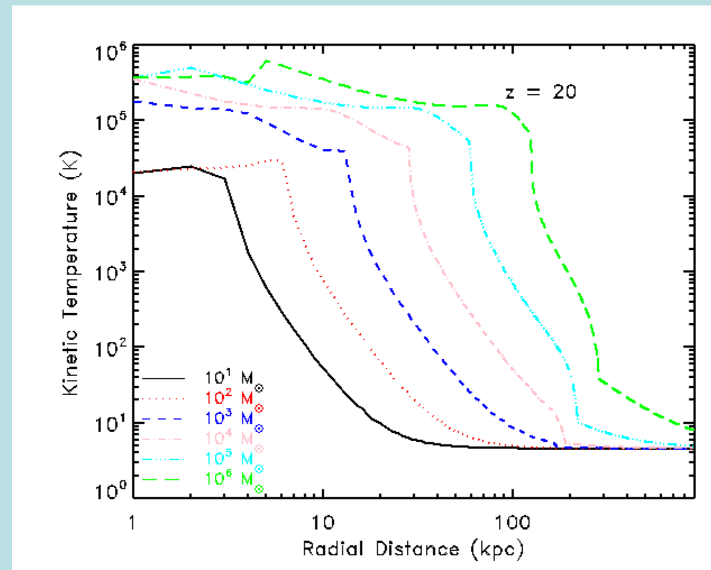
Miniqso: Heating



E_{low} = 200eV



E_{low} = 10.4eV

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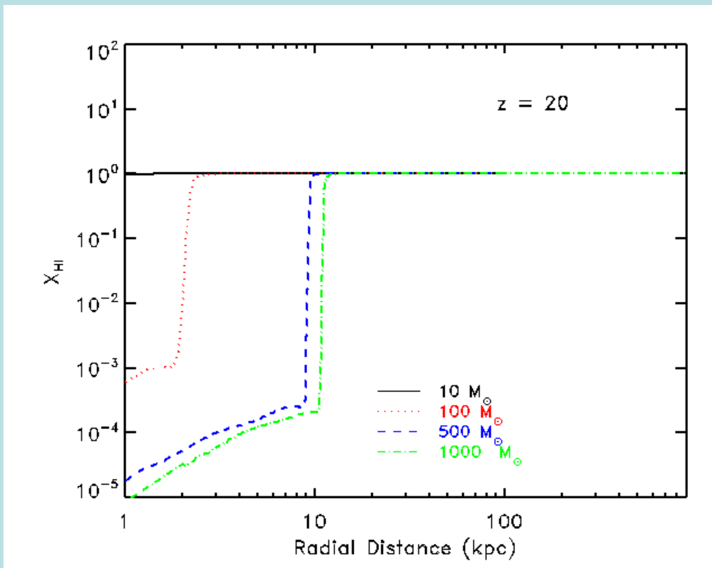
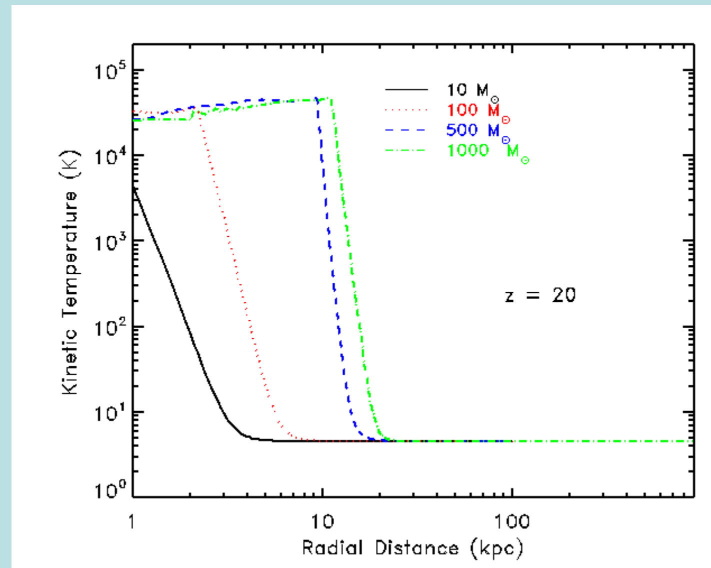
Stars

Ionization



Heating



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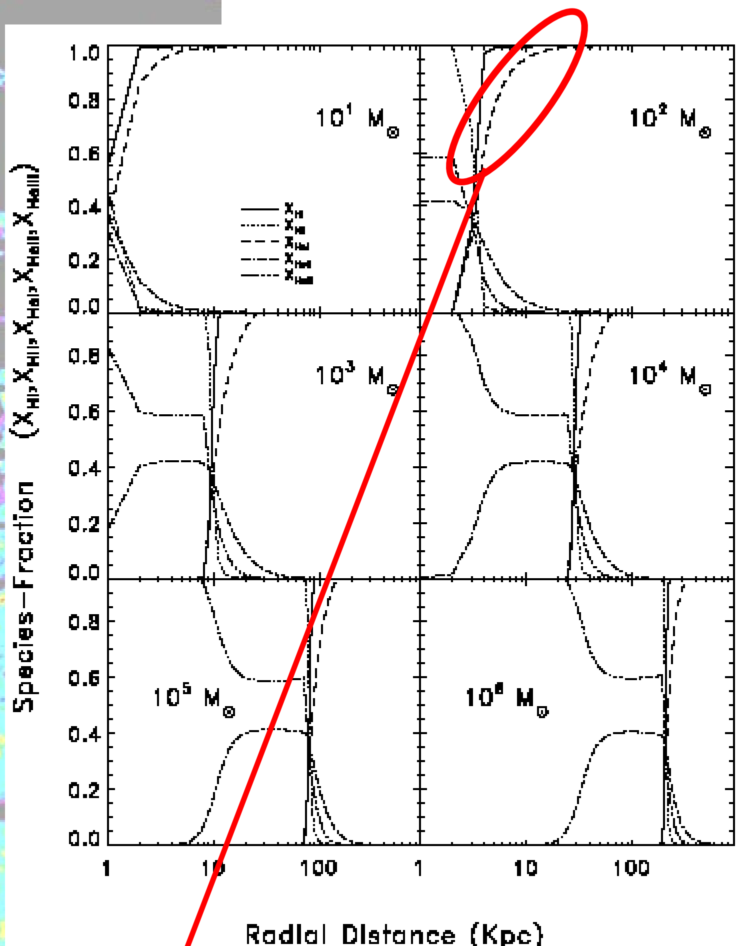
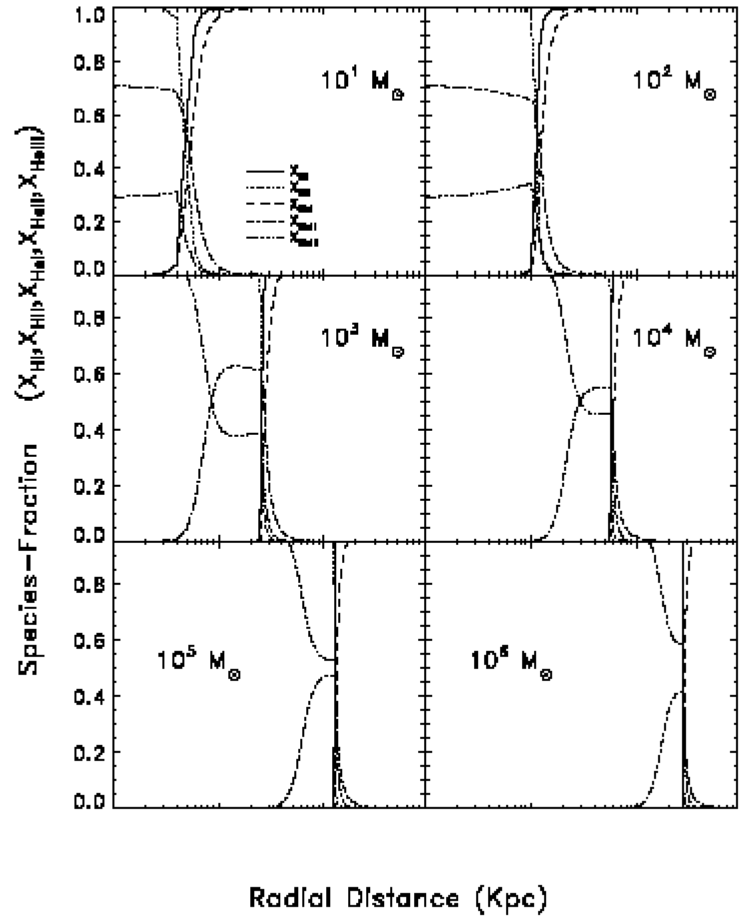
Interesting….

Quasars: ionization

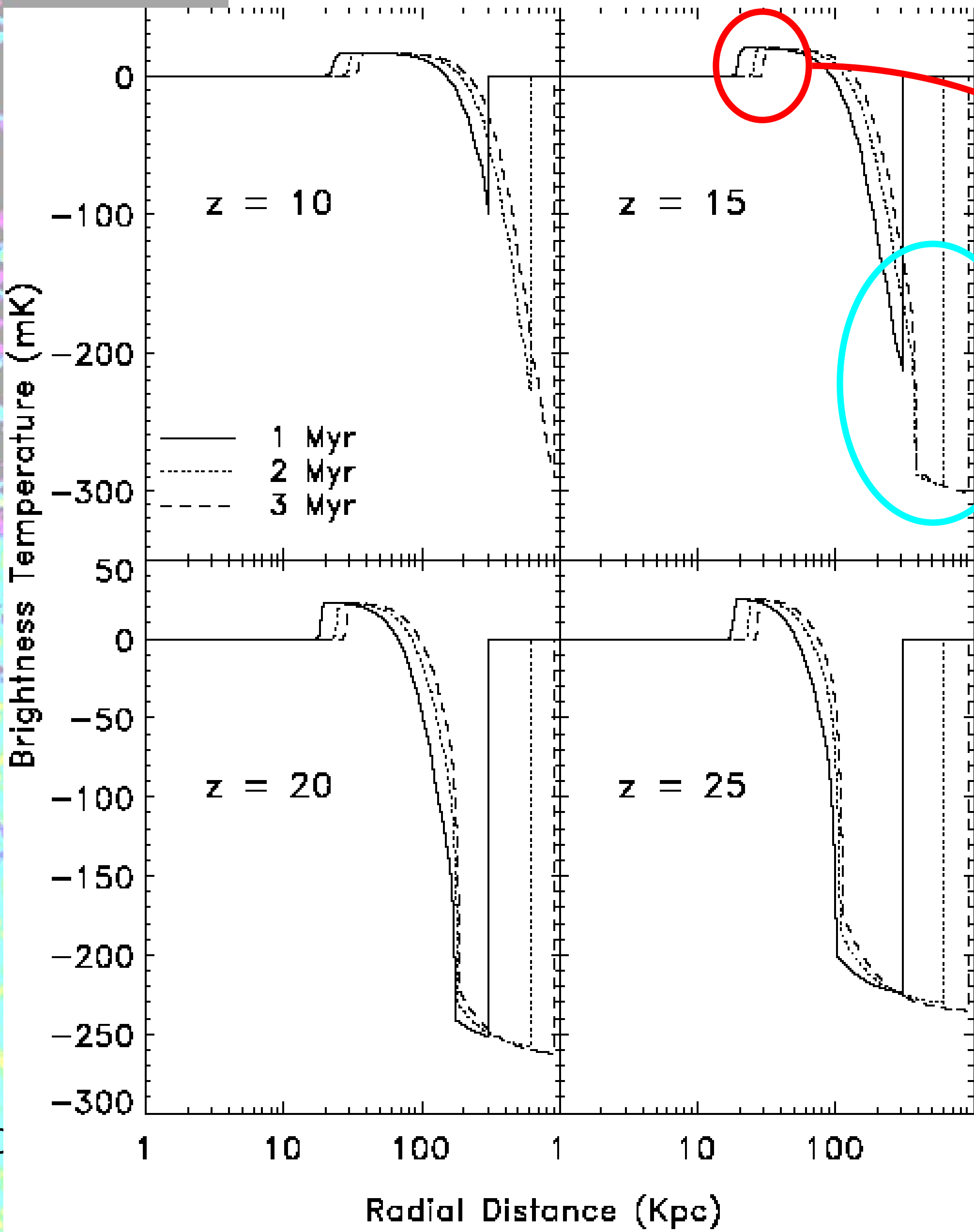




He front

HE Thomas & Zaroubi, in prep **LE**

First sources & their signatures : ***Brightness Temperature***



~20 to 30 mK (emission)

~-250 to -350 mK (absorption)

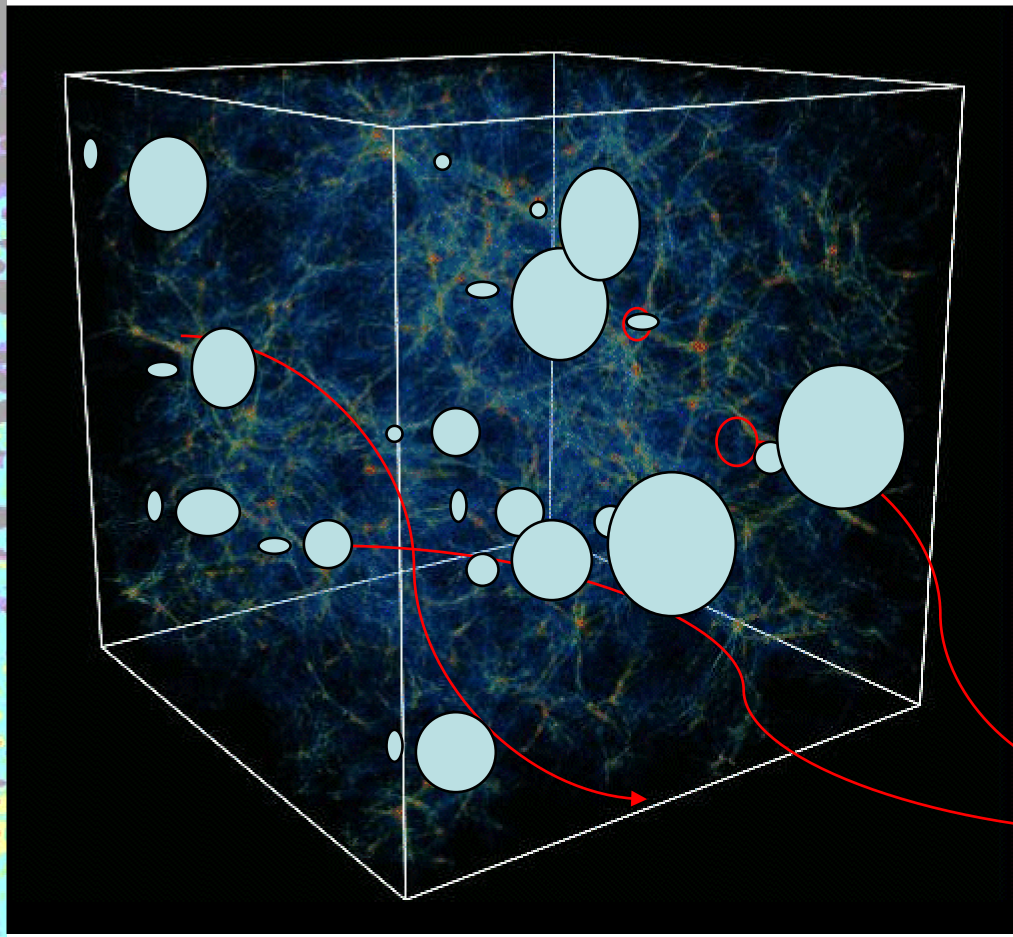
Uncertainties encountered

- Energy spectrum
- Span of energies
- Lyα coupling issues
- Cluster properties
- Redshift of turn-ON
- Spectral indices…

Simulate as many scenarios as possible

Pseudo 3D –RT

Thomas et al., 2008, MNRAS



BEARS -

Bubble

Expansion

Around

Radiative

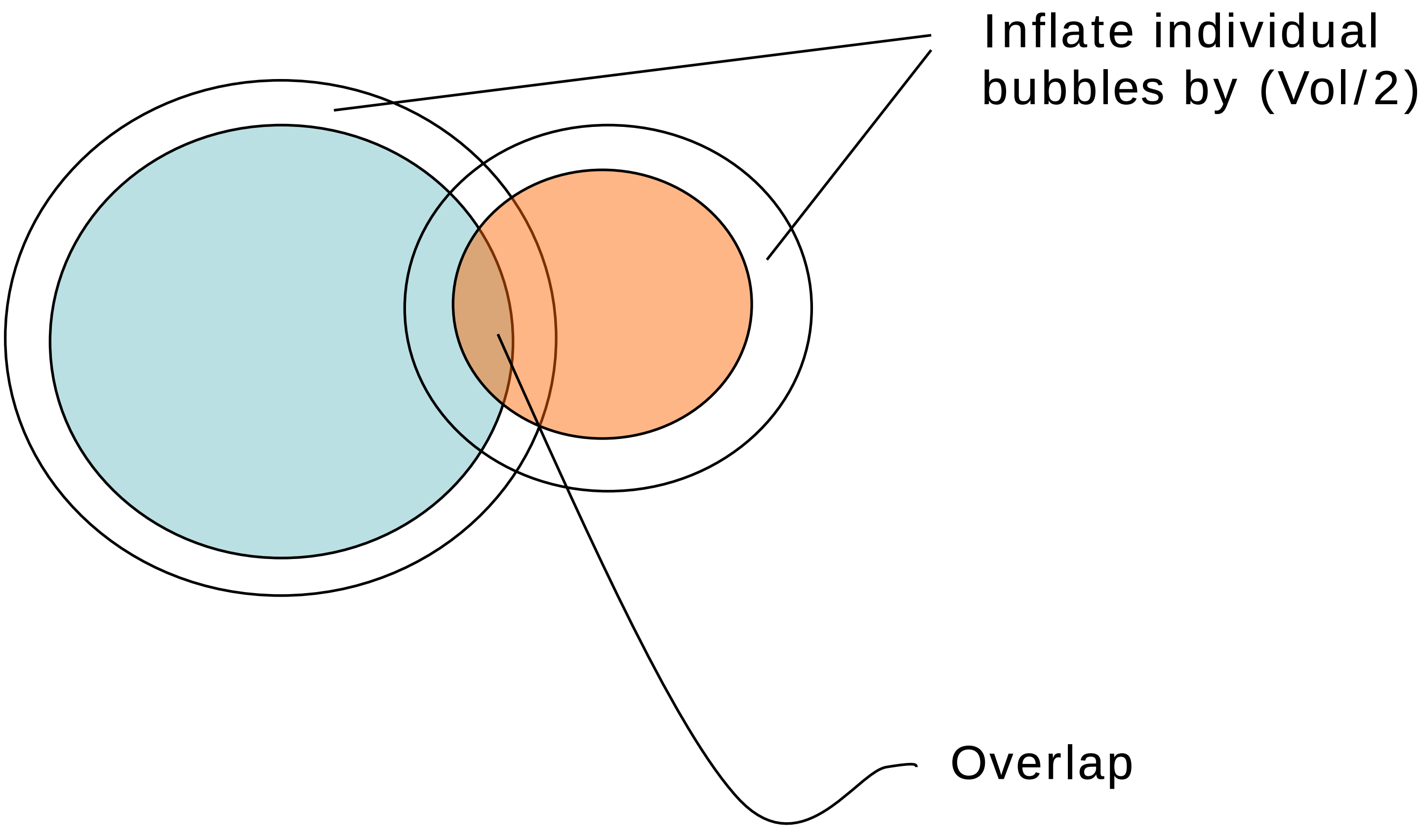
Sources

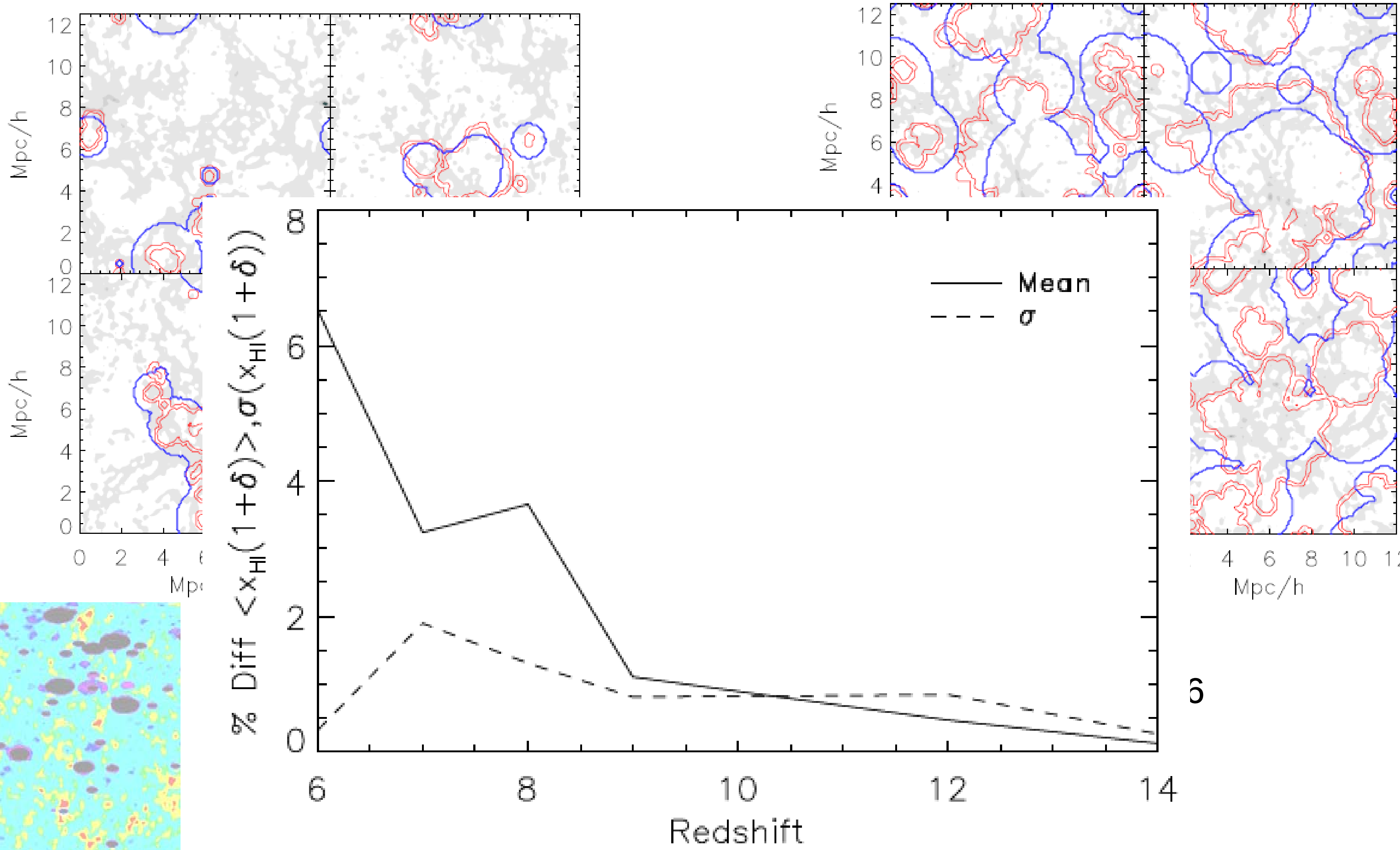
Identify the haloes

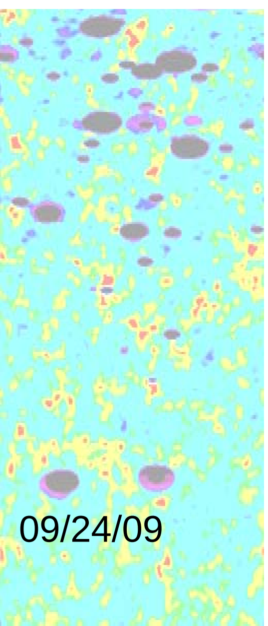
Why should this approach work?

- 6<z<12 : The Universe is still considerably homogeneous and isotropic even at small scales.
- Overdensity around the source is corrected for.

Correction for overlap: Photon conservation







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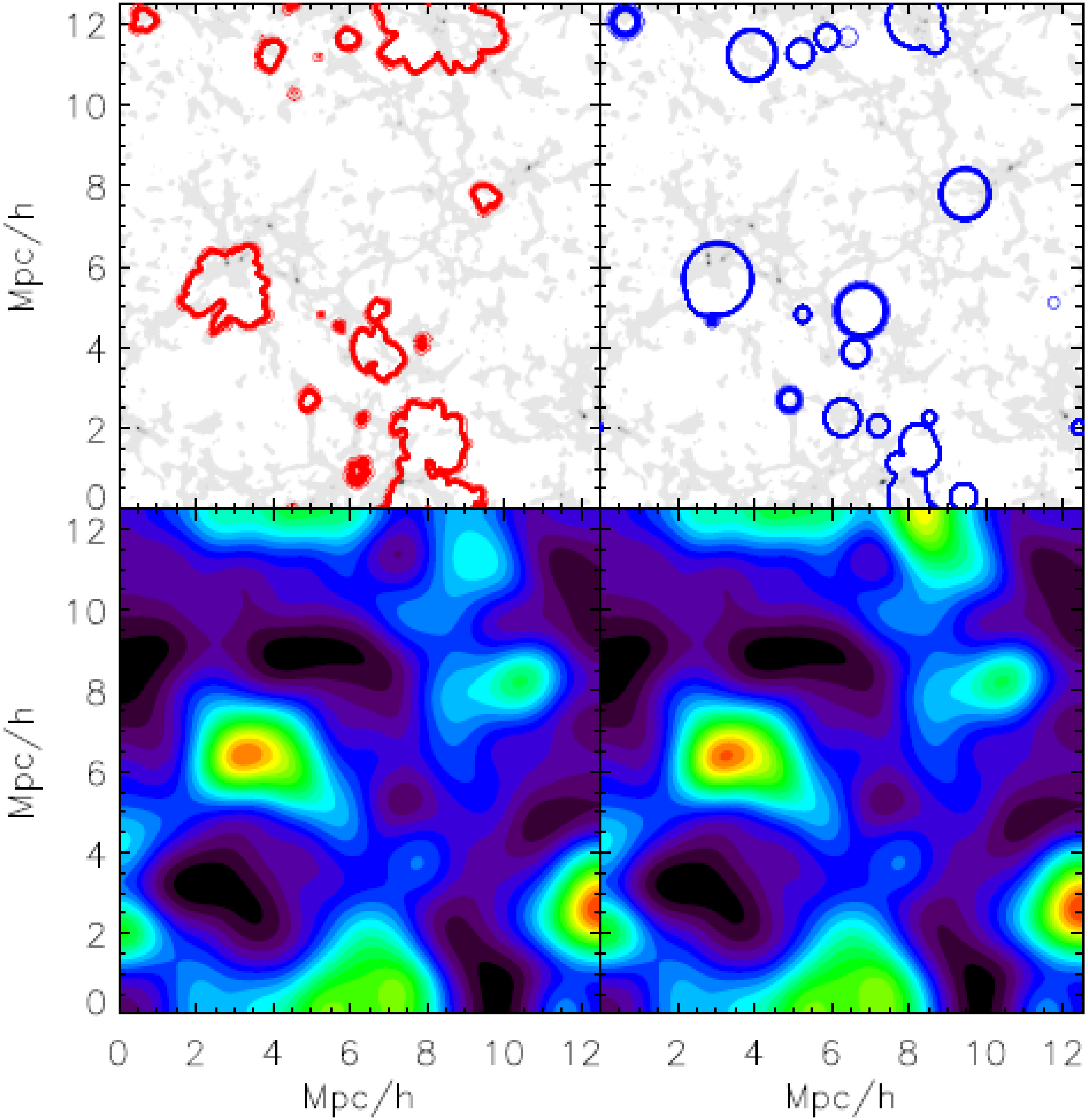
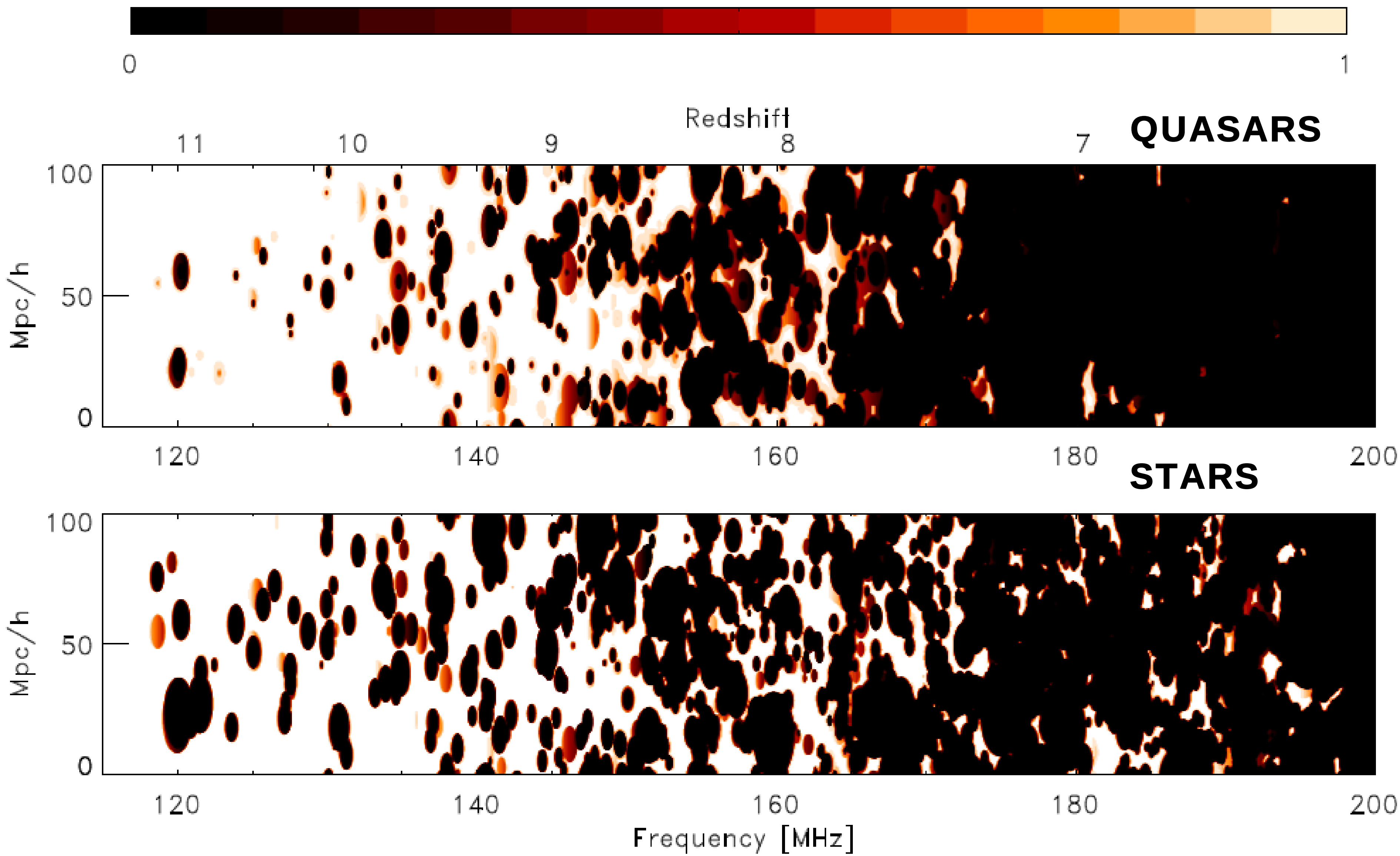


Mpc/h
Mpc/h
Mpc/h
Mpc/h
0 2 4 6 8 10 12



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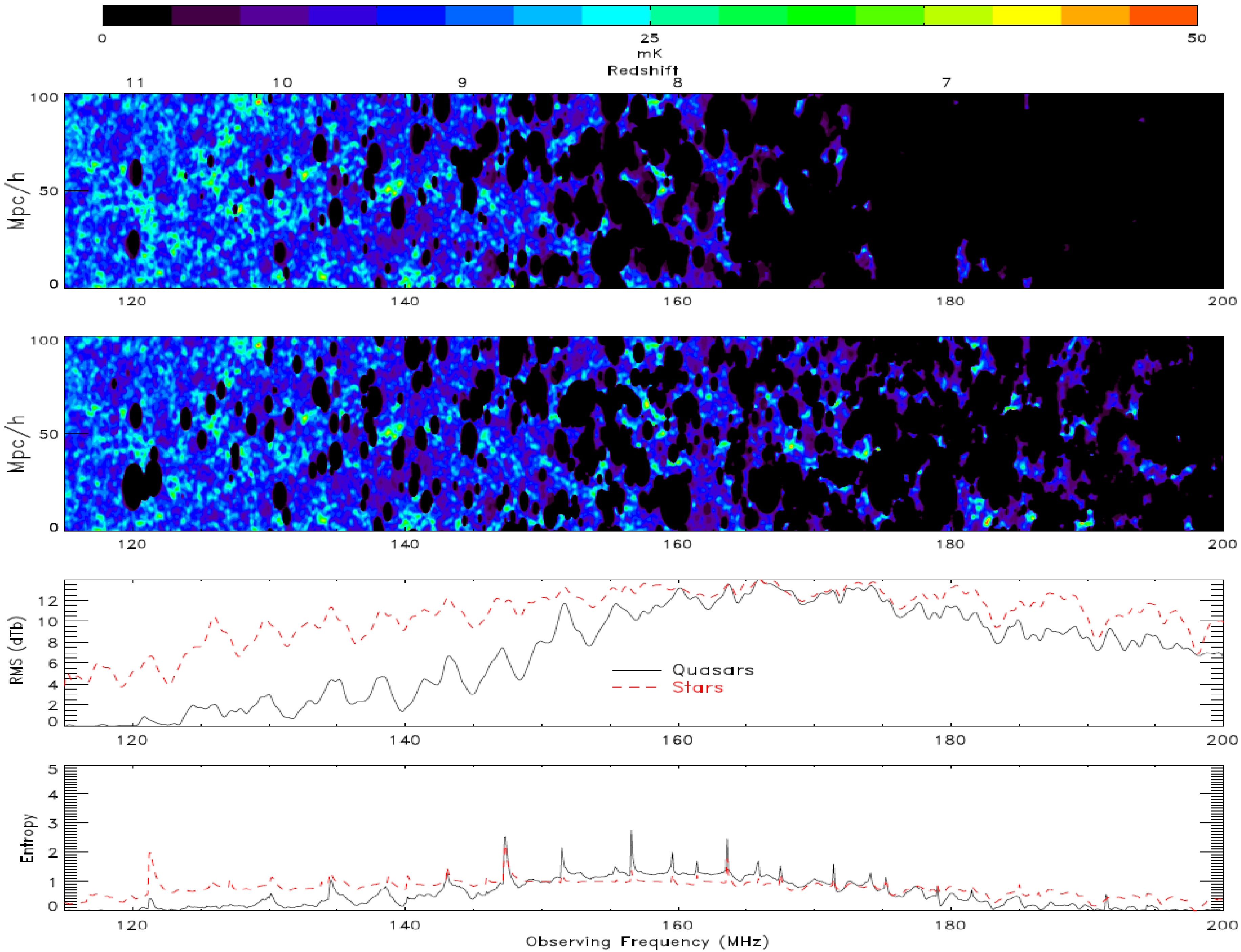
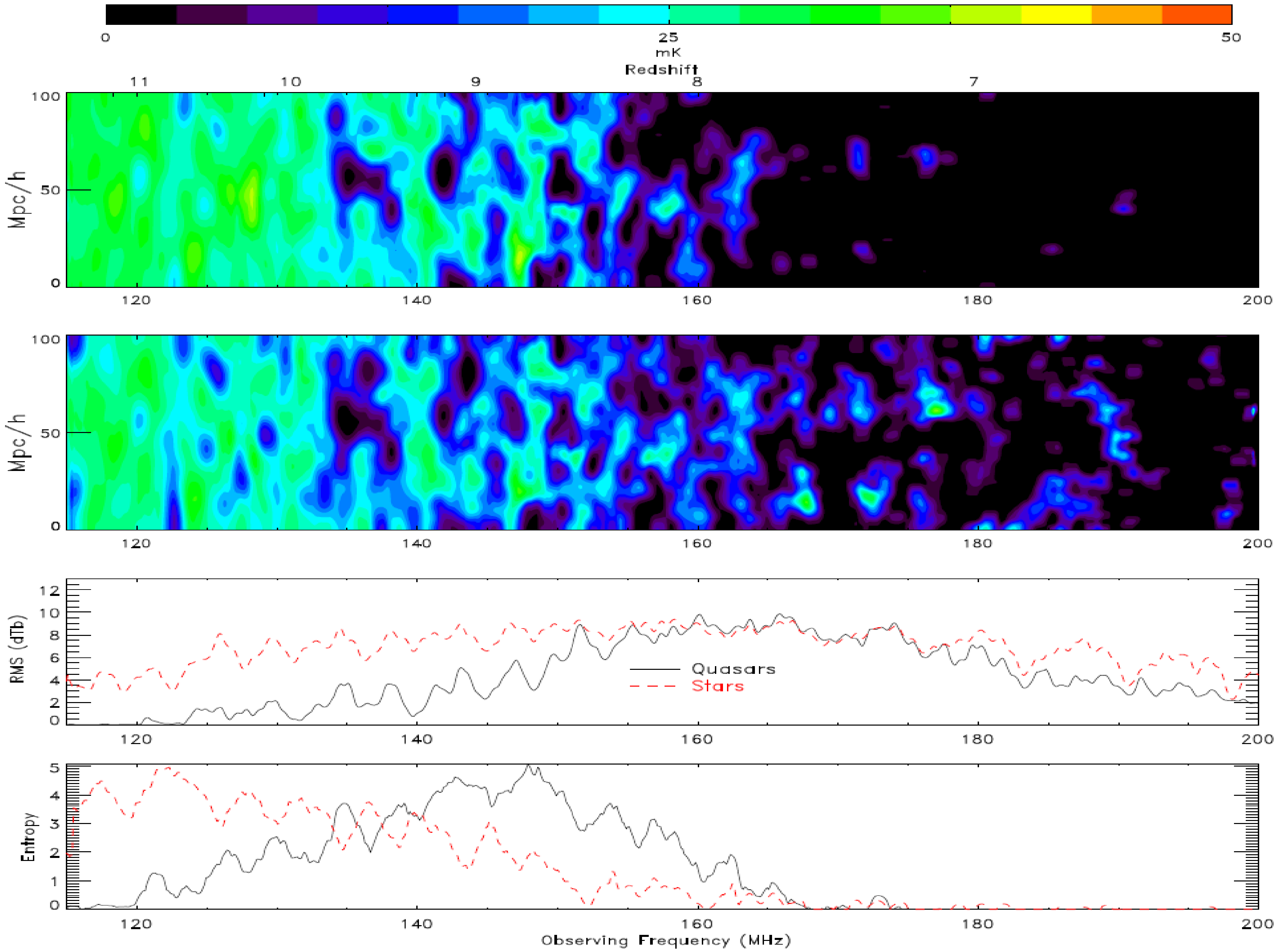


0
25
50
mK
Redshift
11
10
9
8
7
100
50
0
Mpc/h
120
140
160
180
200
RMS (dTb)
Quasars
Stars
Entropy
Observing Frequency (MHz)



0
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100
50
0
120
140
160
180
200
RMS (dTb)
Quasars
Stars
Entropy
Observing Frequency (MHz)

Inclusion of temperature

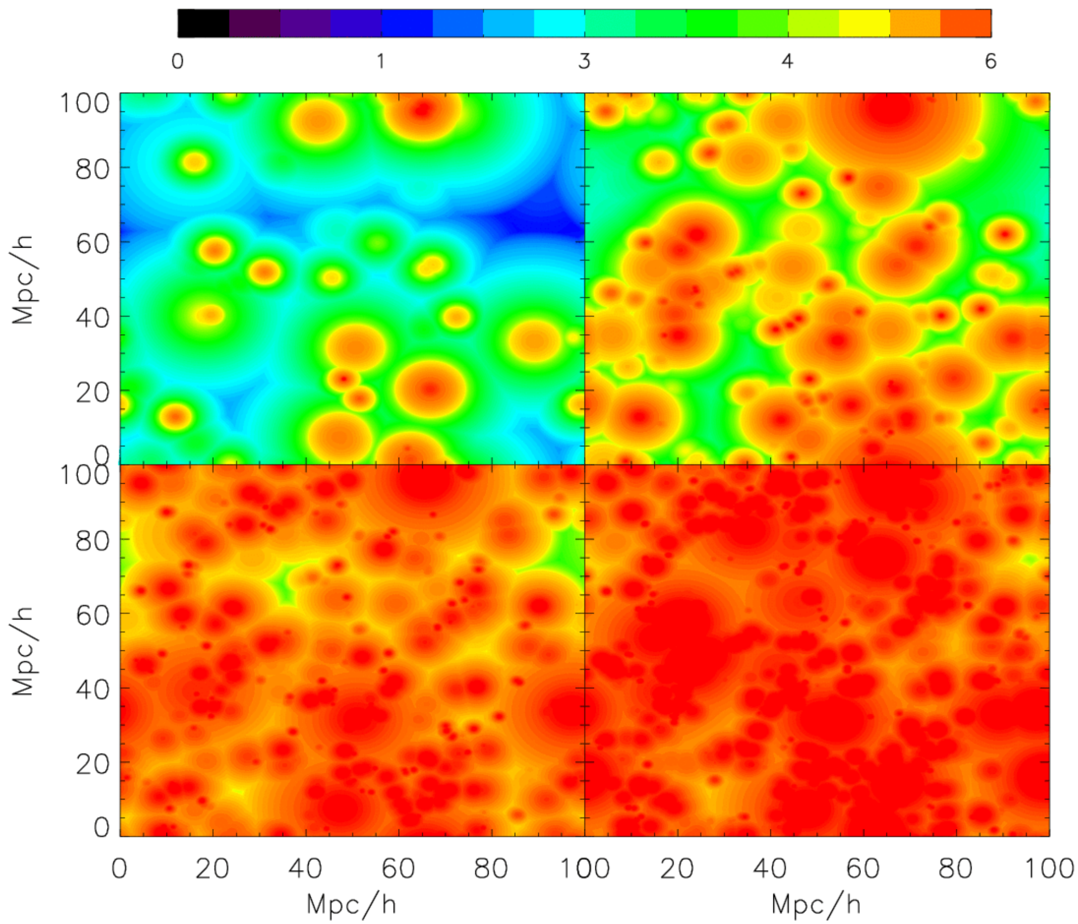
- Previously the spin temperature was assumed to decoupled from the CMB.

$$\delta T_b = (20\,\mathrm{mK})\,(1+\delta)\left(\frac{X_{HI}}{h}\right)\left(1-\frac{T_{CMB}}{T_{spin}}\right)\left(\frac{\Omega_b h^2}{0.0223}\right)\left[\left(\frac{1+z}{10}\right)\left(\frac{0.24}{\Omega_m}\right)\right]^{1/2}$$

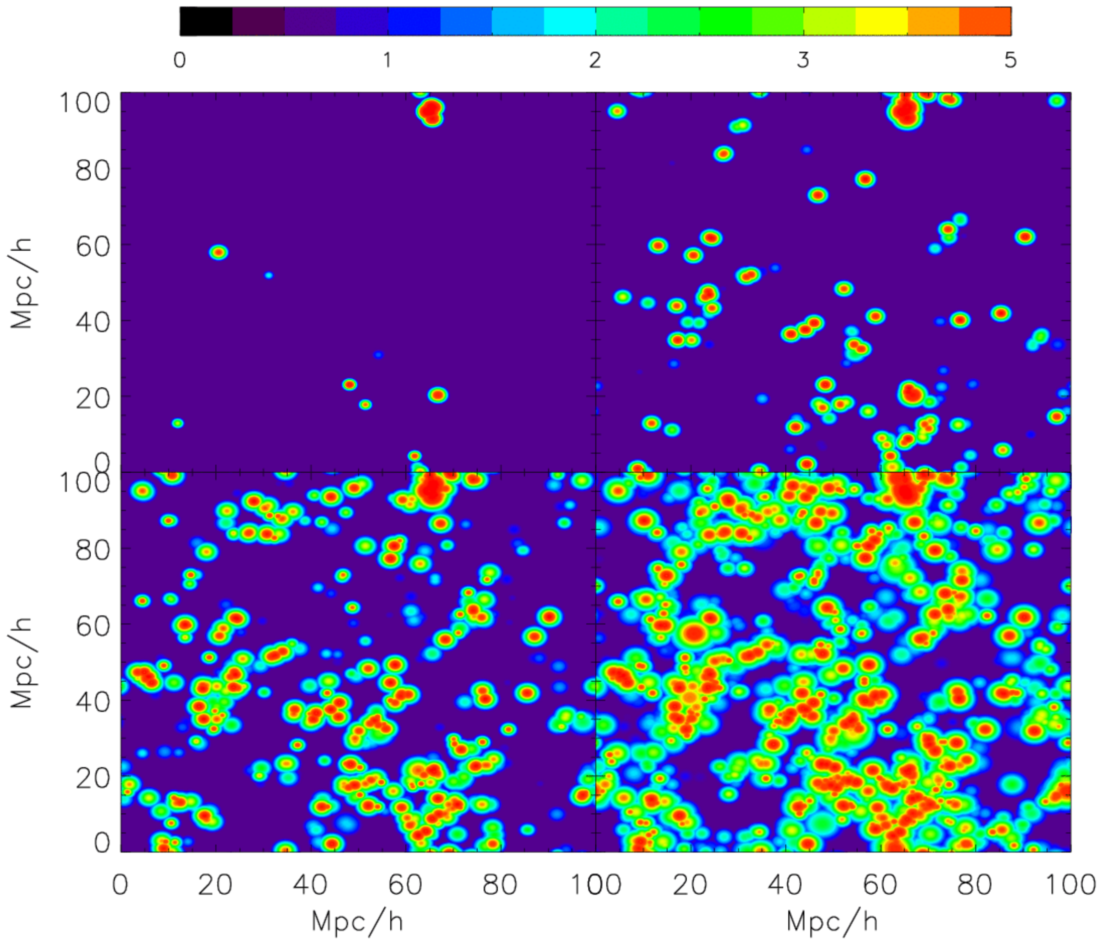
- The IGM in the Universe can be heated very differently depending on the sources.

- Therefore we need a self-consistent manner of including the temperature.

Quasars: Temperature



Stars: Temperature



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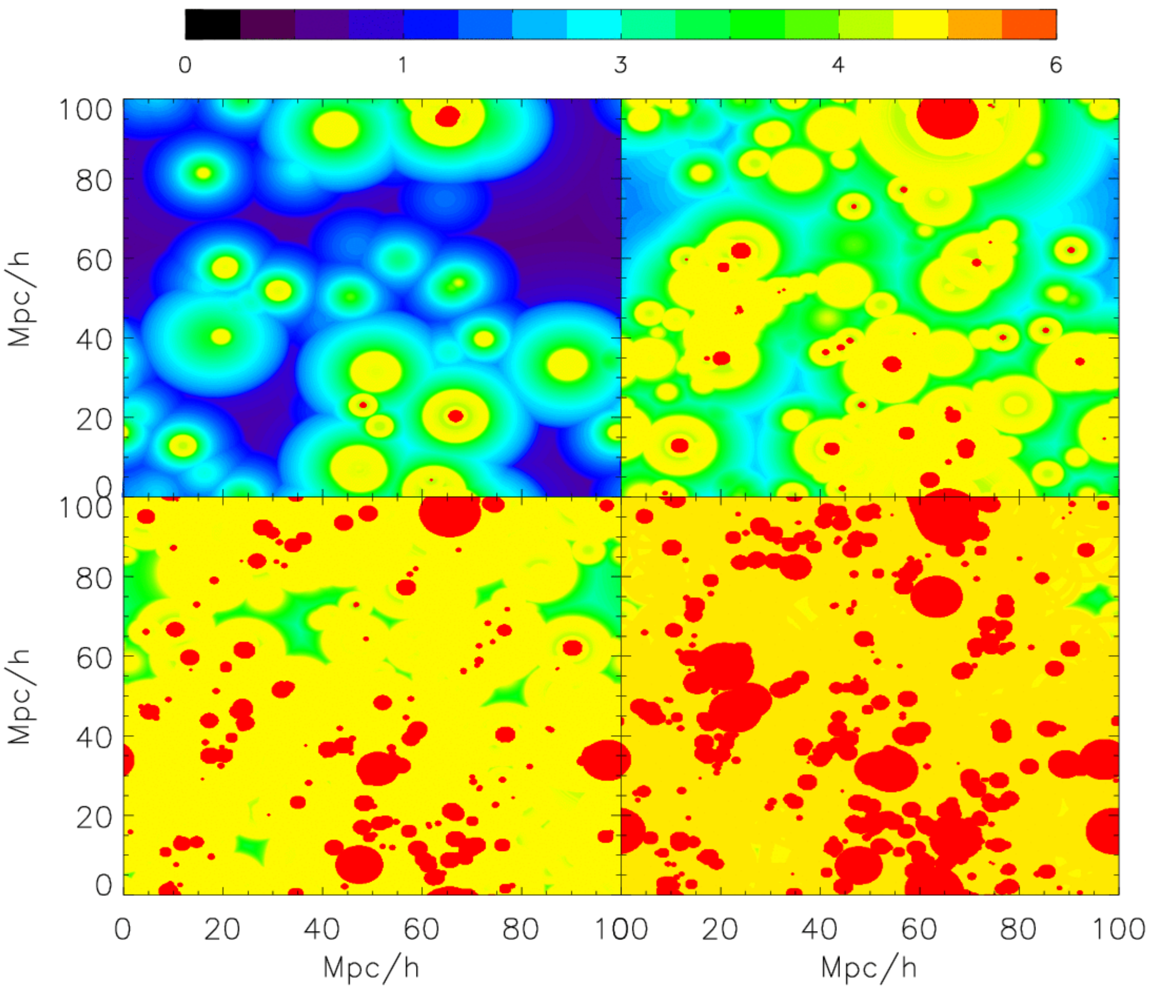
Combi : Temperature



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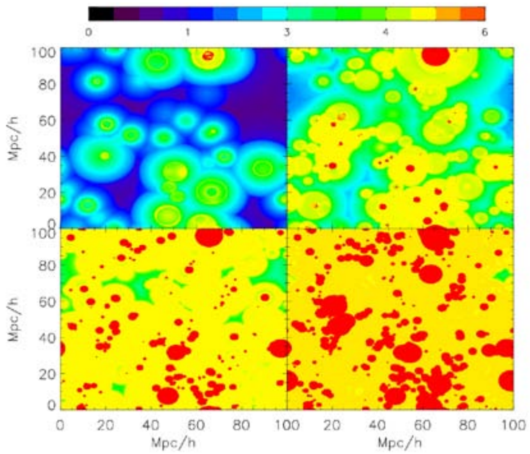
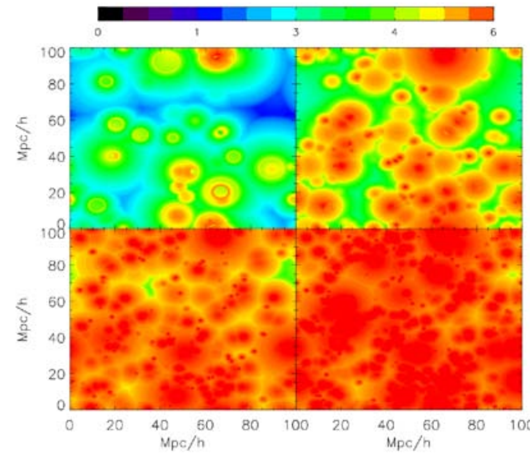
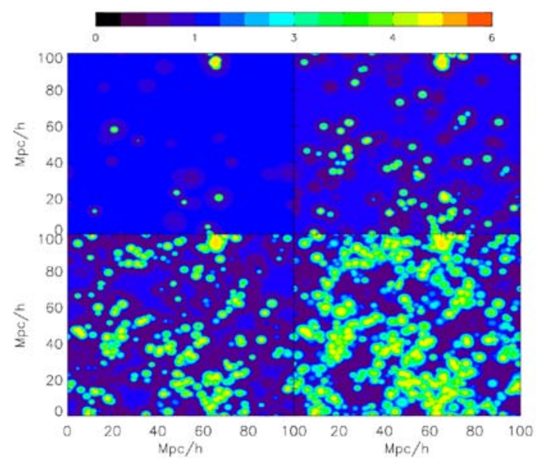
Spin Temperatures



Combi

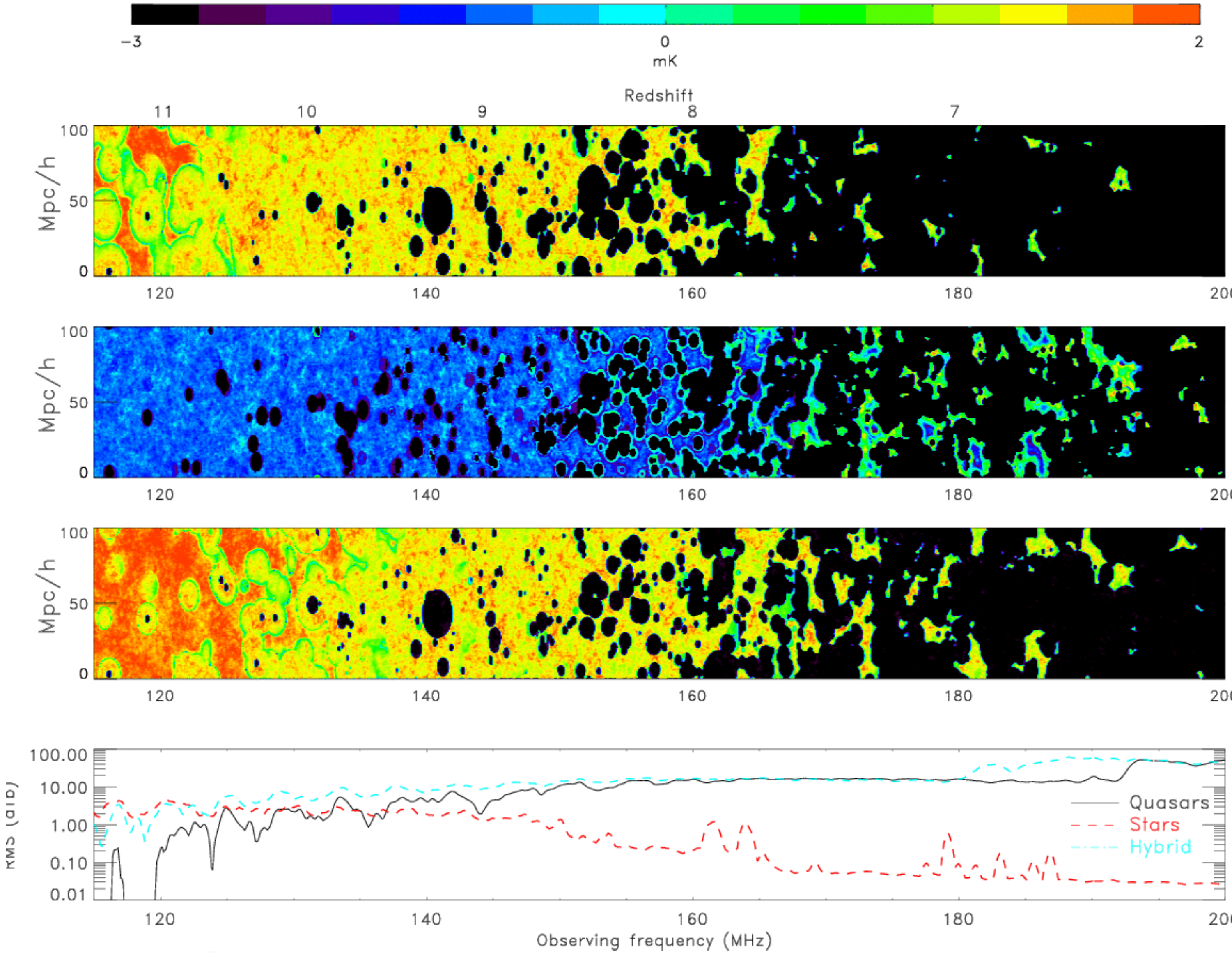


Qsos



Stars

EoR Histories - I



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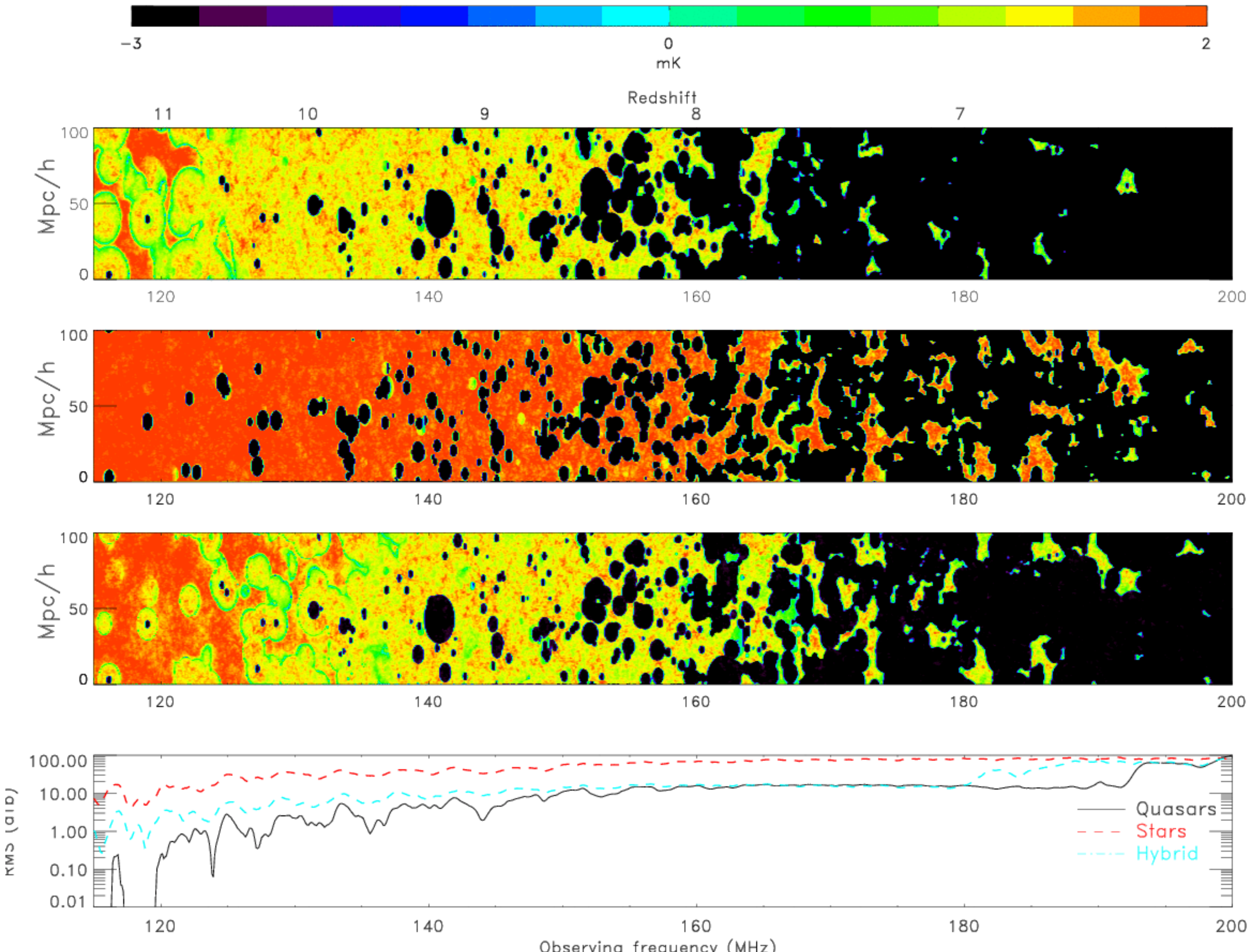
EoR Histories - II



To summarize

- Soft X-ray background is not a very strict constrain.
- Influence of Qsos on heating the IGM is significant.
- Various SEDs manifests themselves differently in the ionization and heating profiles around them. (a 1-D CODE will suffice to study these properties)
- We need to span a very large parameter space to get begin to get an idea of the numerous plausible reionization signals.
- BEARS is a good approximation to perform radiative transfer at high redshifts
- Tracking the temperature (spin) evolution self-consistently does make a lot of difference.

Looking forward…

- LOFAR field: 5º X 5º … translates to about 1 Gpc-comoving at EoR redshifts which will allow the measurement of:
  - Matter power spectrum at large z
  - Sources of ionization and heating
  - The speed at which ionization occurs
  - Influence of reionization on galaxy formation at later stages.
- Cross-correlations studies…. not good to patch-up smaller boxes.
- Thinking of newer ways to accomplish larger boxes and better resolutions.

Thank you!

&

Stay tuned ....
First fringes from LOFAR CORE in 2009