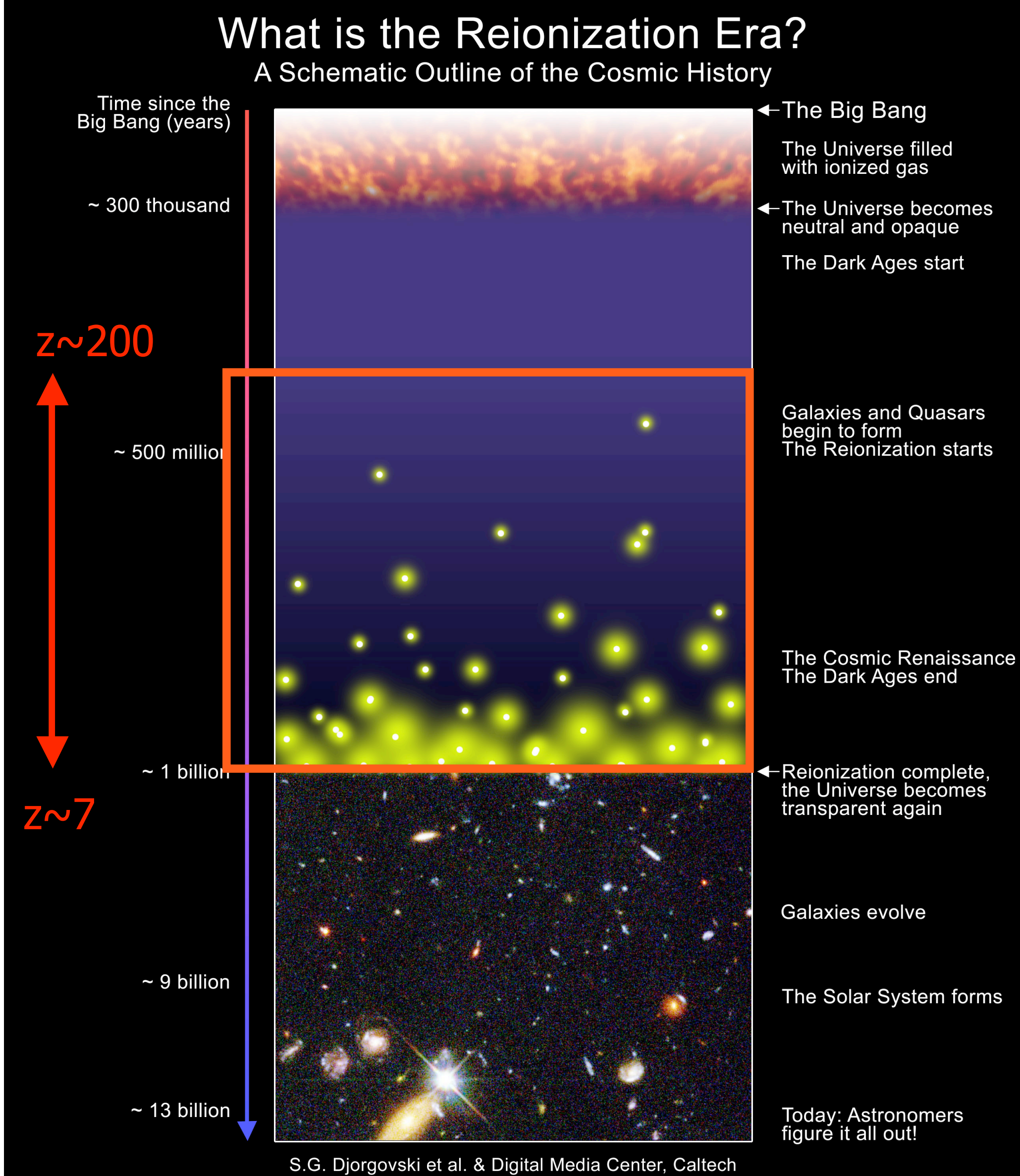
Probing the cosmic dark ages using the 21 cm line

Jonathan Pritchard
(Caltech)

Collaborators: Steve Furlanetto (Yale)
Marc Kamionkowski (Caltech)

Particle Physics and Cosmology: The Fabric of Spacetime
Les Houches Summer School 2006

Overview



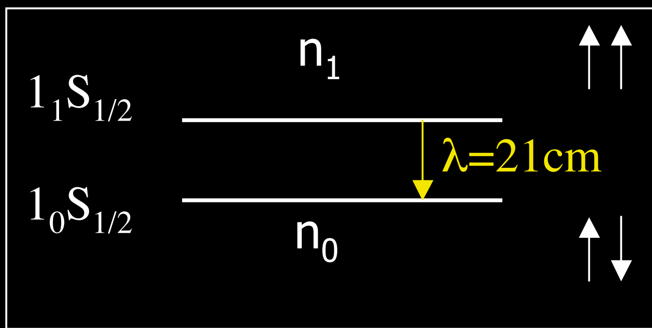
- 21 cm line as probe of the “Dark Ages”
- “Gastrophysics”
  - First luminous sources
  - IGM thermal history
  - Reionization

  (reasonable soon)
- Cosmology
  - Density power spectrum
  - BBN - D/H
  - Dark matter decay

  (more speculative)

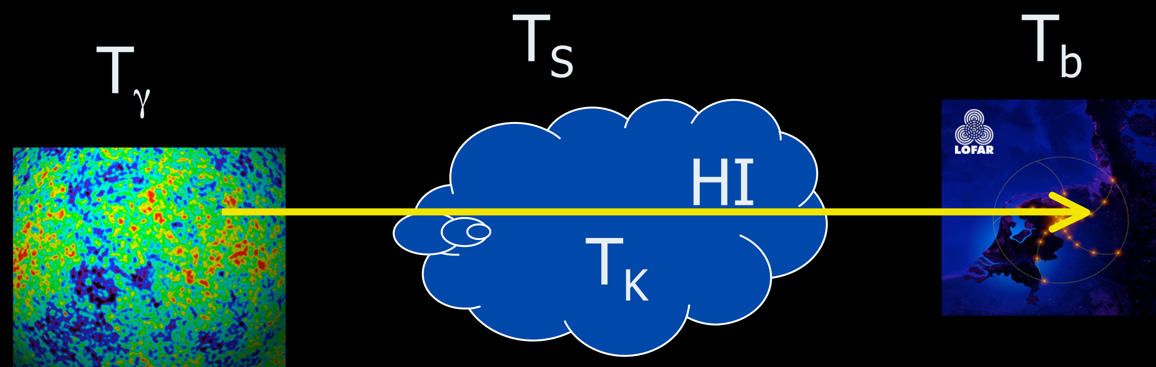
21 cm basics

- HI hyperfine structure



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

- Use CMB backlight to probe 21cm transition



z=13
f_{21cm}=1.4 GHz

z=0
f_{obs}=100 MHz

- 3D tomography possible - angles + frequency
- 21 cm brightness temperature

$$T_b = 27 x_{\rm HI}(1+\delta_b)\left(\frac{T_S - T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\right)^{1/2}\ {\rm mK}$$

- 21 cm spin temperature

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

- Coupling mechanisms:
  - Radiative transitions (CMB)
  - Collisions
  - Wouthysen-Field

Wouthysen-Field effect

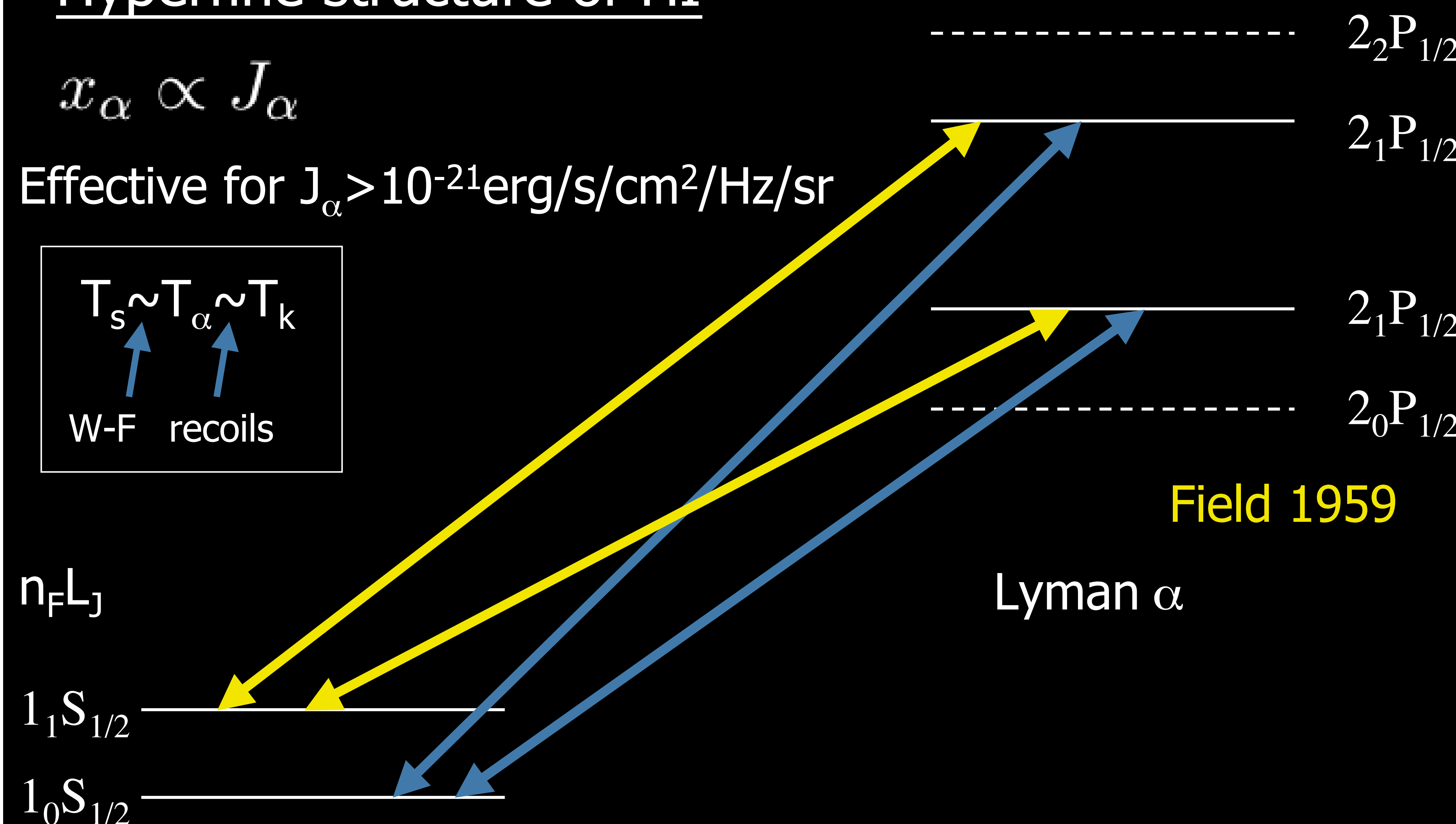
Hyperfine structure of HI

$$x_\alpha \propto J_\alpha$$

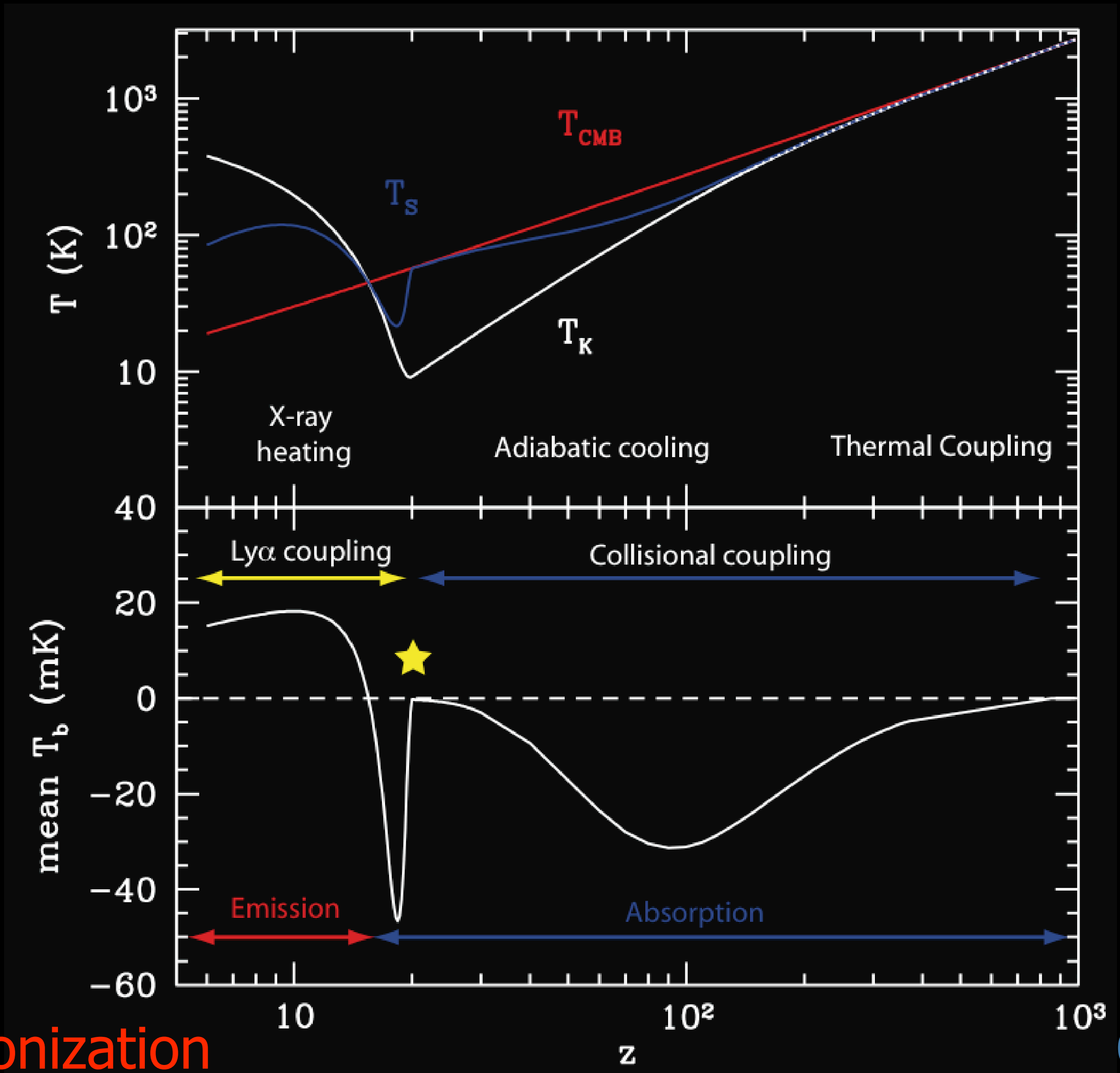
Effective for $J_\alpha > 10^{-21}$ erg/s/cm^2/Hz/sr

$T_s \sim T_\alpha \sim T_k$

W-F recoils



Thermal History



Reionization

CMB

21 cm fluctuations

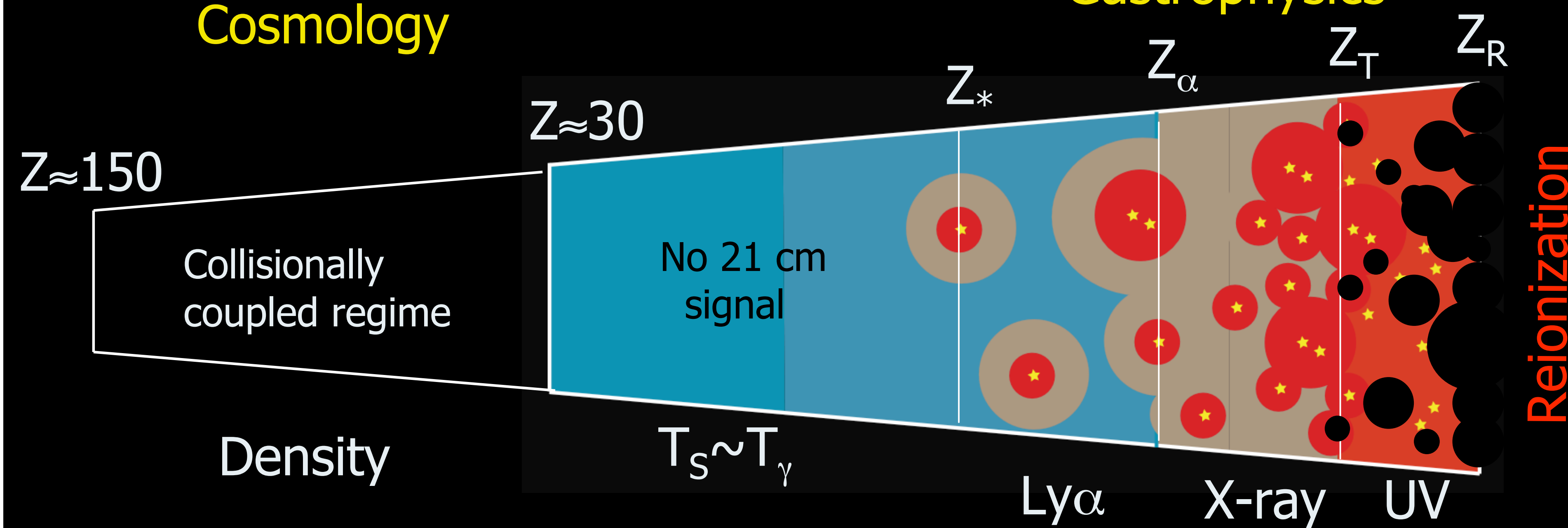
Baryon Density	Neutral fraction	Gas Temperature	W-F Coupling	Velocity gradient

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

Cosmology	Reionization	X-ray sources	Lyα sources	Cosmology

Gastrophysics

Cosmology



Experimental efforts

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

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

PAST: China
Freq: 70-200 MHz

SKA: ???
Freq: 60 MHz-35 GHz
Baselines: 20m-3000km

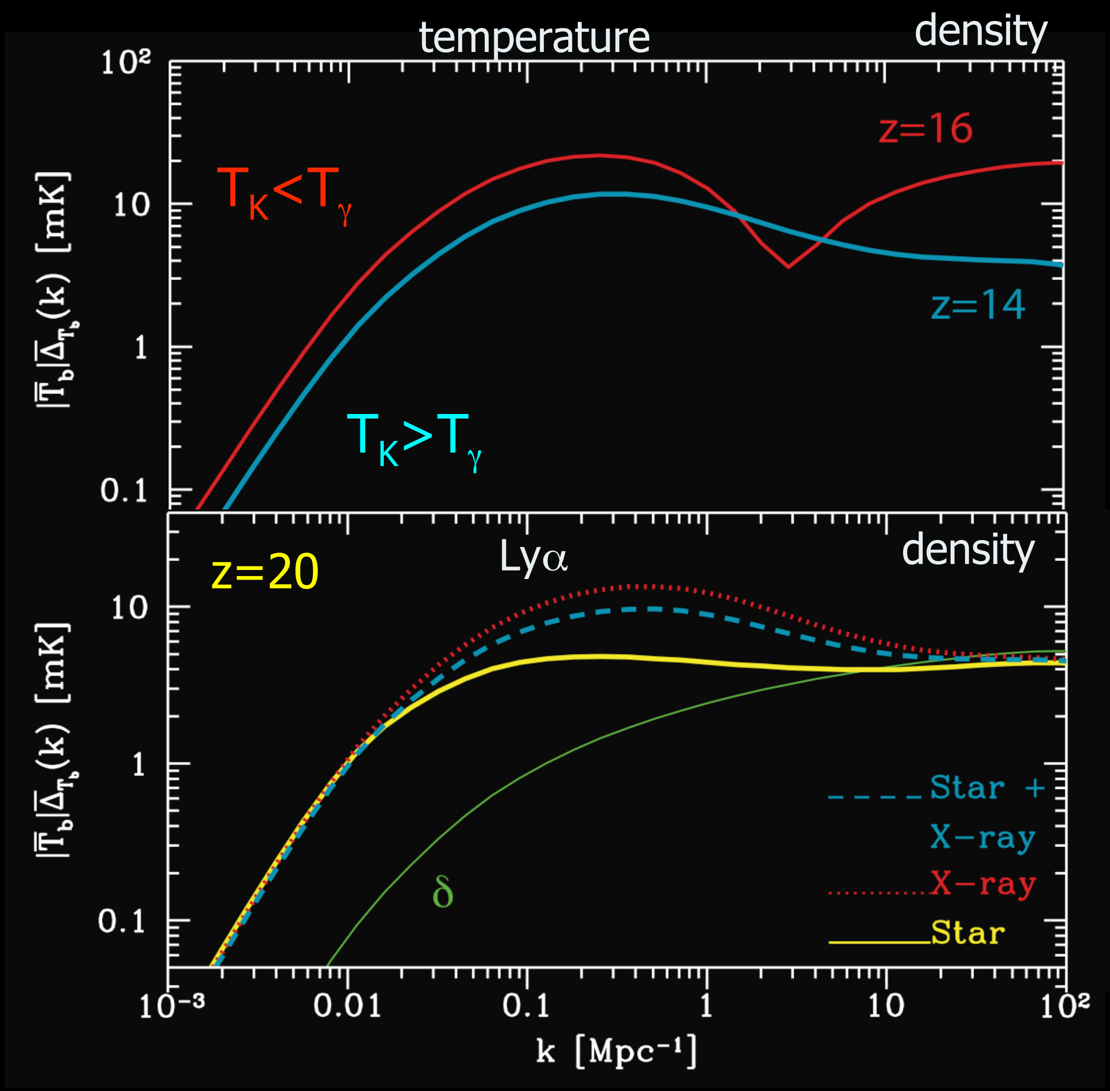
Foregrounds are the big problem!

First Sources

$\Delta = k^3 P(k)/2\pi^2$

Gas temperature fluctuations

Lyα flux fluctuations



- trough if $T_K<T_\gamma$: competition between density and temperature fluctuations
- Probe thermal history

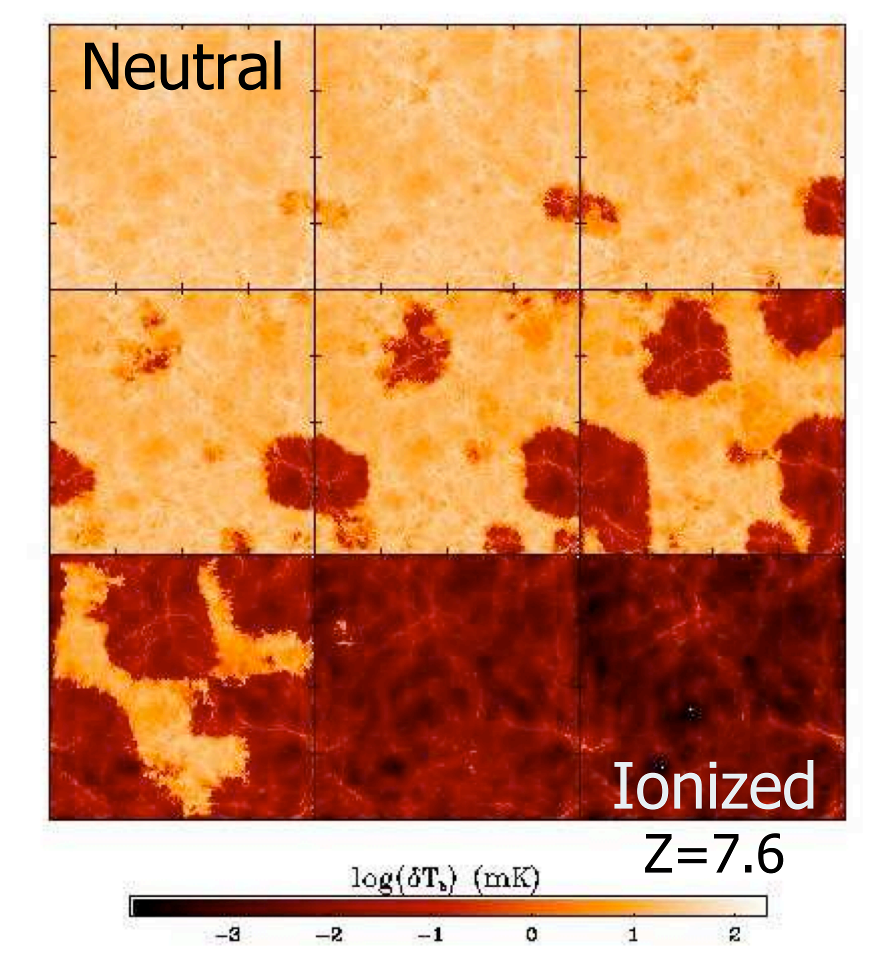
- power spectrum sensitive to sources of Lyα photons
- Probe first sources

Pritchard & Furlanetto 2005 + 2006

Reionization

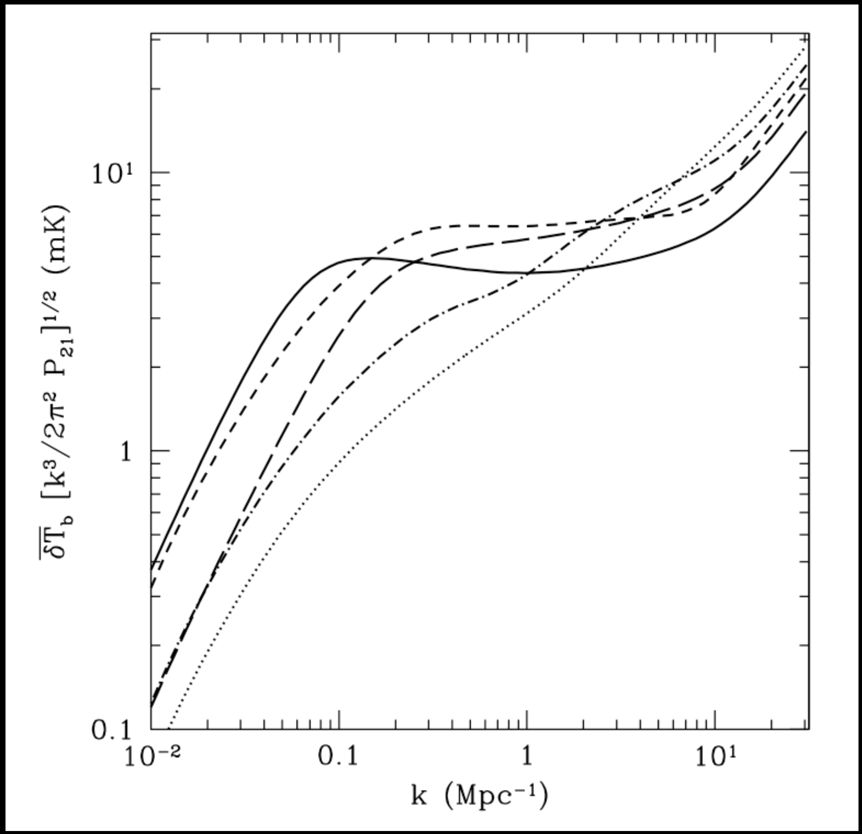
- Main target of first experiments

Z=12



Furlanetto, Sokasian, Hernquist 2003

- HII regions grow around sources
- Characteristic size imprinted in 21 cm power spectrum
- Also get evolution of ionized fraction



Furlanetto, Oh, Briggs 2006

Density power spectrum

- 21 cm fluctuations probe density fluctuations
- Non-linear scale is smaller at high red-shift

-> smaller scales accessible than for galaxy surveys

- Independent cross-check on cosmological parameters
- Moderate gains on CMB constraints possible with SKA

TABLE 2

ERRORS ON COSMOLOGICAL PARAMETER ESTIMATES WHEN DENSITY FLUCTUATIONS DOMINATE THE 21CM SIGNAL FOR TWO YEAR OBSERVATIONS WITH 21 CM INTERFEROMETERS AND IN COMBINATION WITH CURRENT CMB OBSERVATIONS (CCMB) AND WITH PLANCK.[a]

	τ	Ω_w	w	$\Omega_m h^2$	$\Omega_b h^2$	n_s	$\delta_H \times 10^5$ [b]	α_s	Ω_ν	$\bar{x}_H$
	0.1	0.7	-1.0	0.14	0.022	1.0	3.91	0.0	0.0	1.0
LOFAR	-	0.09	-	0.14	0.04	0.14	3.9	-	-	-
MWA	-	0.10	-	0.13	0.03	0.13	3.9	-	-	-
MWA5000	-	0.007	-	0.011	0.003	0.03	0.31	0.012	0.008	-
SKA	-	0.005	-	0.011	0.003	0.06	0.42	0.017	0.016	-
SKA[c]	-	0.14	-	0.051	0.003	0.07	2.4	0.020	0.09	-
SKA*	-	0.005	-	0.009	0.002	0.04	0.26	0.011	0.009	-
MWA50K*	-	0.002	-	0.005	0.001	0.01	0.11	0.004	0.005	-
CCMB	0.060	0.084	-	0.017	0.0014	0.072	0.29	0.039	0.12	-
CCMB+ LOFAR	0.058	0.058	-	0.011	0.0012	0.031	0.22	0.025	0.03	0.2
CCMB+ MWA	0.057	0.058	-	0.011	0.0012	0.033	0.22	0.025	0.02	0.2
CCMB+ MWA5000	0.049	0.007	-	0.003	0.0009	0.013	0.18	0.006	0.005	0.06
CCMB + SKA	0.049	0.005	-	0.003	0.0009	0.014	0.18	0.005	0.007	0.06
Planck	0.0050	0.029	0.09	0.0023	0.00018	0.0047	0.026	0.008	0.010	-
Planck +MWA5000	0.0046	0.019	0.07	0.0011	0.00013	0.0034	0.018	0.004	0.003	0.05
Planck + SKA	0.0046	0.022	0.08	0.0009	0.00013	0.0034	0.018	0.003	0.004	0.06
Planck + SKA*	0.0046	0.018	0.07	0.0009	0.00013	0.0033	0.018	0.003	0.004	0.05
Planck + MWA50K*	0.0045	0.008	0.03	0.0004	0.00010	0.0029	0.015	0.002	0.001	0.02

<- Optimistic

improve
n_s and Ω_ν
most

McQuinn et al.
2006

Deuterium abundance

- Deuterium also has hyperfine structure

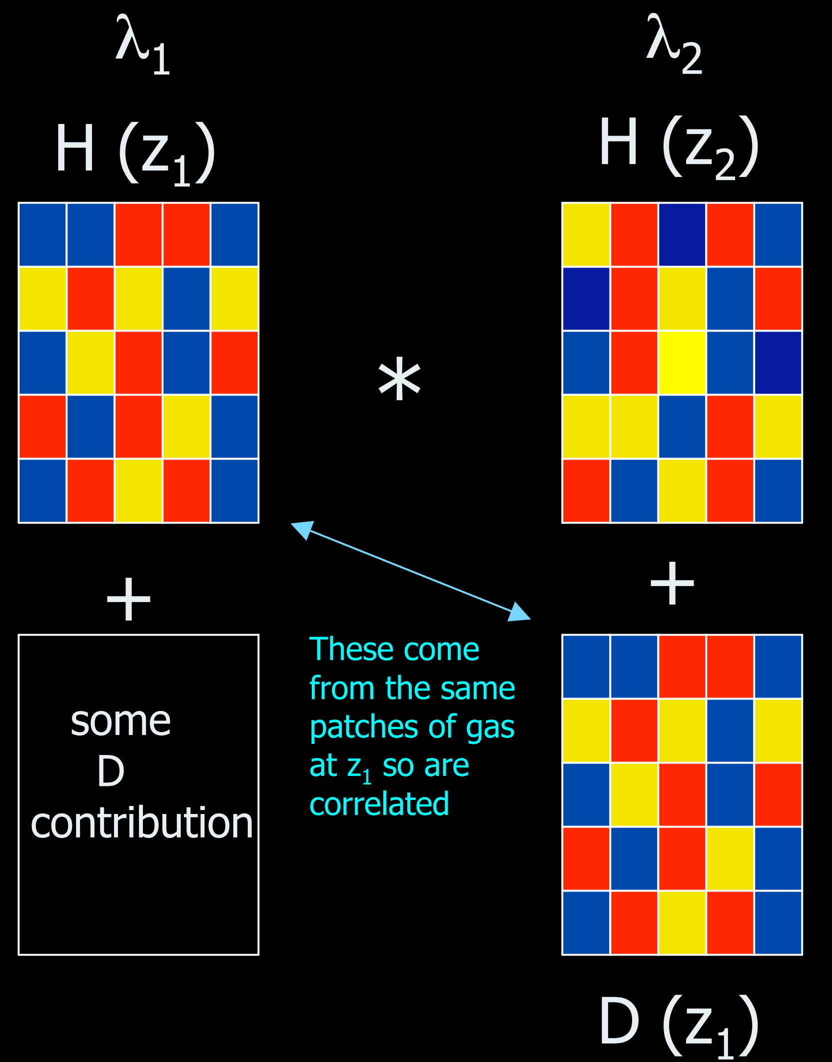
  λ_D=91.6cm

  λ_H=21.1cm
- Cross-correlate signal pixels at two wavelengths to extract D/H ratio

  $\lambda_1 = \lambda_H\ (1+z)$

  $\lambda_2 = \lambda_D\ (1+z)$

  $= \lambda_1 * (\lambda_{D/}\ \lambda_H)$
- Measure primordial D/H ratio to 1% level
- Technically challenging and well beyond currently proposed experiments



Sigurdson & Furlanetto 2005

Dark matter decays

- Some dark matter candidates can decay during dark ages
  DM lifetime ~ 10^{17}-10^{20} years   i.e. $\Gamma << H_0$
  e.g. sterile neutrinos with m~2-4 keV
  axinos with m~1-100 GeV
- Energetic photons produced heat and ionize the IGM
- Detect resulting 21 cm fluctuations
- Constrain DM parameter space

Furlanetto, Oh, Pierpaoli 2006

•Also technically demanding and far in the future

Conclusions

- 21 cm signal contains an enormous wealth of information…
  … the trick is separating it all out
- Best region for doing cosmology is z>30, but also hardest to observe
- At z<30, "gastrophysics" tends to obscure cosmology but is interesting in its own right
- 21 cm should provide moderate gains in cosmological parameters in the next decade or so
- Very early days yet and still unclear what will and will not be possible
- Foregrounds are still a largely unresolved issue

Recent review: Furlanetto, Oh, Briggs (2006)
astro-ph/0608032