Cosmology from the high redshift 21cm line
or
Fast Large Volume Simulations of the 21cm signal from the Reionization and pre-Reionization Epochs

arXiv:0911.2219v1

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IBERICOS 2010

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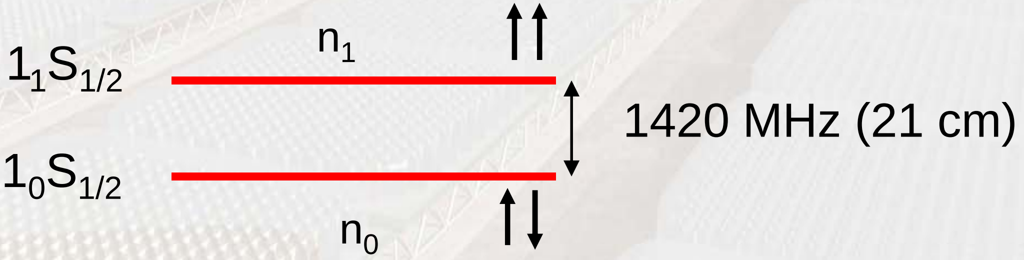
21cm radiation

- Measurements of neutral fraction are required at a range of redshifts and along many lines-of sight => 21cm tomography.
- Hyperfine transition (electron/proton spin in hydrogen atom):



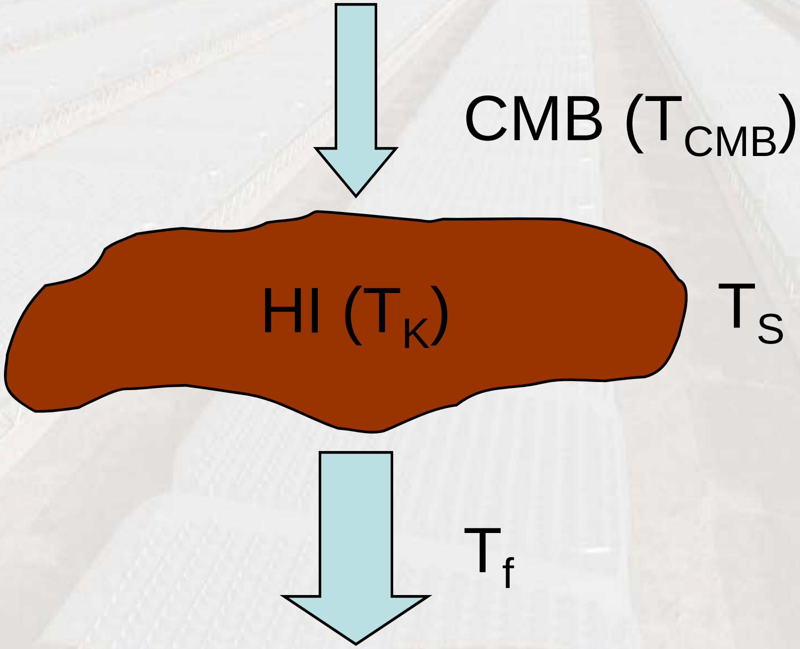
1) Directly probes neutral hydrogen
2) Hydrogen – 75% baryonic mass in the Universe
1) Provide redshift information
2) No need for bright background sources

excitation temperature of 21 cm transition $\equiv$ spin temperature T_S:

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-h\nu_{21}/kT_S}$$

Effect on CMB

- Intensity of CMB radiation will increase or decrease depending on temperature of the source



CMB (T_{CMB})

HI (T_K)

T_S

T_f

Radiative transfer:

$$T_f = T_{CMB}\, e^{-\tau_{21}} + T_S(1 - e^{-\tau_{21}})$$

Brightness temperature

As seen from Earth - $T_b(\nu) = (T_f - T_{CMB}(z)/(1+z)$:

$$T_b(\nu) \sim 27(1+\delta_b)x_{HI}\left(1-\frac{1+z}{H(z)}\frac{\partial v}{\partial r}\right)\left(\frac{T_S-T_{CMB}}{T_S}\right)\left(\frac{1+z}{10}\right)^{1/2}\ (\mathrm{mK})$$

??

- 3D mapping of HI possible - angles + frequency
- δ_b – baryon density perturbation
- $\partial v/\partial r$ – peculiar velocity gradient (gravitational Potential – CDM)

"Cosmological"

- $_{\mathrm{xHI}}$ – neutral fraction
- T_S – spin temperature

"Astrophysical"

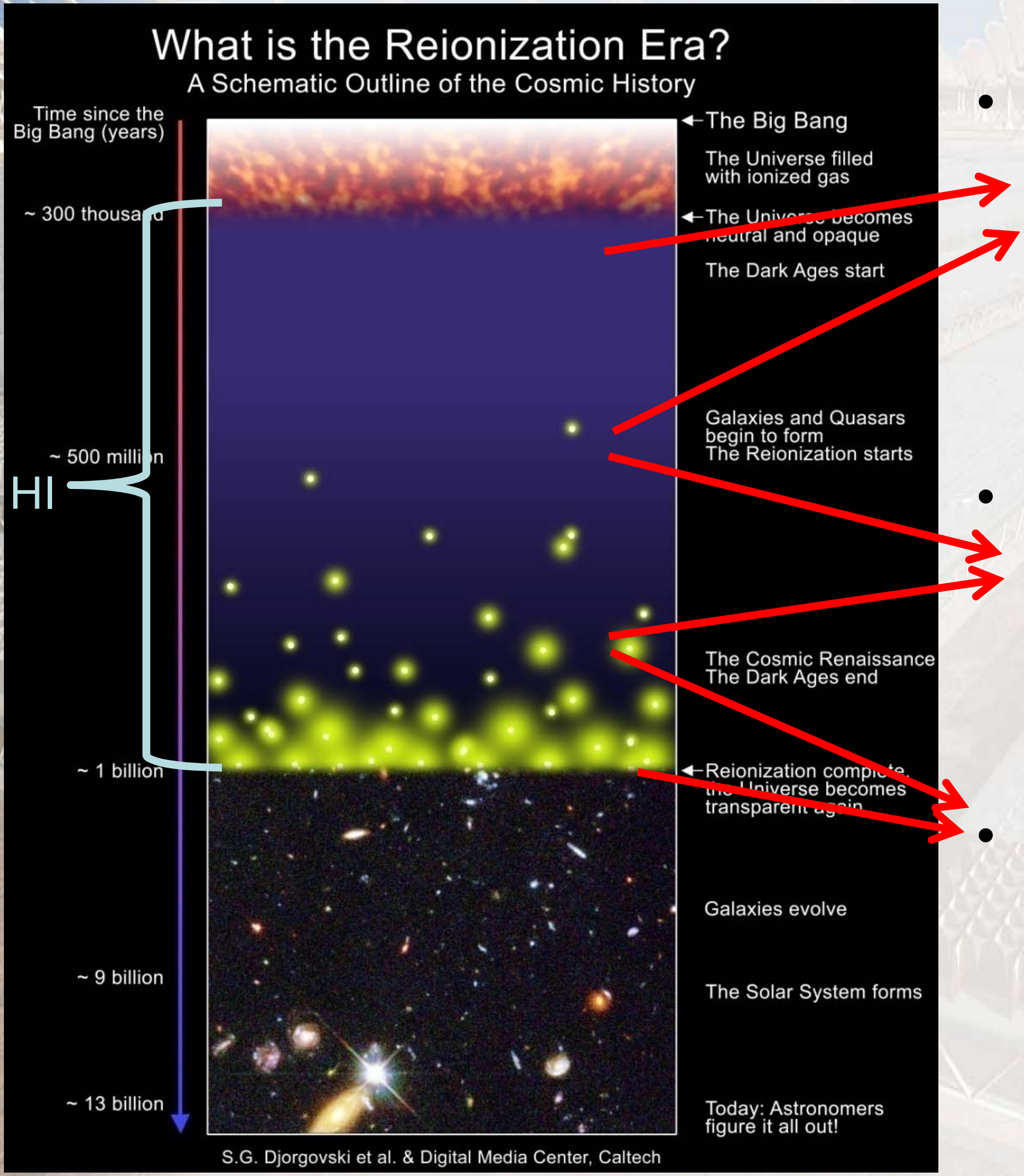
Spin Temperature

$$T_S^{-1} = \frac{T_{CMB}^{-1} + (x_\alpha + x_c)T_K^{-1}}{1 + x_\alpha + x_c}$$

- Already assuming Lyα color temperature = T_K
- Coupling mechanisms:
  - Radiative transitions (CMB)
  - Collisions (x_c)
  - Wouthuysen-Field effect (x_α) – $x_\alpha \propto J_\alpha$ (Lyα flux)
- Brightness temperature non-zero when $T_K \neq T_{CMB}$ and $x_\alpha + x_c > 0$ (coupling saturates when >> 1)

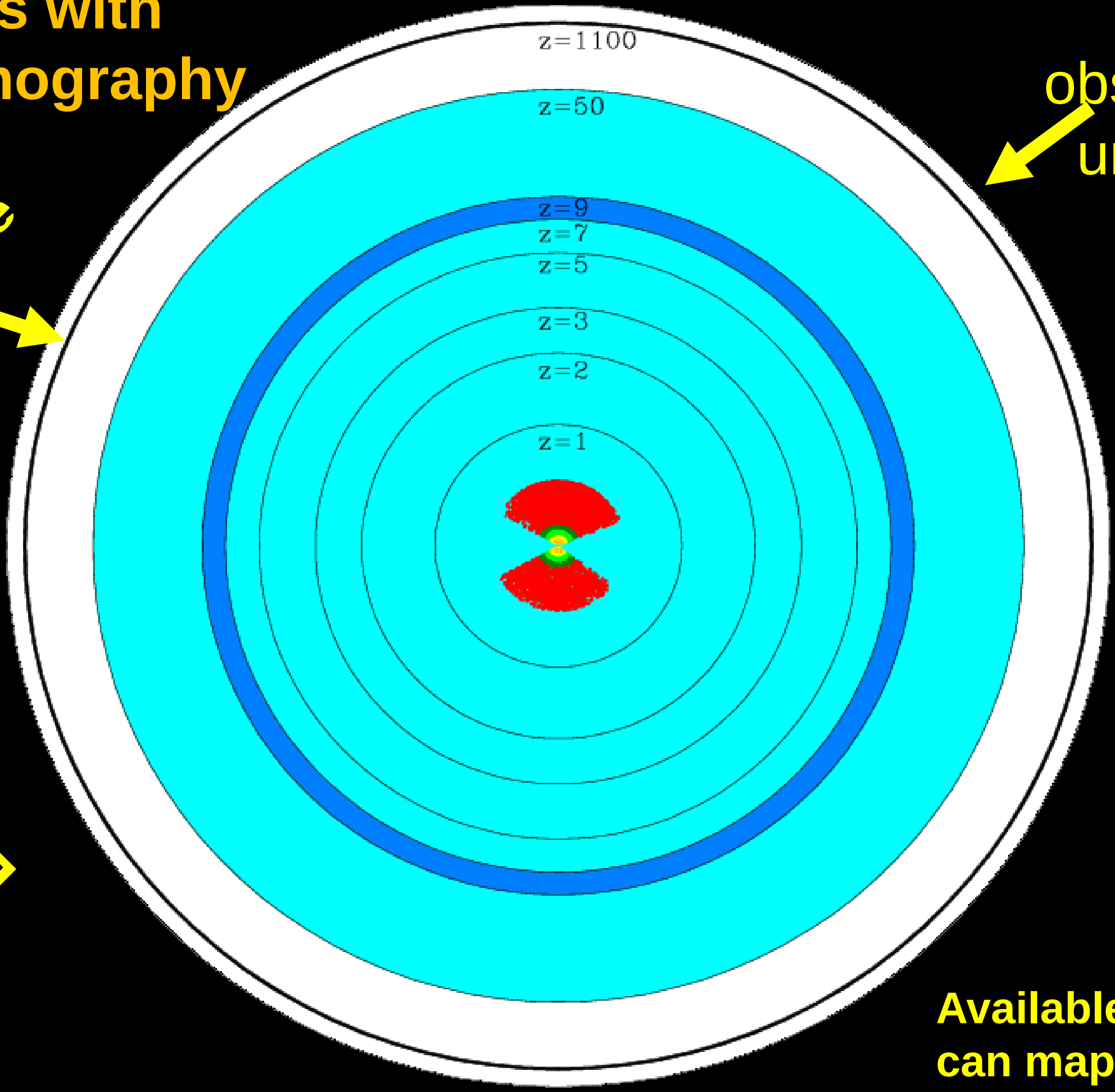
$$T_b \propto \frac{T_S - T_{CMB}}{T_S}$$

Cosmological evolution



- The dark ages ($30 \lesssim z \lesssim 150$ – $46\ \text{MHz} < \nu < 9\ \text{MHz}$):
  - simple physics
  - Great for Cosmology! (matter power spectrum)
- Twilight ($12 \lesssim z \lesssim 30$ – $46\ \text{MHz} < \nu < 118\ \text{MHz}$)
  - first galaxies
  - “astrophysics begins”
- Reionization ($6 \lesssim z \lesssim 12$ – $118\ \text{MHz} < \nu < 203\ \text{MHz}$)
  - IGM becomes transparent to UV light

Physics with 21cm tomography



Our observable universe

Last scattering surface

Red - SDSS

Available space in blue – can map most of our Observable Universe!

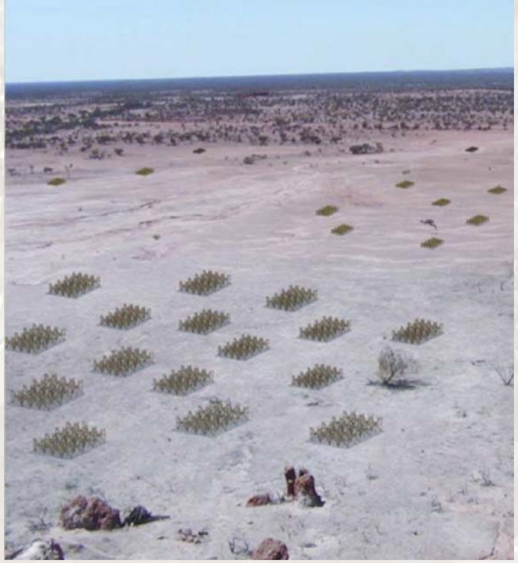
Mao et al, PRD 2008

How to measure the signal?

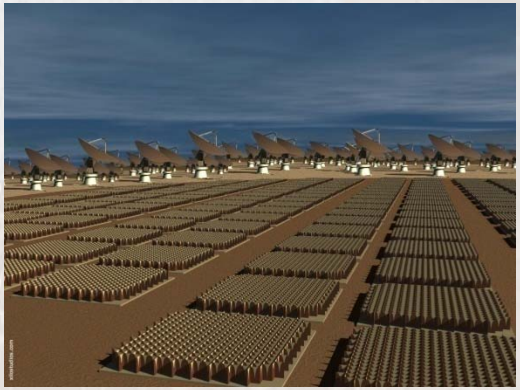
- Signal at 1420MHz redshifts to 60MHz-200MHz
- With resolution ~ 2’, telescope size must be $\sim$ 2 Km → Need radio interferometers

LOFAR: Netherlands
Freq: 120-240 MHz
Baselines: 50m-
100km

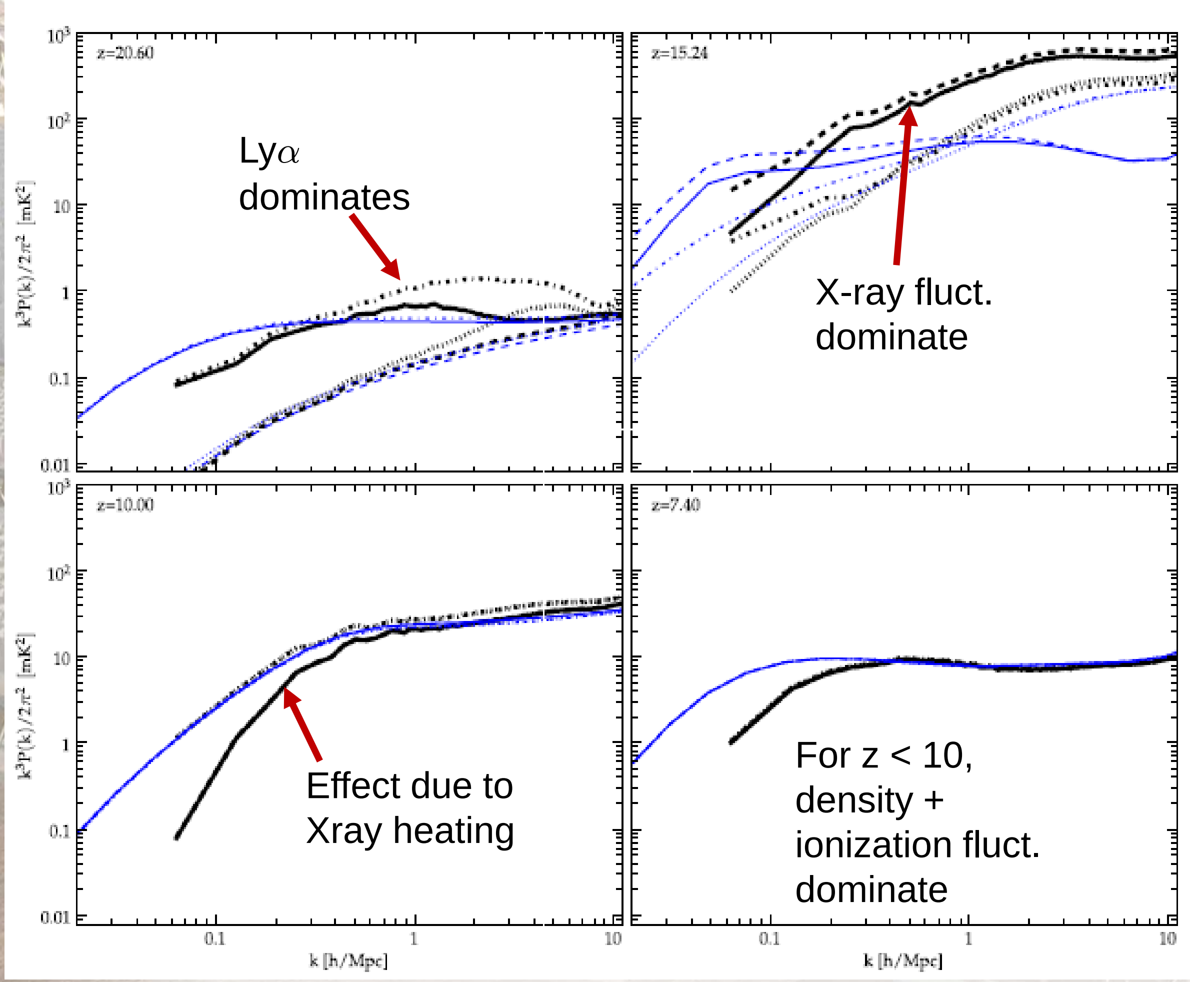
MWA: Australia
Freq: 80-300 MHz
Baselines:
10m - 1.5km



SKA: S. Africa/Australia
Freq: 70 MHz-35 GHz
Baselines:
20m - 3000km ?



21cm power spectrum – Analytical / Simulation



Lyα dominates

X-ray fluct. dominate

Effect due to Xray heating

For z < 10, density + ionization fluct. dominate

Santos et al., 2008, ApJ, 689, 1

Black - simulation

Blue - semi-analytical model

Analytical:

- OK for z < 10 (e.g. first generation experiments)
- At $z \gtrsim 10$ (SKA…) X-ray and Lyα fluctuations are important – need further improvements
- Also 21cm signal is non-Gaussian – P(k) enough?

Full Simulation:

- Description from first principles
- But slow to run – hard to check parameter space
- Limited to small volumes ~ (143 Mpc)^3

EoR 21cm measurements Constraints

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

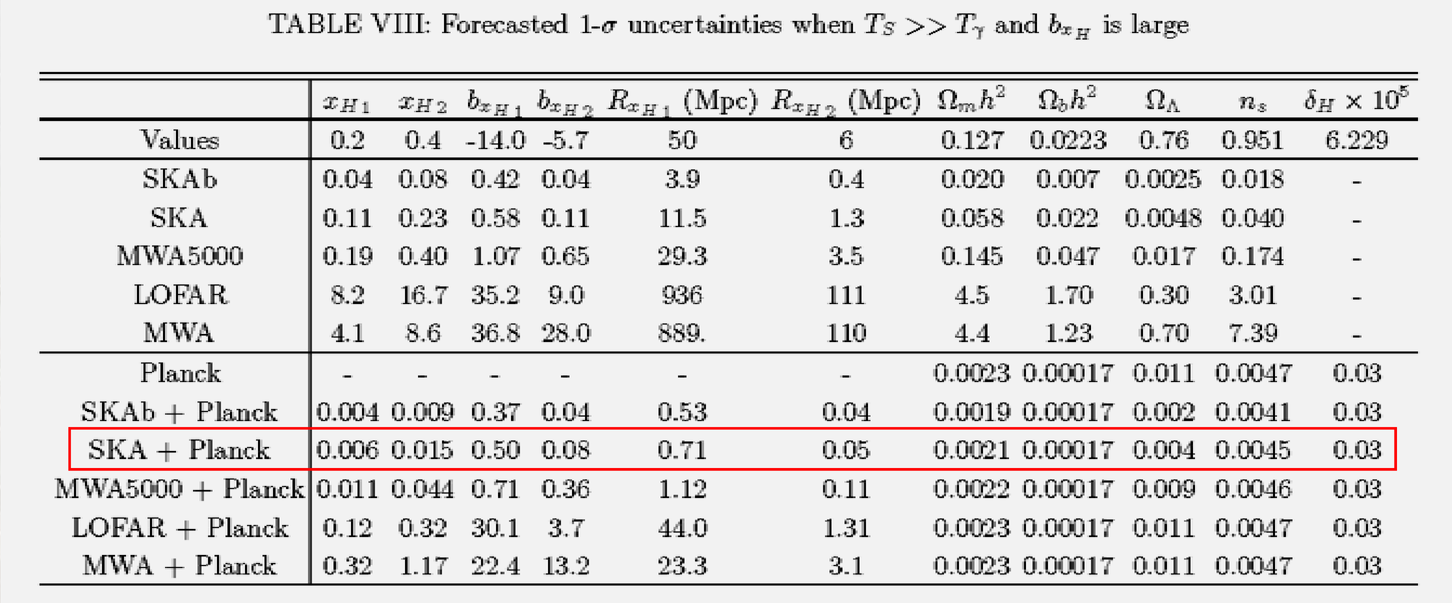


TABLE VIII: Forecasted 1-σ uncertainties when $T_S >> T_\gamma$ and b_{x_H} is large

	$x_{H\,1}$	$x_{H\,2}$	$b_{x_{H\,1}}$	$b_{x_{H\,2}}$	$R_{x_{H\,1}}$ (Mpc)	$R_{x_{H\,2}}$ (Mpc)	$\Omega_m h^2$	$\Omega_b h^2$	Ω_Λ	n_s	$\delta_H \times 10^5$
Values	0.2	0.4	-14.0	-5.7	50	6	0.127	0.0223	0.76	0.951	6.229
SKAb	0.04	0.08	0.42	0.04	3.9	0.4	0.020	0.007	0.0025	0.018	-
SKA	0.11	0.23	0.58	0.11	11.5	1.3	0.058	0.022	0.0048	0.040	-
MWA5000	0.19	0.40	1.07	0.65	29.3	3.5	0.145	0.047	0.017	0.174	-
LOFAR	8.2	16.7	35.2	9.0	936	111	4.5	1.70	0.30	3.01	-
MWA	4.1	8.6	36.8	28.0	889.	110	4.4	1.23	0.70	7.39	-
Planck	-	-	-	-	-	-	0.0023	0.00017	0.011	0.0047	0.03
SKAb + Planck	0.004	0.009	0.37	0.04	0.53	0.04	0.0019	0.00017	0.002	0.0041	0.03
SKA + Planck	0.006	0.015	0.50	0.08	0.71	0.05	0.0021	0.00017	0.004	0.0045	0.03
MWA5000 + Planck	0.011	0.044	0.71	0.36	1.12	0.11	0.0022	0.00017	0.009	0.0046	0.03
LOFAR + Planck	0.12	0.32	30.1	3.7	44.0	1.31	0.0023	0.00017	0.011	0.0047	0.03
MWA + Planck	0.32	1.17	22.4	13.2	23.3	3.1	0.0023	0.00017	0.011	0.0047	0.03

Santos and Cooray, PRD 2006

- X_H – neutral fraction, R_{x_H} – bubble size
- Frequency range: 135MHz – 167 MHz (7.5 < z <9.5)
- Marginalized over foregrounds
- Learn a lot about statistical properties of reionization astrophysics, not possible by other means…
- Not so good for Cosmology

EoR 21cm measurements Constraints

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

OPT **MID/PES**

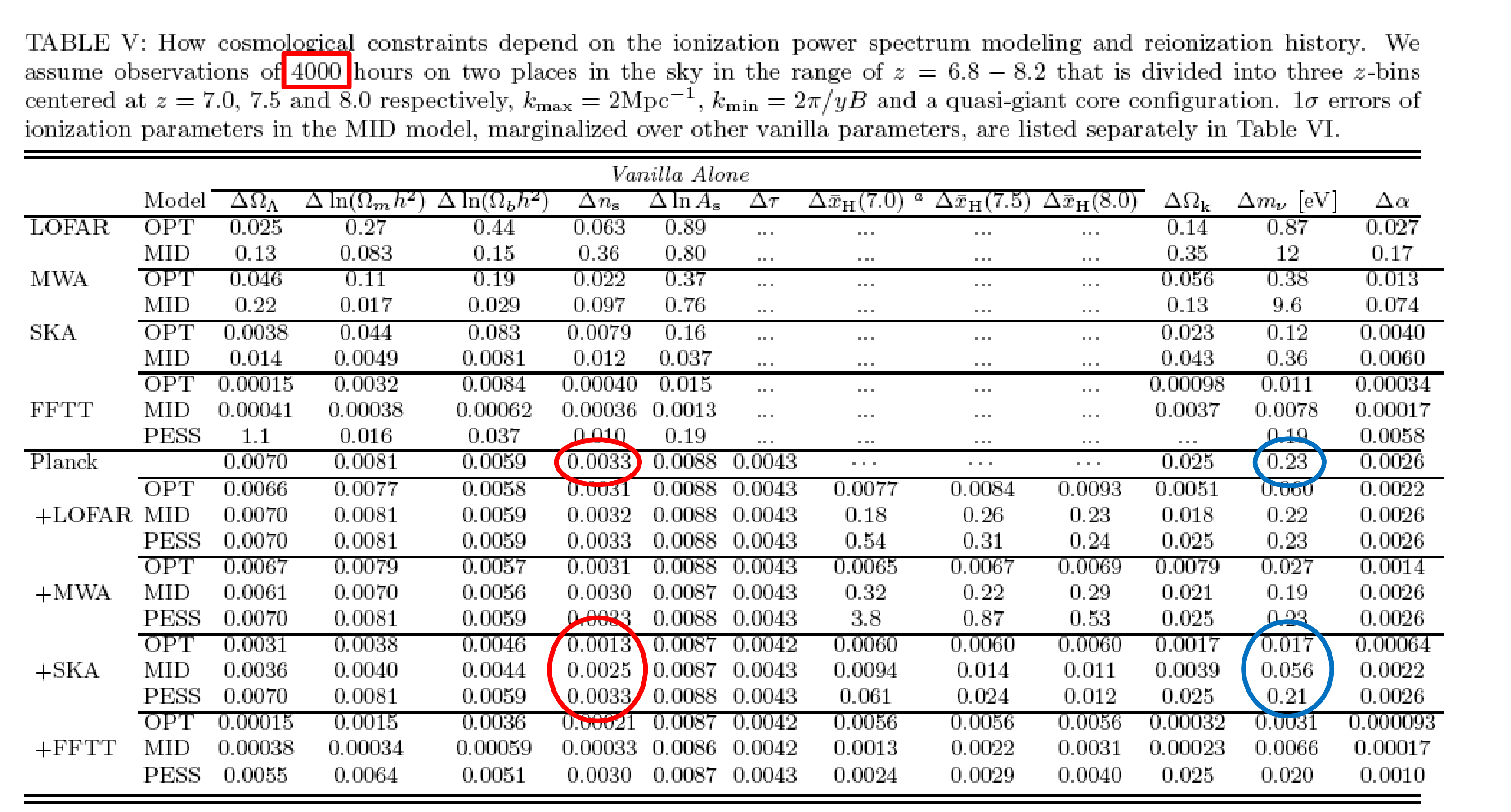


TABLE V: How cosmological constraints depend on the ionization power spectrum modeling and reionization history. We assume observations of 4000 hours on two places in the sky in the range of $z = 6.8 - 8.2$ that is divided into three z-bins centered at $z = 7.0$, 7.5 and 8.0 respectively, $k_{\max} = 2\mathrm{Mpc}^{-1}$, $k_{\min} = 2\pi/yB$ and a quasi-giant core configuration. 1σ errors of ionization parameters in the MID model, marginalized over other vanilla parameters, are listed separately in Table VI.

		Vanilla Alone											
	Model	$\Delta\Omega_\Lambda$	$\Delta\ln(\Omega_m h^2)$	$\Delta\ln(\Omega_b h^2)$	Δn_s	$\Delta\ln A_s$	$\Delta\tau$	$\Delta\bar{x}_{\mathrm{H}}(7.0)$ [a]	$\Delta\bar{x}_{\mathrm{H}}(7.5)$	$\Delta\bar{x}_{\mathrm{H}}(8.0)$	$\Delta\Omega_k$	Δm_ν [eV]	$\Delta\alpha$
LOFAR	OPT	0.025	0.27	0.44	0.063	0.89	...	...	...	...	0.14	0.87	0.027
	MID	0.13	0.083	0.15	0.36	0.80	...	...	...	...	0.35	12	0.17
MWA	OPT	0.046	0.11	0.19	0.022	0.37	...	...	...	...	0.056	0.38	0.013
	MID	0.22	0.017	0.029	0.097	0.76	...	...	...	...	0.13	9.6	0.074
SKA	OPT	0.0038	0.044	0.083	0.0079	0.16	...	...	...	...	0.023	0.12	0.0040
	MID	0.014	0.0049	0.0081	0.012	0.037	...	...	...	...	0.043	0.36	0.0060
FFTT	OPT	0.00015	0.0032	0.0084	0.00040	0.015	...	...	...	...	0.00098	0.011	0.00034
	MID	0.00041	0.00038	0.00062	0.00036	0.0013	...	...	...	...	0.0037	0.0078	0.00017
	PESS	1.1	0.016	0.037	0.010	0.19	...	...	...	...	...	0.19	0.0058
Planck		0.0070	0.0081	0.0059	0.0033	0.0088	0.0043	...	...	...	0.025	0.23	0.0026
+LOFAR	OPT	0.0066	0.0077	0.0058	0.0031	0.0088	0.0043	0.0077	0.0084	0.0093	0.0051	0.060	0.0022
	MID	0.0070	0.0081	0.0059	0.0032	0.0088	0.0043	0.18	0.26	0.23	0.018	0.22	0.0026
	PESS	0.0070	0.0081	0.0059	0.0033	0.0088	0.0043	0.54	0.31	0.24	0.025	0.23	0.0026
+MWA	OPT	0.0067	0.0079	0.0057	0.0031	0.0088	0.0043	0.0065	0.0067	0.0069	0.0079	0.027	0.0014
	MID	0.0061	0.0070	0.0056	0.0030	0.0087	0.0043	0.32	0.22	0.29	0.021	0.19	0.0026
	PESS	0.0070	0.0081	0.0059	0.0033	0.0088	0.0043	3.8	0.87	0.53	0.025	0.23	0.0026
+SKA	OPT	0.0031	0.0038	0.0046	0.0013	0.0087	0.0042	0.0060	0.0060	0.0060	0.0017	0.017	0.00064
	MID	0.0036	0.0040	0.0044	0.0025	0.0087	0.0043	0.0094	0.014	0.011	0.0039	0.056	0.0022
	PESS	0.0070	0.0081	0.0059	0.0033	0.0088	0.0043	0.061	0.024	0.012	0.025	0.21	0.0026
+FFTT	OPT	0.00015	0.0015	0.0036	0.00021	0.0087	0.0042	0.0056	0.0056	0.0056	0.00032	0.0031	0.000093
	MID	0.00038	0.00034	0.00059	0.00033	0.0086	0.0042	0.0013	0.0022	0.0031	0.00023	0.0066	0.00017
	PESS	0.0055	0.0064	0.0051	0.0030	0.0087	0.0043	0.0024	0.0029	0.0040	0.025	0.020	0.0010

Mao et al, PRD 2008

- Still not competitive with a weak lensing survey like LSST, JDEM…

Note: Field of View…

SKA ~ 200 degree^2

Resolution ~ 1’

143 Mpc sim

50’

- 21cm experiments will have low resolution but large FoV
- Need larger simulations for proper testing of the observation pipeline - foreground removal…
- High dynamic range:

- Need ~ 1000 (comoving) Mpc to achieve 5x5 deg^2 FoV (high z)
- But also need to resolve 10^8 solar mass halos – 0.14 Mpc…
- $(7000)^3$ cells!

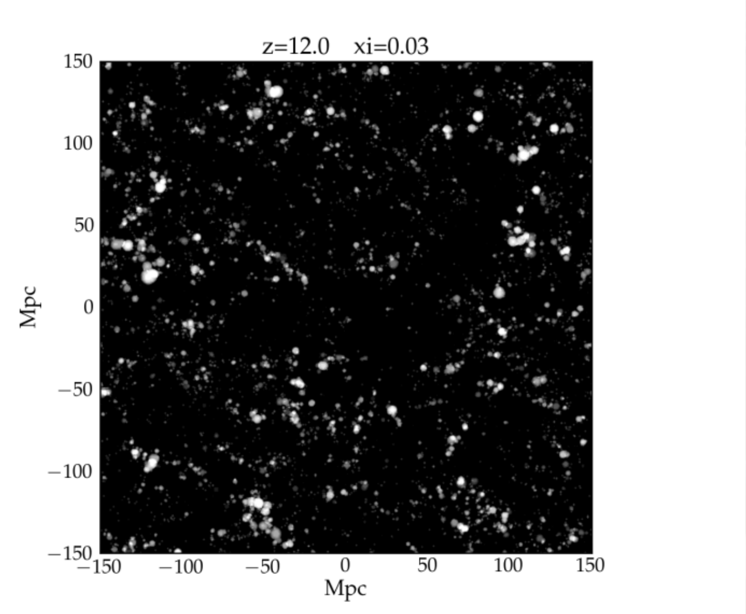
New Simulation

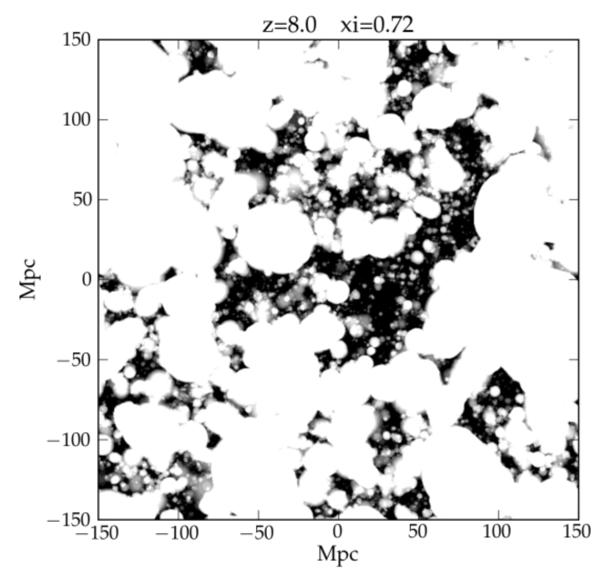
- Semi-numerical: based on 3-d realizations of the density field
- Extended to very large Volumes (1000 Mpc)
- Extended to very high redshifts (z~25)
- Large dynamical range
- Much faster than numerical simulations (but calibrated to them)
- Easy to run on your “small” computer!
- Defined by small set of parameters – easy to change

(See also Mesinger and Furlanetto 07,
Zahn et al. 07,Thomas et al. 09)

From density to ionization field

- 3-d Monte Carlo realization of dark matter
- Halo catalog (M $\geq 10^8 M_\odot$)
- Velocity field - Non-linear corrections (Zel'dovich)
- Ionization bubbles around halos (efficiency parameter)
- Halos/bubbles defined through excursion-set formalism
- Include LOS velocity gradient

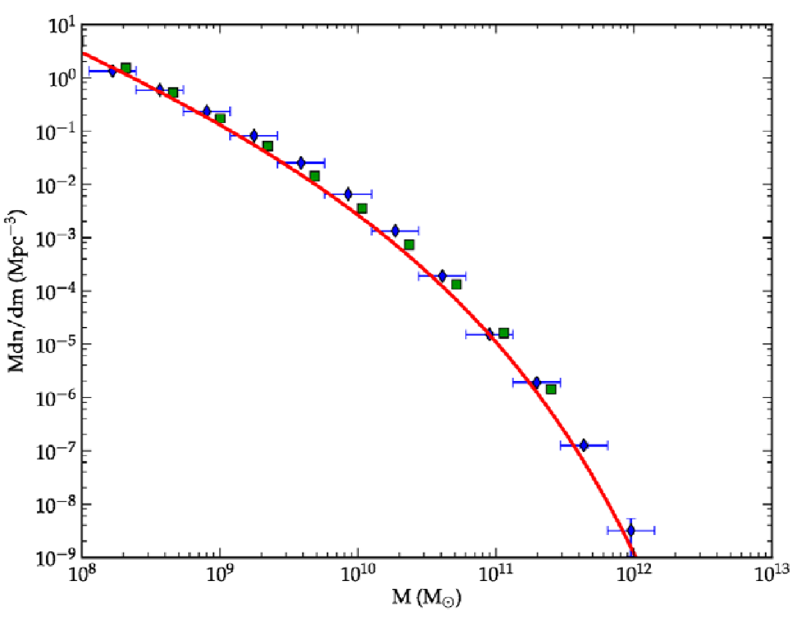


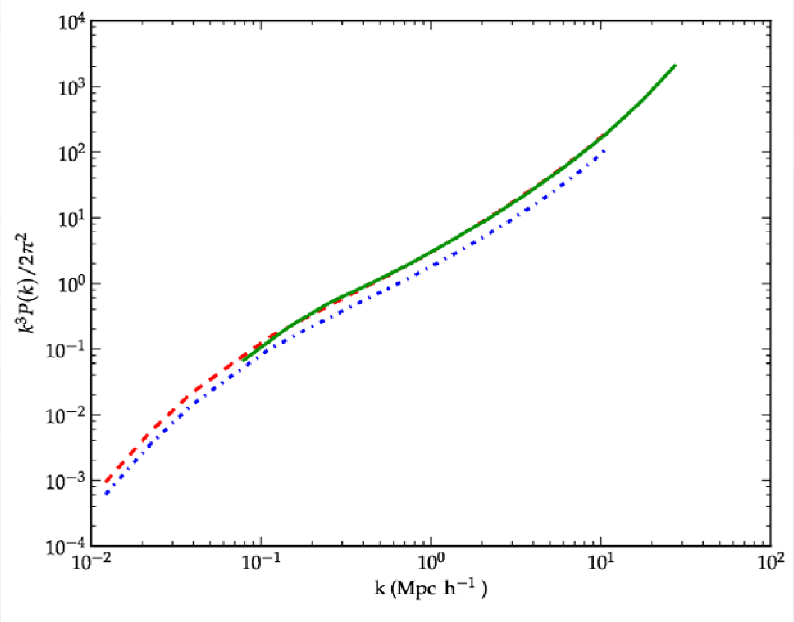


Ionization field

Extending to Very Large Volumes

- 1000 Mpc, $(1800)^3$ cells – $M_{min}=10^{10}\ M_\odot$
- Add $10^8 - 10^{10}$ solar mass halos from Poisson using mass function with bias to density field (Wilman et al. 08)

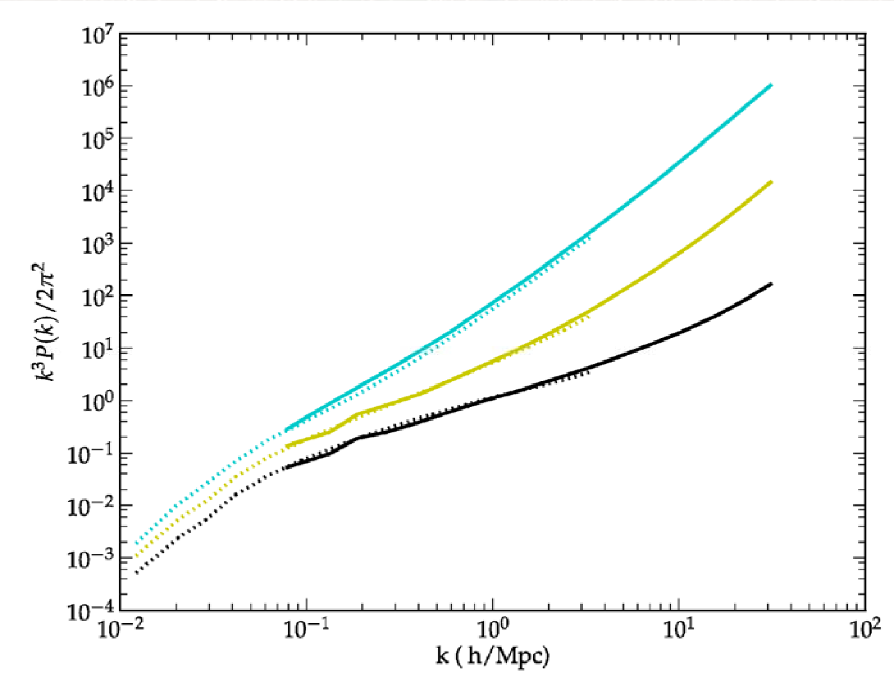




Halo mass function (z=10):
Red – theory (Sheth & Tormen 99 + Jenkins et al. 01)
Blue – 1000 Mpc simulation
Green – N-body simulation (Trac 08)

Halo mass power spectrum:
Blue – 1000 Mpc
Red – 1000 Mpc (non-linear corrections)
Green – N-body (Trac 08)

Extending to Very Large Volumes…

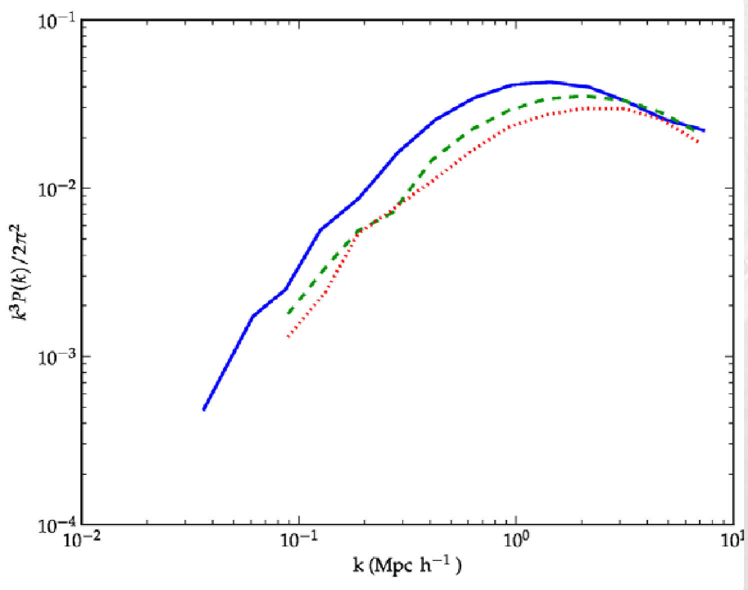


Dotted: our sim.
Solid: N-body dark matter sim.
Black: $M < 10^9\ M_\odot$
Yellow: $10^9\ M_\odot < M < 10^{10}\ M_\odot$
Blue: $M > 10^{10}\ M_\odot$

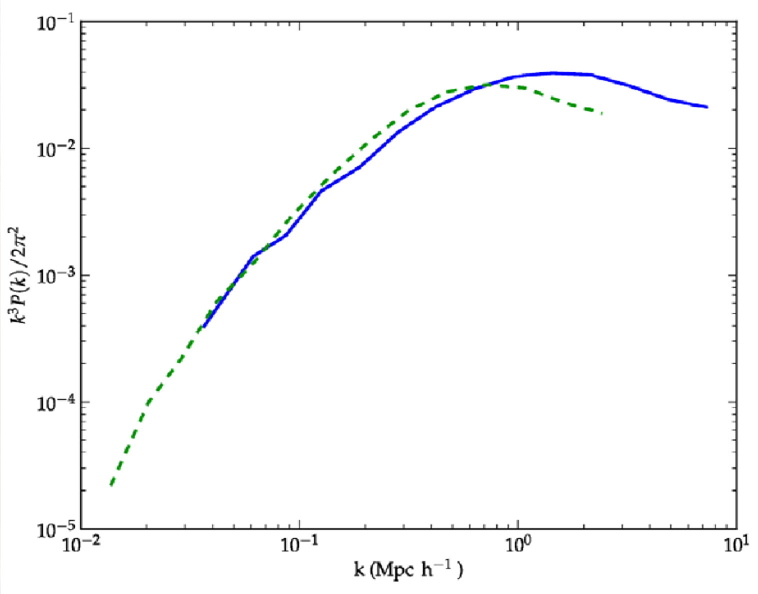
Power Spectrum: Ionization fraction

- For same volumes or low xi P(k) agrees
- For high x_i need large volumes to get right power spectrum on large scales…

x_i=0.55



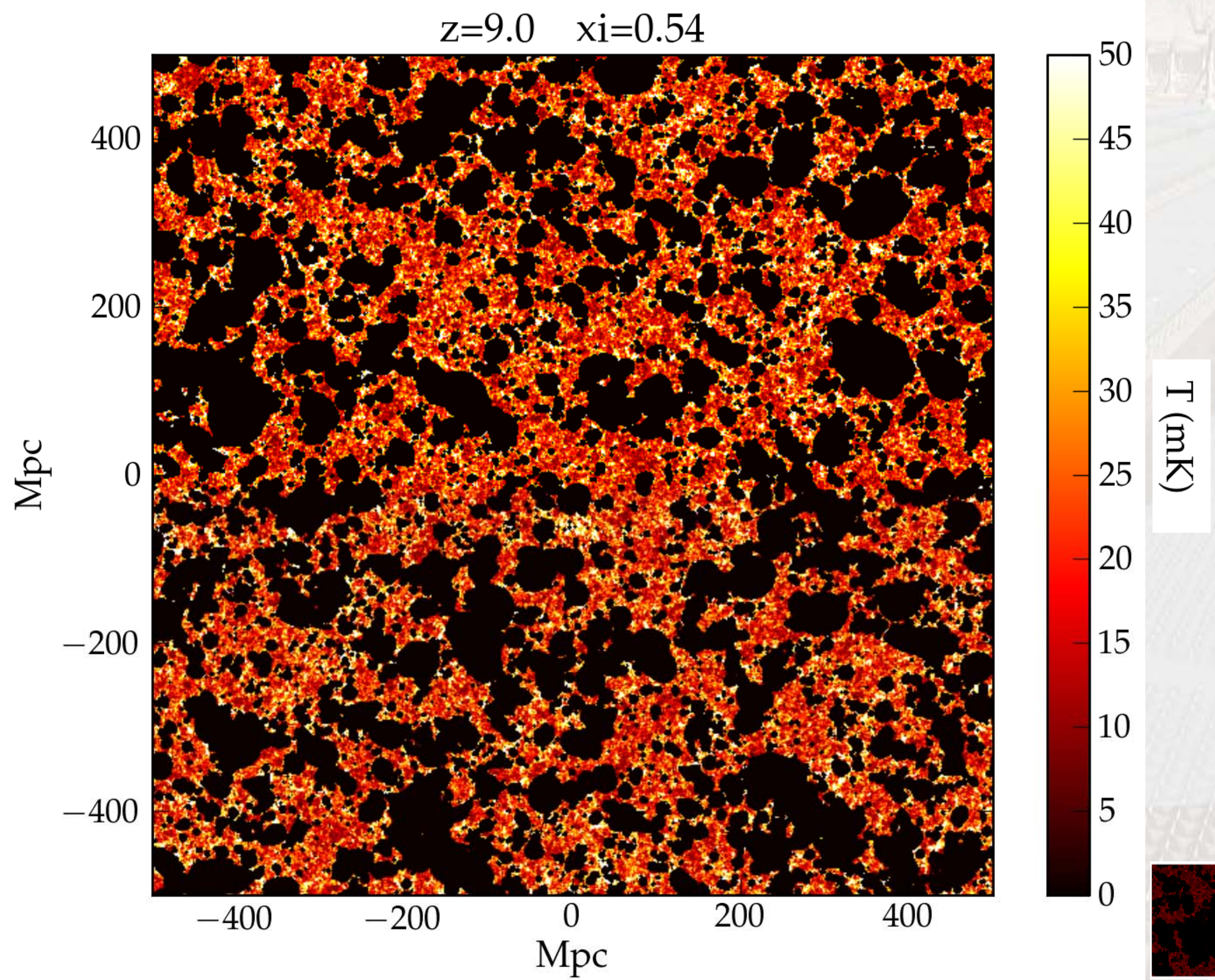
Blue: L=300 (xi=0.55)
Red: L=143
Green: L=143 with radiative transfer



x_i=0.1

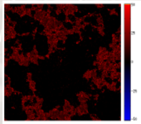
Blue : L=1000 Mpc
Green: L=300 Mpc

Large FoV…



New simulation with L=1000 Mpc

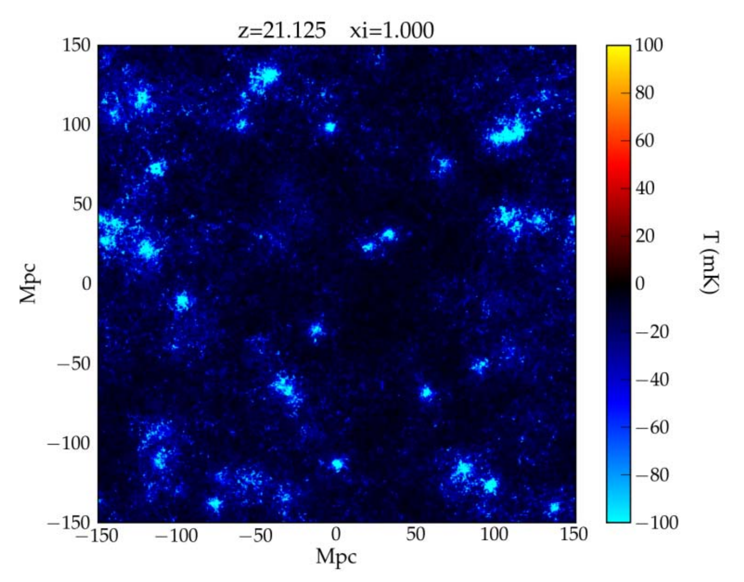
- At z ~ 8 we get 6x6 deg^2
- Good to test observation pipeline (foreground removal)



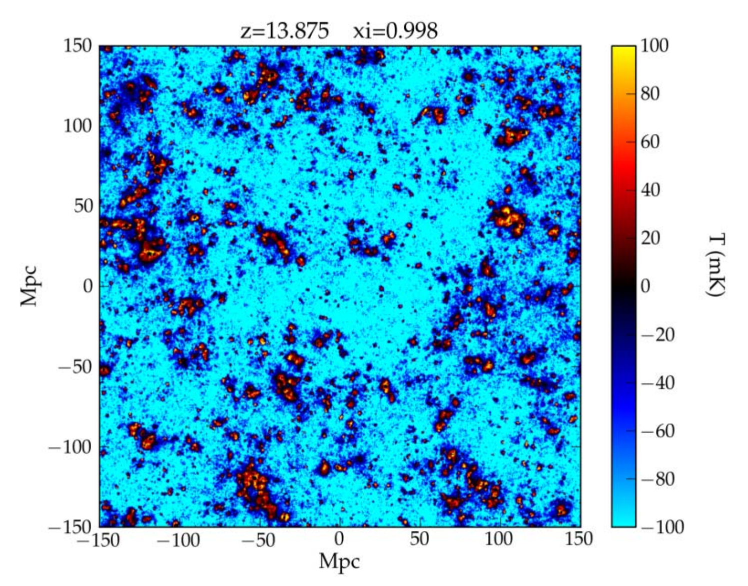
Simulation with RT code (L=143 Mpc)

Extending to very high redshifts

Ly$_\alpha$



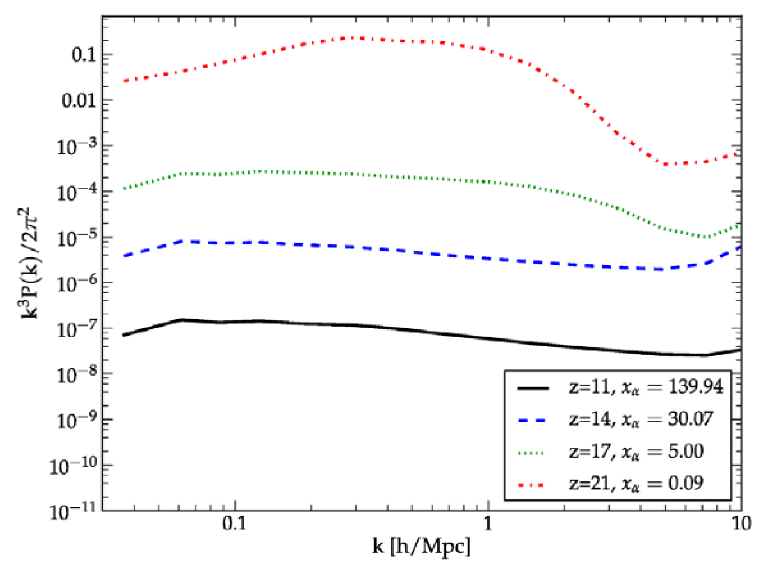
X-ray heating



- Need to calculate HI Spin temperature:
  - Use halo catalog to calculate SFR
  - Use power law model for Ly$_\alpha$ / x-ray emission (4 parameters - easy to change)
  - Calculate IGM temperature from heating due to x-rays
  - Calculate coupling due to Ly$_\alpha$
  - Calculate flux through convolution with SFR + FFT
  - Also includes collisional coupling

Extending to very high redshifts: Fluctuations…

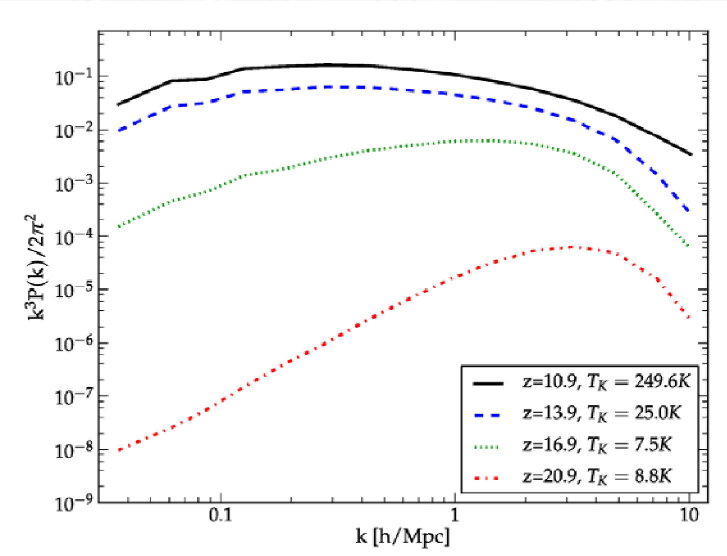
Ly$_\alpha$



- Ly$_\alpha$ traces star formation
- Important for z $\gtrsim$ 15
- Dominates over collisions up to z=22

$$T_b \propto \frac{x_\alpha}{1 + x_\alpha}$$

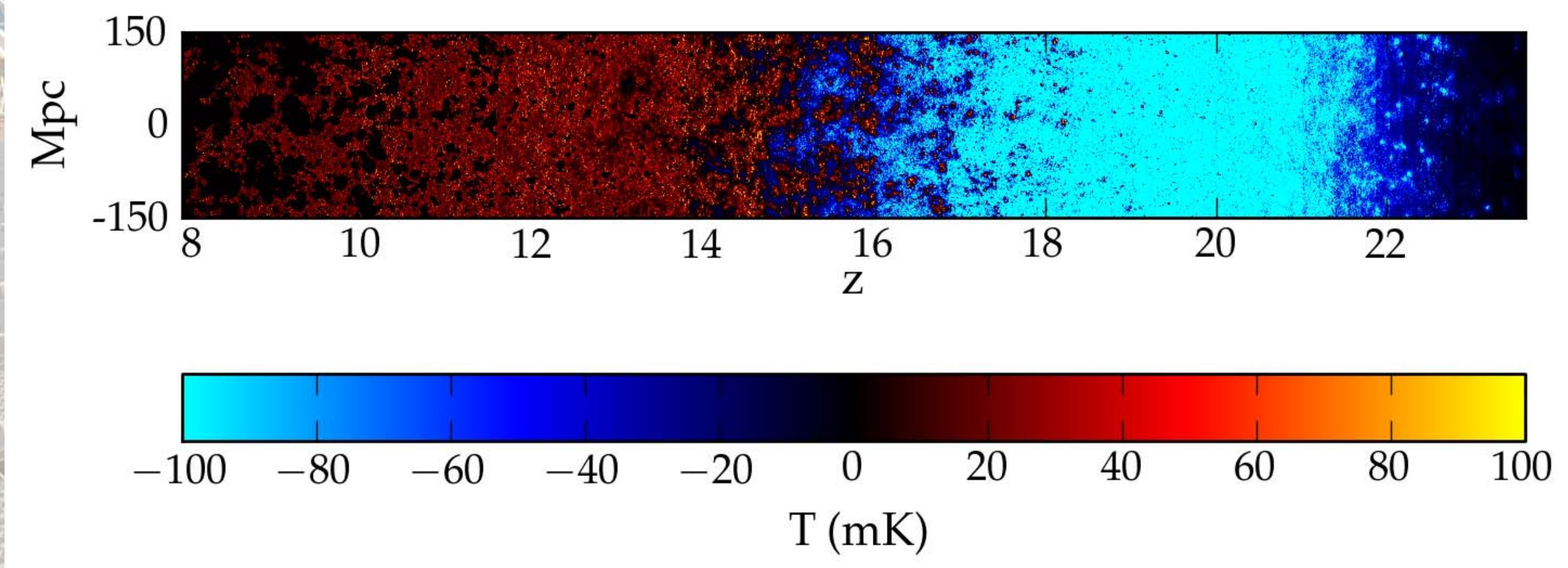
X-ray heating

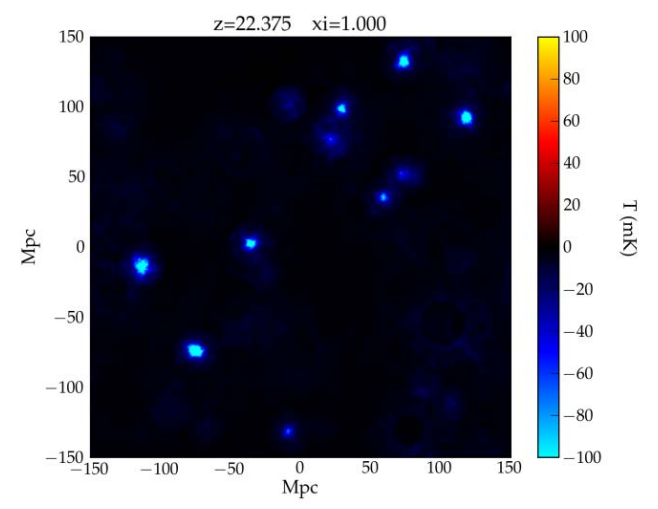


- Assumed starbursts for x-ray heating (but highly uncertain)
- Heating is inhomogeneous – mostly done by ~100 eV Xrays
- Important for z > 10!

$$T_b \propto (1 - T_{CMB}/T_K)$$

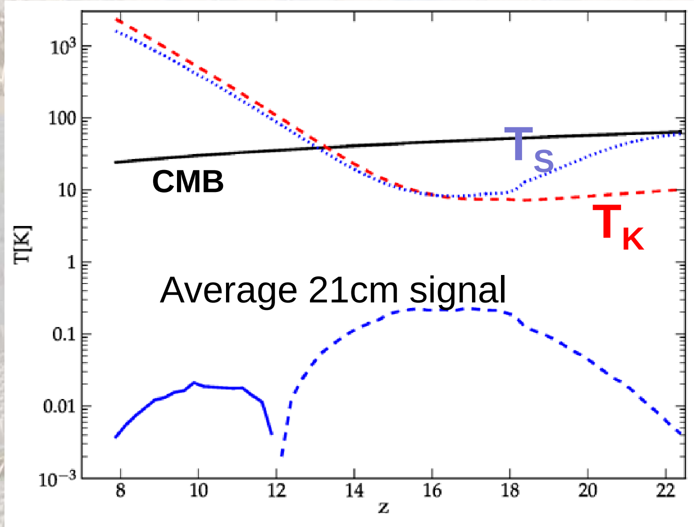
End-to-end Simulation

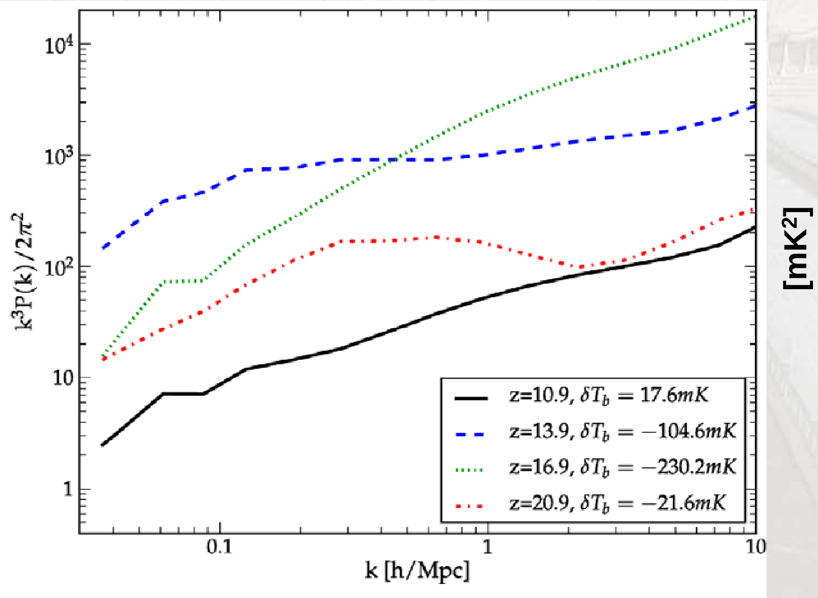


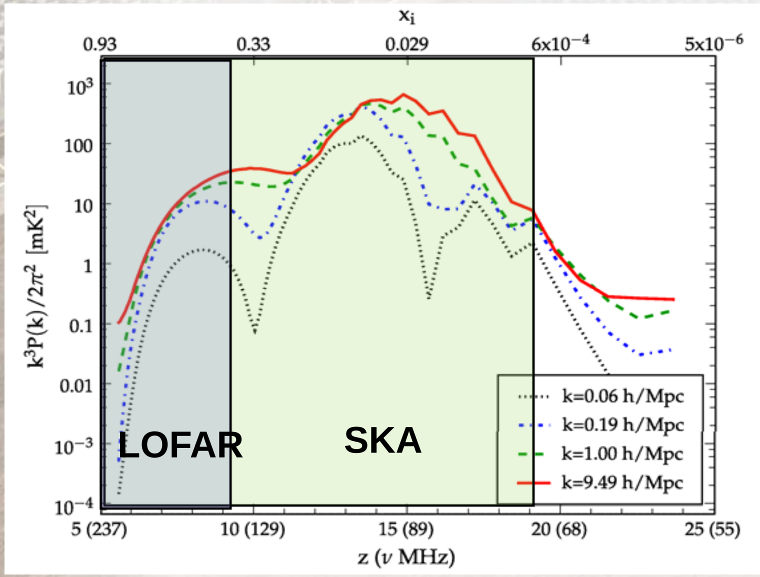


- z > 19 – cold gas, Lyα fluctuations
- z ~ 18 - heating starts
- z ~ 12 - Reionization starts

21cm signal: redshift evolution







- 21cm Power Spectrum at high redshifts
- Lots of info at high z – need next generation experiment (SKA)…

What can we learn?
e.g.: Determining the first sources

δ_α dominates

Sources

$J_{\alpha,*}$ vs $J_{\alpha,X}$

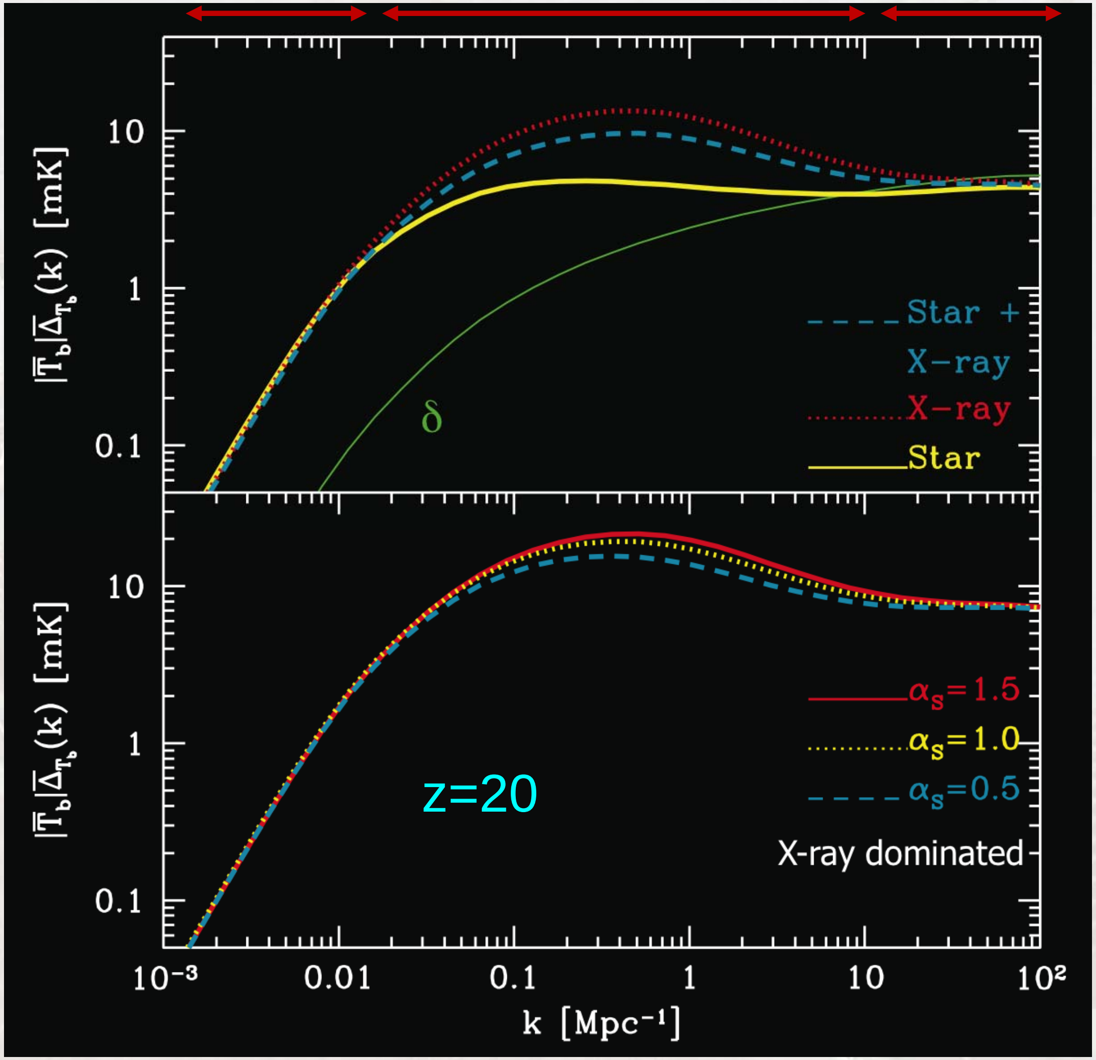
Spectra

α_S

bias

source properties

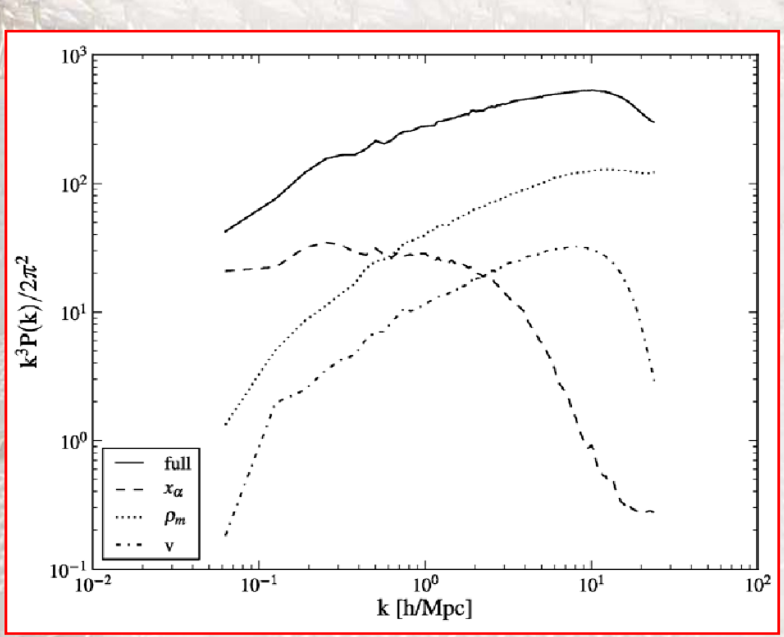
density



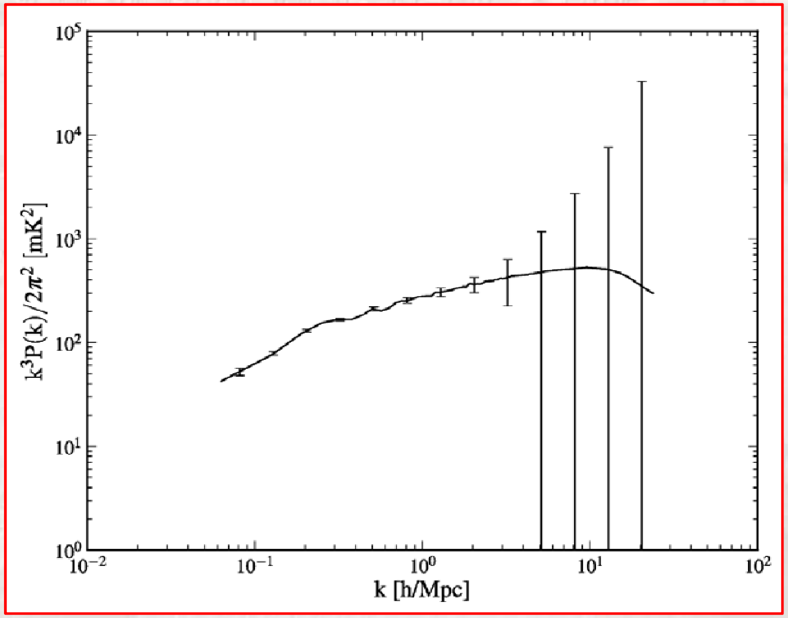
Chuzhoy,
Alvarez,
& Shapiro
2006

Pritchard &
Furlanetto
2007

Constraining galaxies at z ~ 20 through Lyα emission



Contributions to the signal



Constraints

- “SKA type” experiment can constrain signal at z ~ 20:
  - 4000 m^2/K @ 100 MHz | 8 MHz bandwidth
  - 10x10 deg^2 FoV | 5 Km core
- Use dependence on angle with LoS to separate the signal (uncorrelated part depends only on Lyα…)

Summary

- Presented a new method to generate very large volume, high redshift simulations of the 21cm signal
- Useful to generate sky models for future 21cm experiments (crucial to test calibration issues and foreground removal)
- Code will be publicly available (SimFast21)
  - Easy to run/play – no need for supercomputers
  - “Fast” + small number of parameters – good to probe the huge intrinsic parameter space
- Room for continuous improvement!

  - Check www.SimFast21.org (mgrsantos@ist.utl.pt)
  - See http://s-cubed.physics.ox.ac.uk (SKADS Simulated Skies) for simulations (fits files) + point sources, etc

M. Santos, L. Ferramacho, M. Silva, A. Amblard, A. Cooray, MNRAS, 2010, http://arxiv.org/abs/0911.2219


HÁ PORTUGUESES ENVOLVIDOS NO PROJECTO DO NOVO RADIO-TELESCÓPIO "SKA"
A IDEIA É SABER O QUE SE PASSA NO UNIVERSO
CRUZES
O GOVERNO ESTÁ A LEVAR A COISA LONGE DEMAIS.