21cm Cosmology

Tomo Takahashi
(Saga University)

YITP, Kyoto University
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Plan of this talk

- What is 21 cm?
- Basics of 21cm cosmology

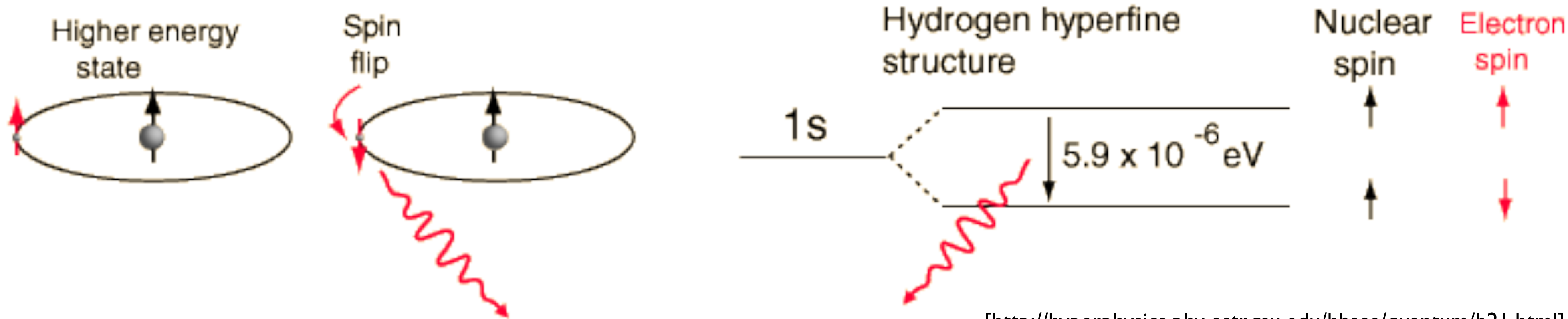
  21cm global signal

  Power spectrum

- Some examples:

  Dark matter, primordial fluctuations,…

What is 21cm?



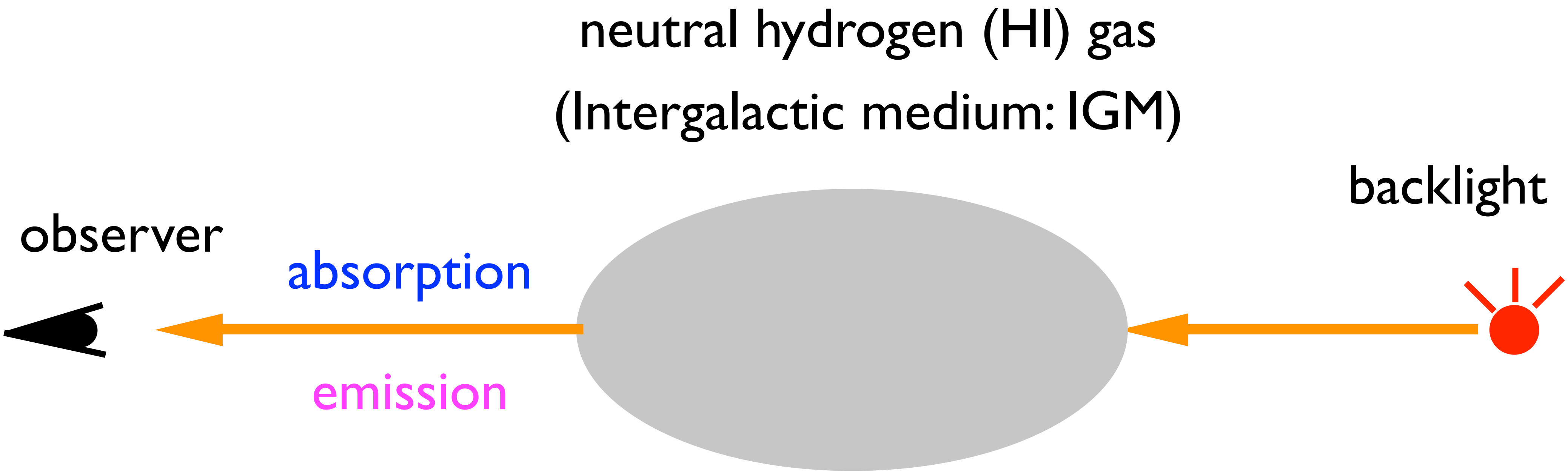
[http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/h21.html]

$$\nu_0 = 1420.4057517 \text{ MHz}$$

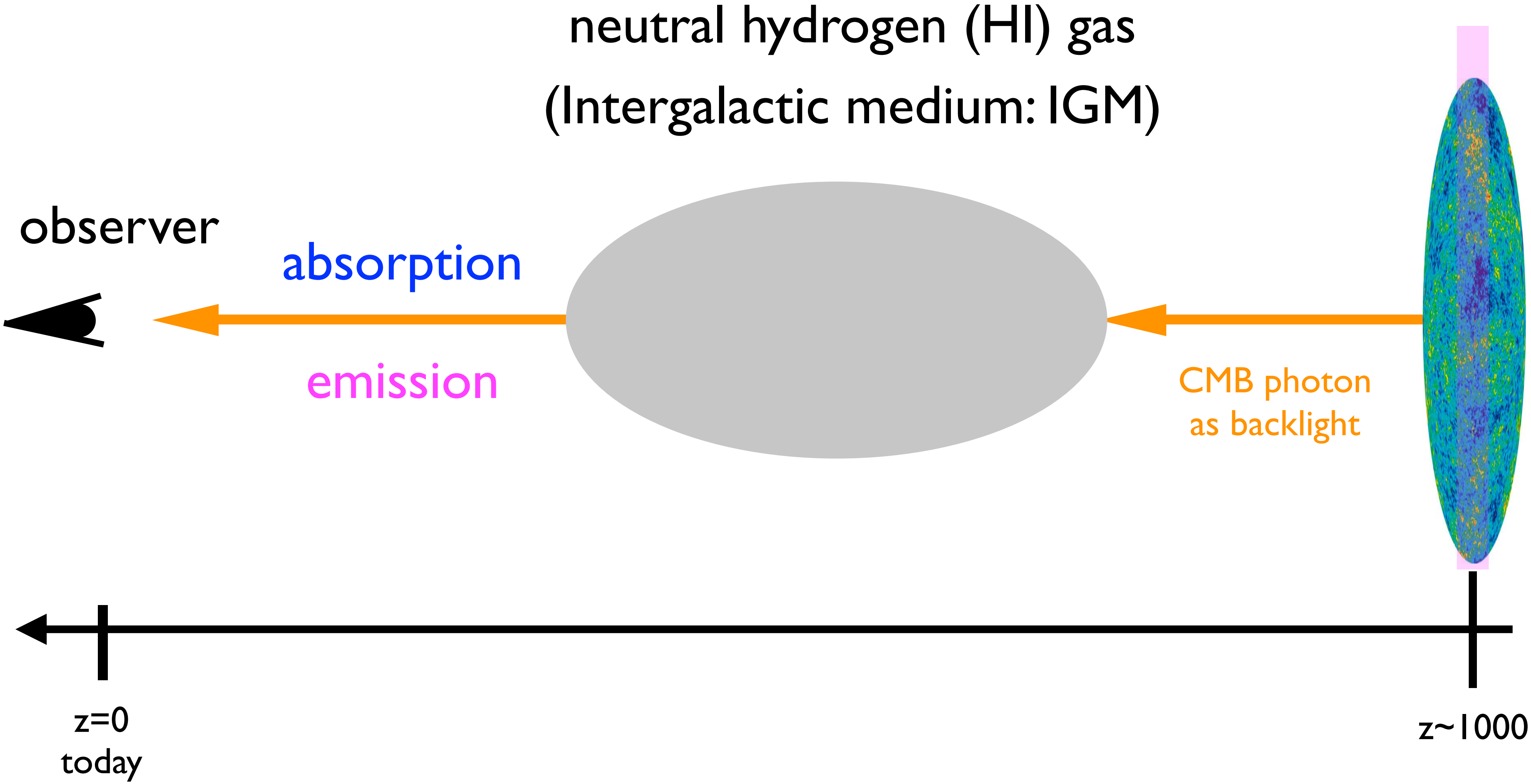
$$\lambda_0 = 21.106114 \text{ cm}$$

Frequency observed: $\nu = \dfrac{\nu_0}{1+z}$

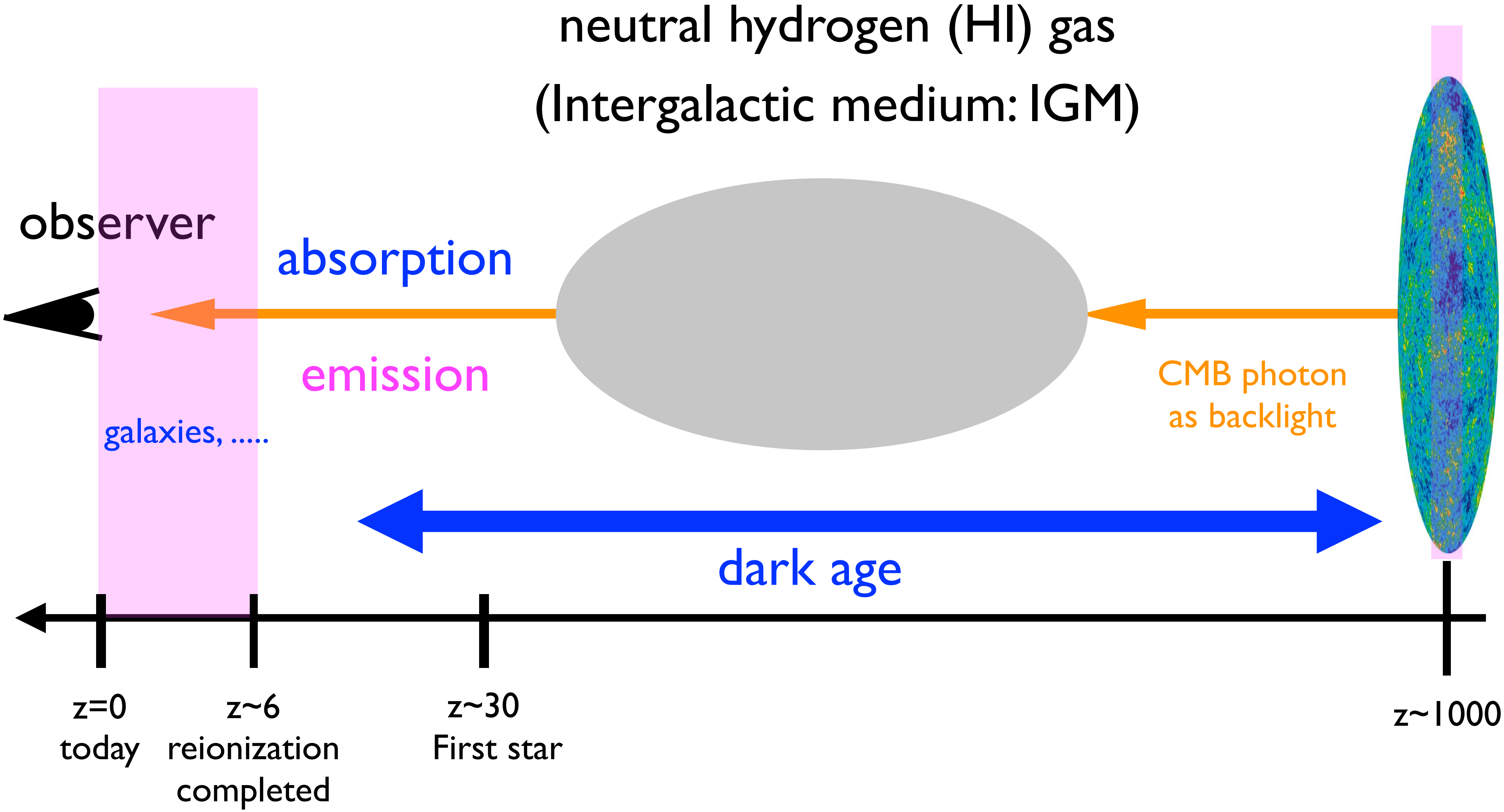
21cm comes from neutral hydrogen



21cm comes from neutral hydrogen



21cm comes from neutral hydrogen



21cm cosmology …

- 21cm line can probe dark ages (which cannot be probed with other observations.)

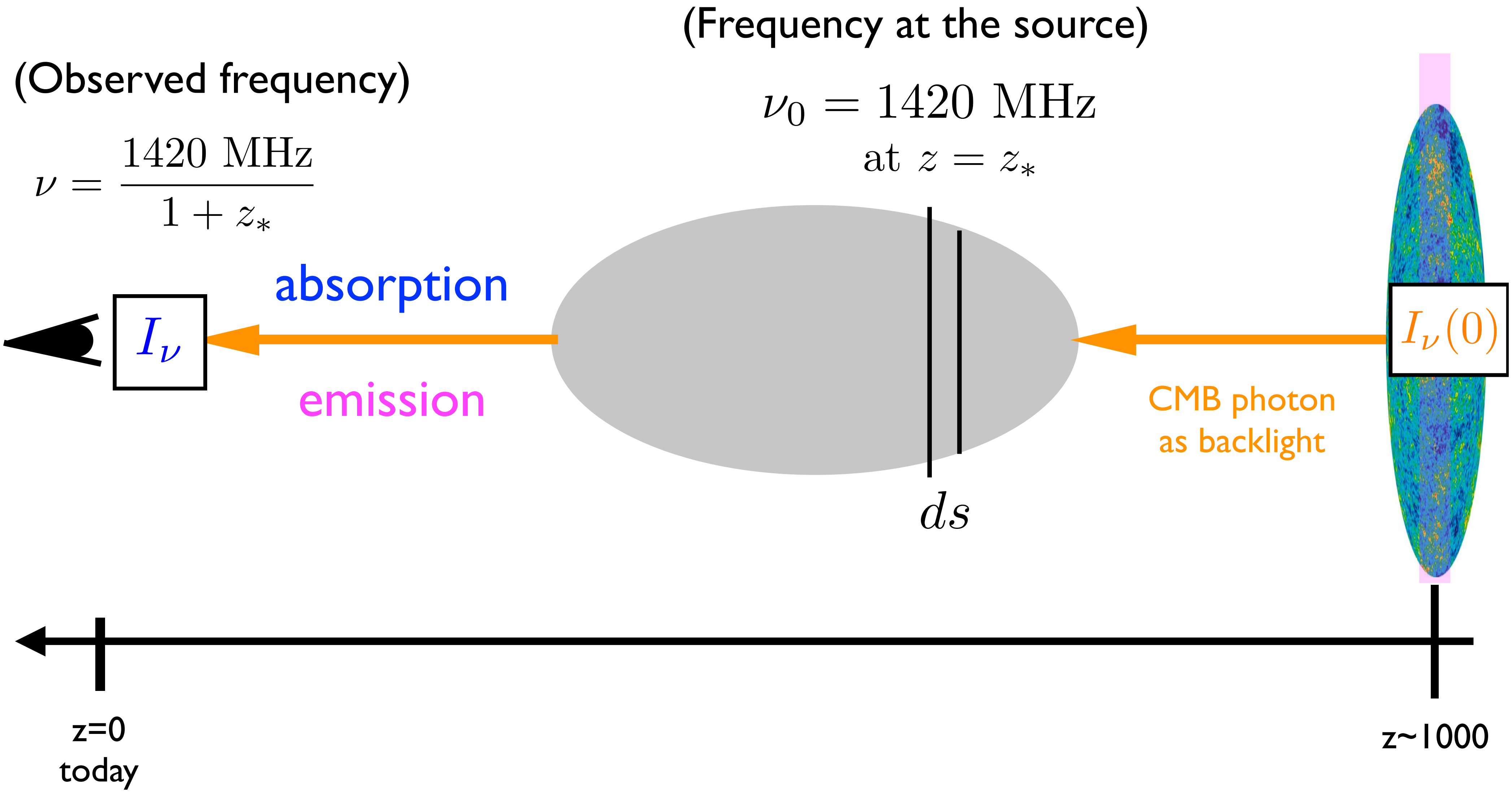
- 21cm can probe 3D directions (can do tomography).

- SKA will operate in 2020s and is expected to give us a lot of information.

(e.g., 21cm can probe fNL better than CMB, …)

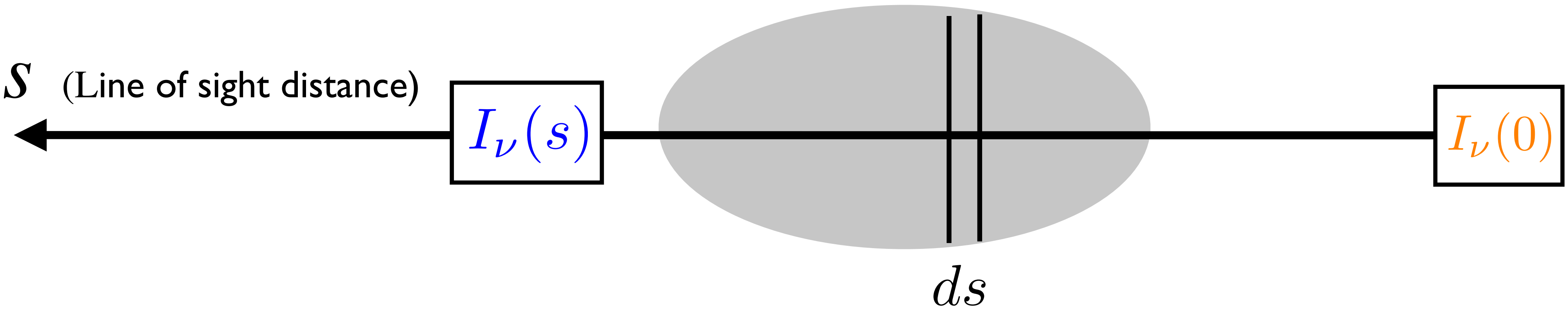
[For review, see Furlanetto, Oh, Briggs astro-ph/0608032; Pritchard, Loeb 1109.6012]

Intensity of absorption/emission



Radiative transfer equation

(describes the evolution of the intensity)



Radiative transfer equation: $$\frac{dI_\nu}{ds} = -\alpha_\nu I_\nu + j_\nu$$

Absorption coefficient

Emission coefficient

→ Rewriting this equation with the optical depth τ_ν

Source function

optical depth: $d\tau_\nu = \alpha_\nu ds$

$$\frac{dI_\nu}{d\tau_\nu} = -I_\nu + \frac{j_\nu}{\alpha_\nu} = -I_\nu + S_\nu$$

Radiative transfer equation

$$\boxed{\frac{dI_\nu}{d\tau_\nu} = -I_\nu + \frac{j_\nu}{\alpha_\nu} = -I_\nu + S_\nu}$$

- When Emission = Absorption $\left(\frac{dI_\nu}{d\tau_\nu} = 0\right)$

  $\rightarrow I_\nu = S_\nu$

- When $S_\nu \, (= j_\nu/\alpha_\nu)$ is constant over the line of sight,

  $\rightarrow I_\nu(s) = I_\nu(0)e^{-\tau_\nu(s)} + S_\nu \left(1 - e^{-\tau_\nu(s)}\right)$

  assuming $\tau_\nu \ll 1$

  Compared to w/ backlight: $\rightarrow I_\nu(s) - I_\nu(0) \simeq \{S_\nu - I_\nu(0)\}\,\tau_\nu(s)$

  - $I_\nu(s) - I_\nu(0) < 0$:Absorption
  - $I_\nu(s) - I_\nu(0) > 0$:Emission

Brightness temperature

- Intensity is often represented by an "effective" temperature called "brightness temperature" T_b

Definition: $I_\nu \equiv B_{\rm bb}(\nu, T_b)$

Black body distribution

- In Rayleigh-Jeans (low frequency) region,

$$B_{\rm BB}(\nu, T) \simeq 2\nu^2 T \rightarrow I_\nu \simeq 2\nu^2 T_b \rightarrow \boxed{T_b = \frac{I_\nu}{2\nu^2}}$$

Brightness temperature

- With Tb, the radiative transfer equation can be written as:

$$T_b(s) - T_b(0) = (\boxed{T} - T_b(0))\,\tau_\nu(s)$$

Temperature of the medium (from S_ν)

$T > T_b(0)$ → Emission

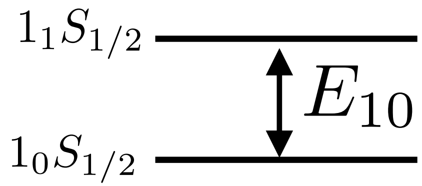
$T < T_b(0)$ → Absorption

$T = T_b(0)$ → No signal

- The evolution of T is very important.

Spin temperature

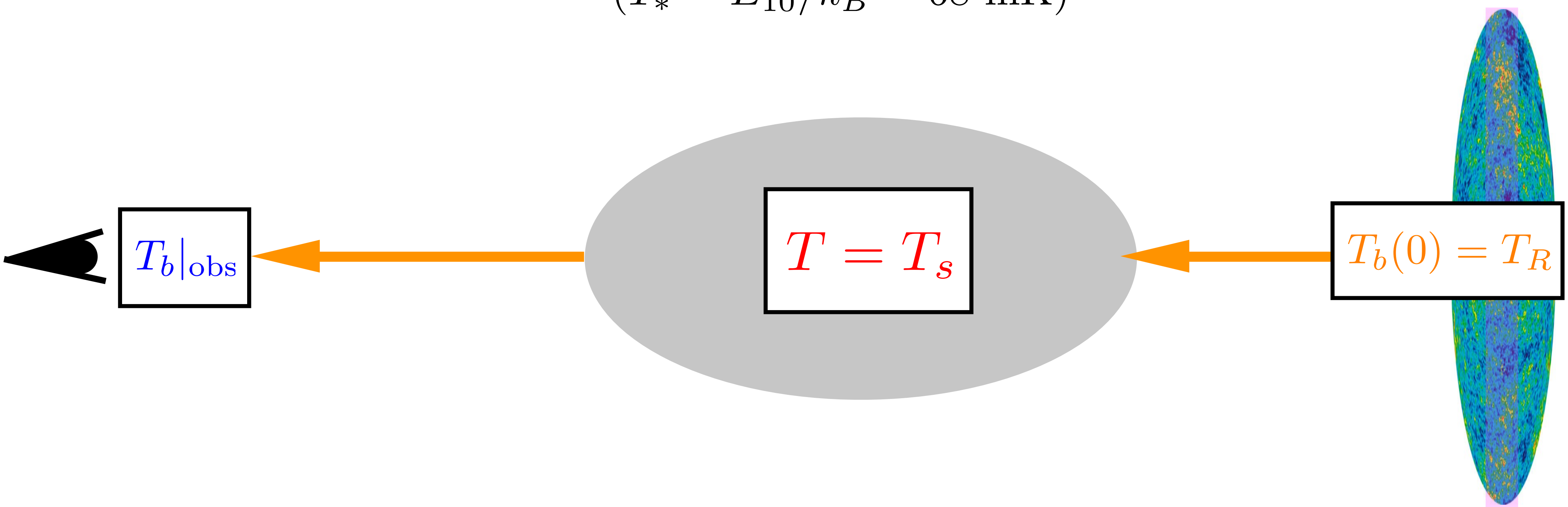
- Number densities of the states (intergalactic medium: IGM) can be described by Boltzmann distribution.



$$\frac{n_1}{n_0} \equiv \frac{\overset{=3}{g_1}}{\underset{=1}{g_0}} e^{-E_{10}/k_B \boxed{T_s}} = 3e^{-T_*/\boxed{T_s}}$$

Spin temperature

$(T_* = E_{10}/k_B = 68 \text{ mK})$



A little wrap up…

- Intensity is often represented by an "effective" temperature called "brightness temperature" T_b

(brightness temperature ~ intensity)

- The temperature of IGM (gas of neutral hydrogen) is called "the spin temperature."

- 21cm signal (absorption, emission) depends on the spin temperature (relative to the CMB).

$$\Delta T_b = T_b - T_R = (T_s - T_R)\,\tau_\nu$$

Optical depth

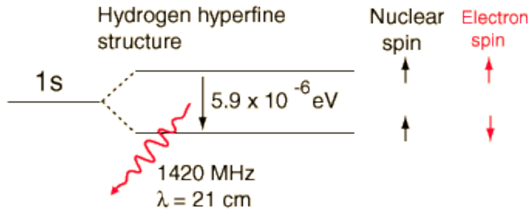
- Definition: $d\tau_\nu = \boxed{\alpha_\nu} ds \longleftarrow \frac{dI_\nu}{ds} = -\boxed{\alpha_\nu} I_\nu + j_\nu$

  Absorption coefficient

- To evaluate the intensity (brightness temperature), we need to know the explicit forms of absorption and emission coefficients.

- The absorption and emission coefficients are determined by microscopic processes.

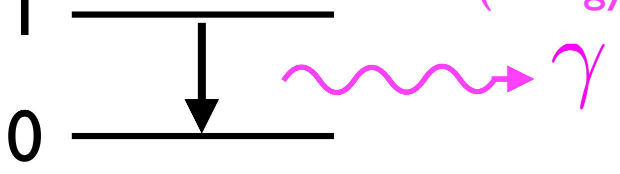
Einstein coefficients



- Description of the 2 level system

  - Spontaneous emission

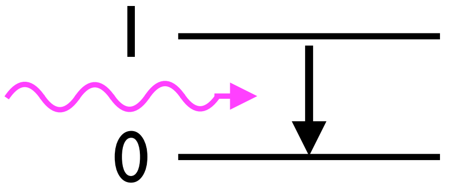
(energy E_{01})



(Einstein A coefficient)

Probability: A_{10}

  - Absorption

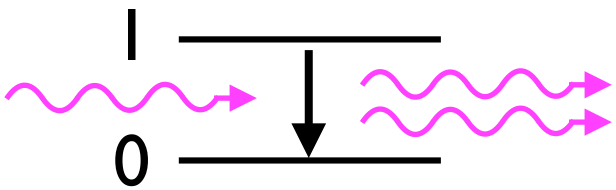


(Einstein B coefficient)

Probability: $B_{01} J_\nu$

(Radiation intensity)

  - Induced emission



Probability: $B_{10} J_\nu$

Microscopic description of radiative transfer equation

Absorption

emission

$$dI_\nu = \boxed{-I_\nu \alpha_\nu ds} + \boxed{j_\nu ds}$$

(Unit: /time/area/sr)

Line profile function

$$= \frac{E_{01}}{4\pi}\phi(\nu) n_1 A_{10} ds$$

$$= \frac{E_{01}}{4\pi}\phi(\nu)\left(n_0 B_{10} - n_1 B_{10}\right) ds$$

(induced emission included here since it depends on I_ν)

→ The absorption coefficient is determined as

$$\alpha_\nu = \frac{E_{01}}{4\pi}\phi(\nu)\left(n_0 B_{10} - n_1 B_{10}\right)$$

Optical depth

After some calculations…

$$\tau_\nu = \int \alpha_\nu ds = \int \frac{E_{01}}{4\pi} \phi(\nu) \left(n_0 B_{10} - n_1 B_{10}\right) ds$$

$$= \int \frac{3A_{10}}{8\pi\nu^2} \left[1 - \exp\left(-\frac{T_*}{T_s}\right)\right] \phi(\nu) n_0 ds$$

$$\boxed{\tau_\nu = \frac{3}{32\pi} \frac{T_*}{T_s} \frac{A_{10}}{\nu_{21}^3} \frac{1}{1+z} \frac{n_{HI}}{\partial v / \partial s}}$$

[Einstein’s relation]

$$(g_0 B_{01} = g_1 B_{10})$$

$$(A_{10} = 4\pi\nu^3 B_{10})$$

[Number density ratio]

$$\left(\frac{n_1}{n_0} = 3e^{-T_*/T_s}\right)$$

[Line profile]

$$\left(\phi(\nu) = \frac{1}{\Delta\nu}\right)$$

Differential brightness temperature

(observed quantity)

$$I_\nu(s) = I_\nu(0)e^{-\tau_\nu(s)} + S_\nu\left(1 - e^{-\tau_\nu(s)}\right)$$

$$\Delta T_b \equiv \frac{T_b(z) - T_\gamma(z)}{1+z}$$

$$= \frac{T_s - T_\gamma(z)}{1+z}(1 - e^{-\tau_\nu}) \simeq \frac{T_s - T_\gamma(z)}{1+z}\tau_\nu$$

$$\boxed{\Delta T_b \simeq 27\ \mathrm{mK}\left(\frac{T_s - T_R}{T_s}\right)\left(\frac{1+z}{10}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.023}\right)\left(\frac{0.15}{\Omega_m h^2}\right)^{1/2} x_{HI}}$$

$T_s < T_\gamma$: absorption $\quad$ $T_s > T_\gamma$: emission

- ΔT_b depends on baryon density, neutral fraction and the spin temperature

What determines the spin temperature?

- Absorption (and spontaneous emission) of CMB photon A_{10} B_{10} B_{01}

- Collisions (HH, He and Hp) C_{01} (excitation rate by collision)

  C_{10} (de-excitation rate by collision)

T_K : Gas temperature $\frac{C_{01}}{C_{10}} = \frac{g_1}{g_0} e^{-T_\star/T_K} \approx 3\left(1 - \frac{T_\star}{T_K}\right)$

- Scattering of Lyα photons (After first astrophysical sources are switched on.)

P_{01} (excitation rate by Lyα photon)

T_c : Color temperature $\frac{P_{01}}{P_{10}} \equiv 3\left(1 - \frac{T_\star}{T_c}\right)$ P_{10} (de-excitation rate by Lyα photon)

Three processes determine the spin temperature

$$n_1(C_{10} + P_{10} + A_{10} + B_{10} I_{\rm CMB}) = n_0(C_{01} + P_{01} + B_{01} I_{\rm CMB})$$

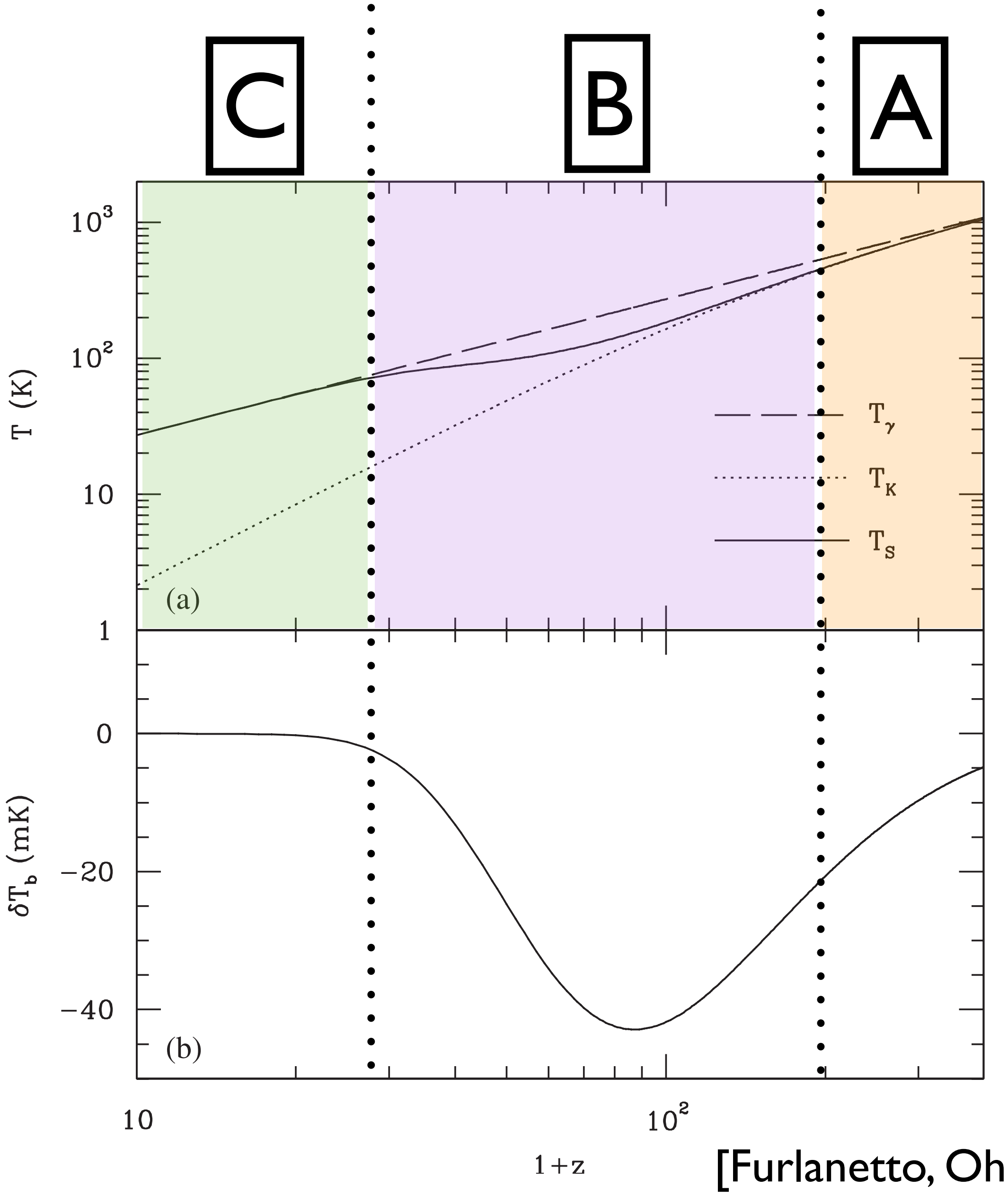
$$\Longrightarrow \quad T_S^{-1} = \frac{T_\gamma^{-1} + x_c T_K^{-1} + x_\alpha T_c^{-1}}{1 + x_c + x_\alpha}$$

Collision — Scattering of Lyα photons

- Coupling coefficients: $x_c \equiv \frac{C_{10}}{A_{10}} \frac{T_*}{T_\gamma}$ $\quad x_\alpha \equiv \frac{P_{10}}{A_{10}} \frac{T_*}{T_\gamma}$

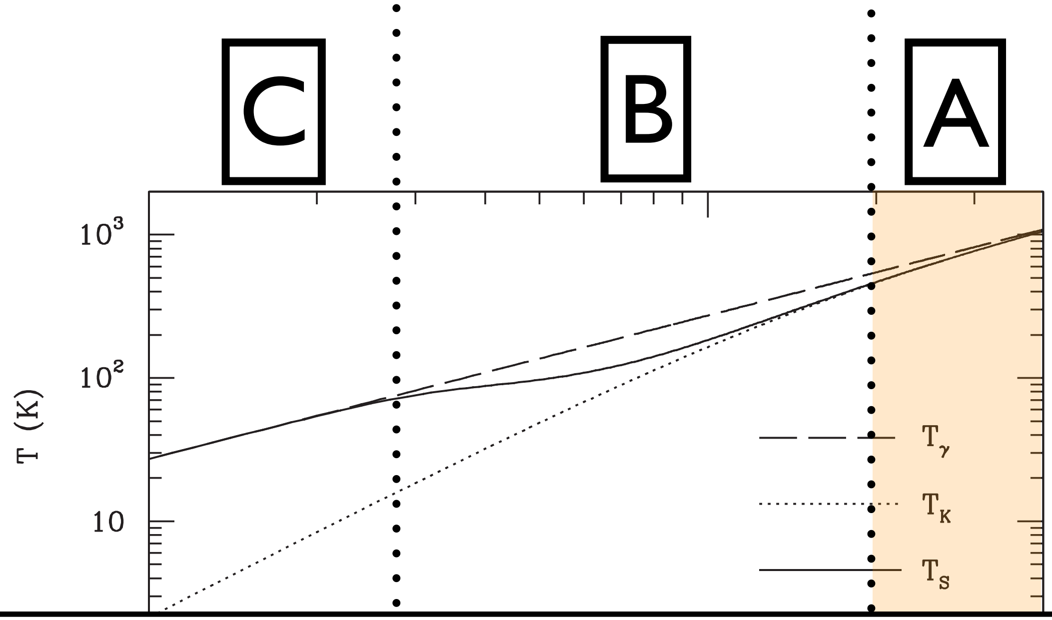
(In most cases of interest, Tk = Tα)

Evolution of ΔT_b (assuming no astrophysical sources)



[Furlanetto, Oh, Briggs astro-ph/0608032]

Evolution of ΔT_b (assuming no astrophysical sources)



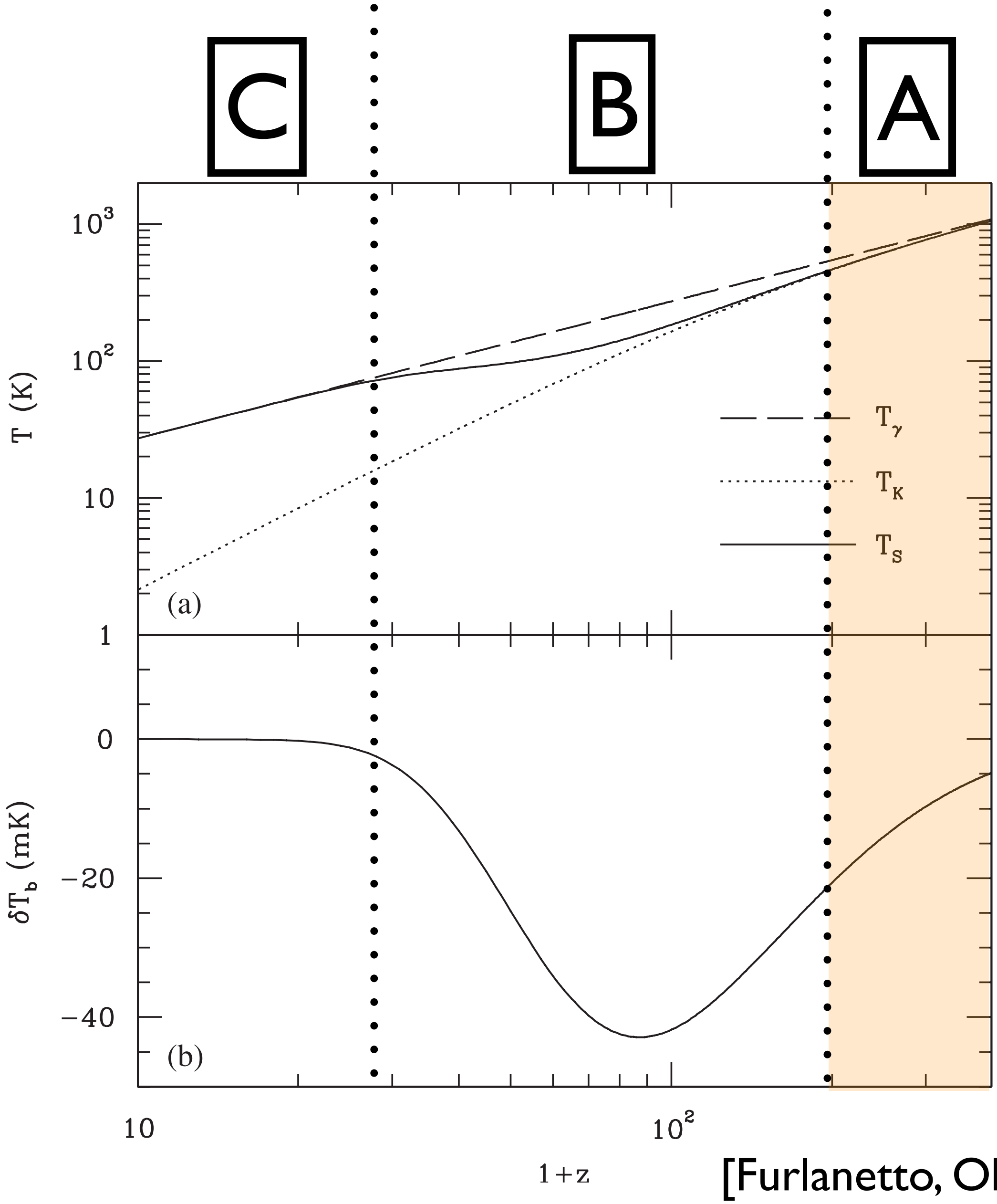
A

- After recombination, there remains residual free electrons to keep T_γ and T_K via Compton scattering.
- Collisional couplings are strong: $T_K = T_s$

$$T_\gamma = T_s = T_K \qquad \Delta T_b = 0 \quad \text{(no 21cm signal)}$$

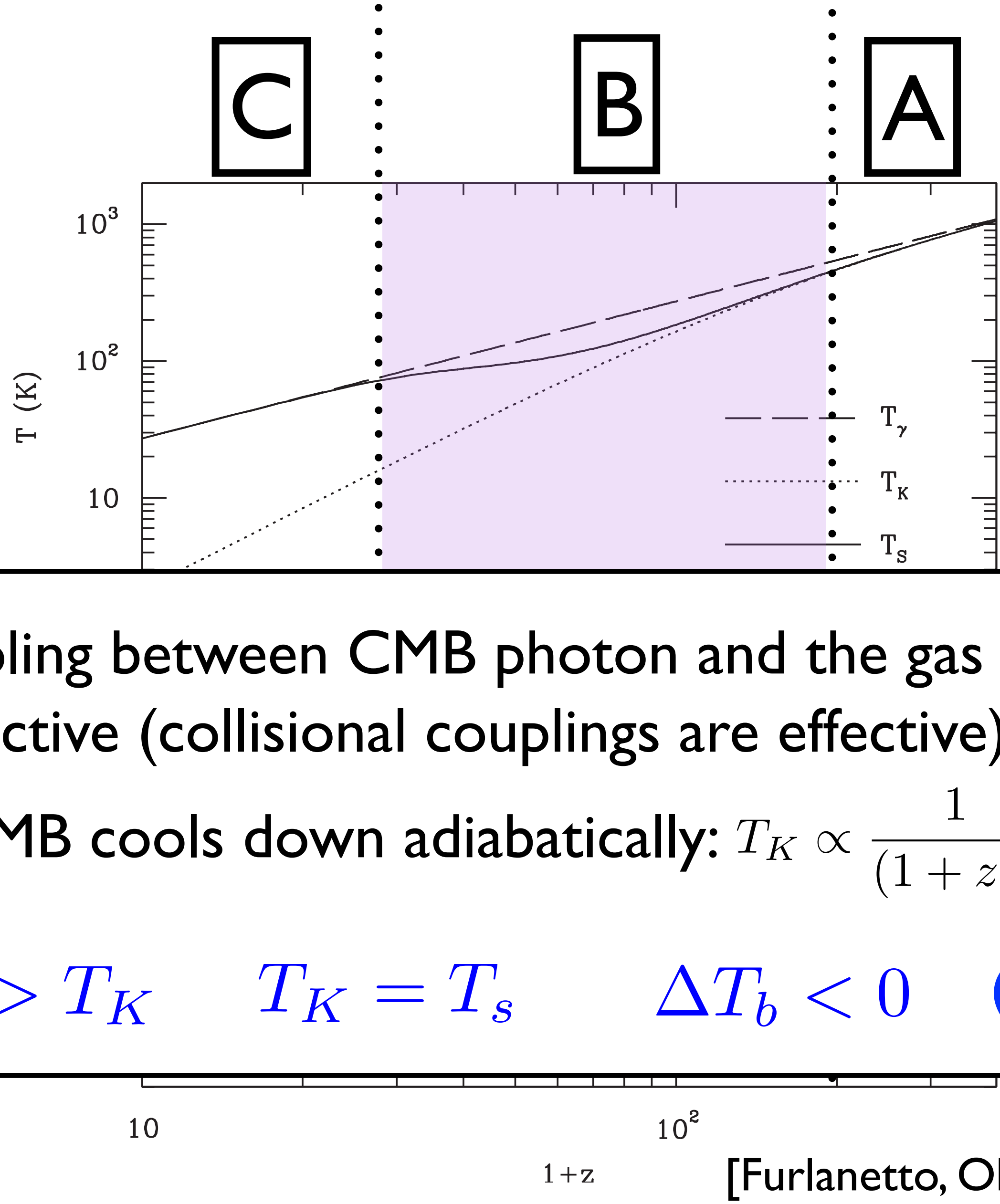
[Furlanetto, Oh, Briggs astro-ph/0608032]

Evolution of ΔT_b (assuming no astrophysical sources)



[Furlanetto, Oh, Briggs astro-ph/0608032]

Evolution of $\Delta T_{\rm b}$ (assuming no astrophysical sources)



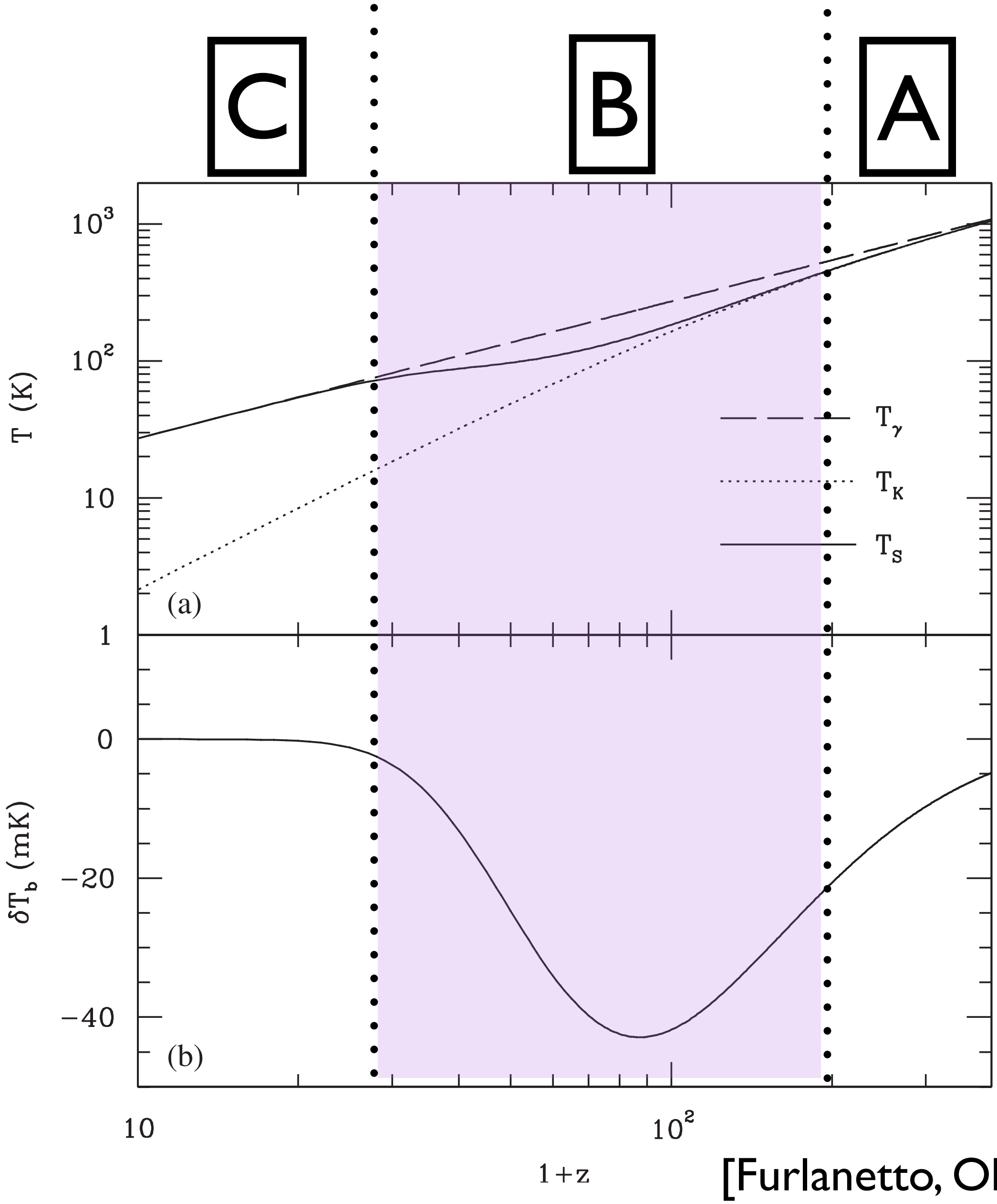
B

- Coupling between CMB photon and the gas becomes ineffective (collisional couplings are effective).
- T_K CMB cools down adiabatically: $T_K \propto \dfrac{1}{(1+z)^2}$

$T_\gamma > T_K$ $T_K = T_s$ $\Delta T_b < 0$ (absorption signal)

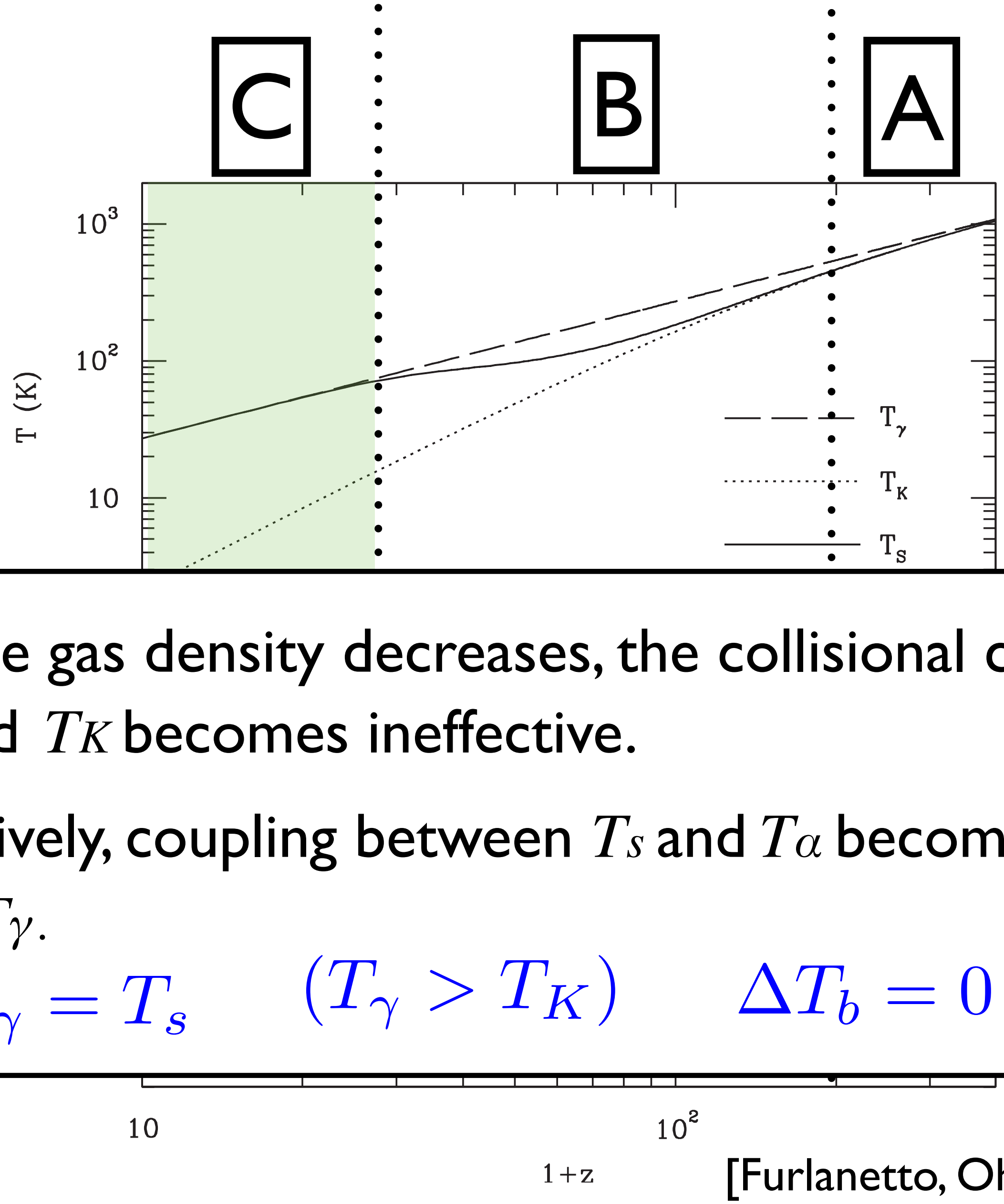
[Furlanetto, Oh, Briggs astro-ph/0608032]

Evolution of ΔT_b (assuming no astrophysical sources)



[Furlanetto, Oh, Briggs astro-ph/0608032]

Evolution of ΔT_b (assuming no astrophysical sources)



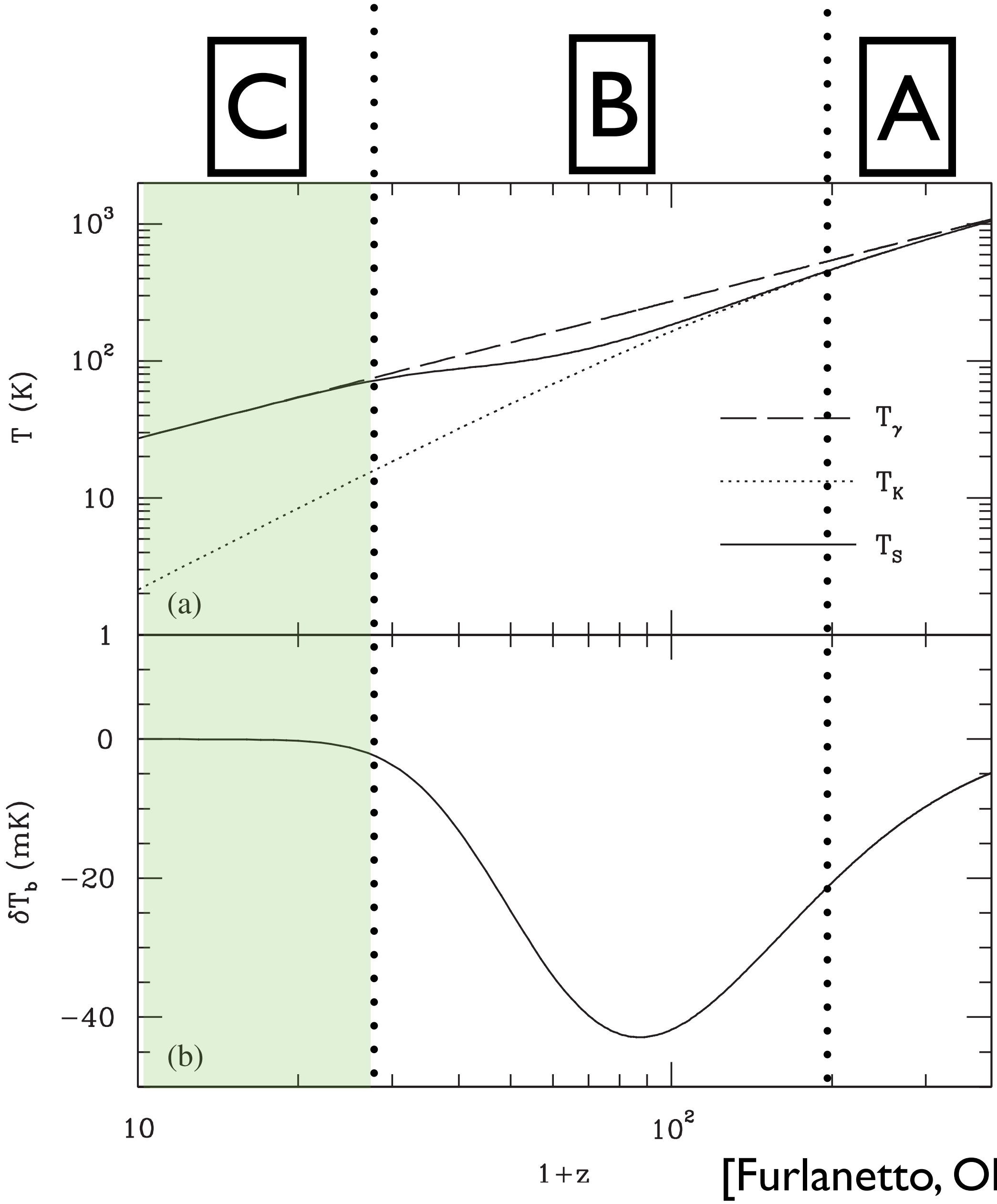
[Furlanetto, Oh, Briggs astro-ph/0608032]

C

- As the gas density decreases, the collisional coupling between T_s and T_K becomes ineffective.
- Relatively, coupling between T_s and T_α becomes bigger to give $T_s = T_\gamma$.

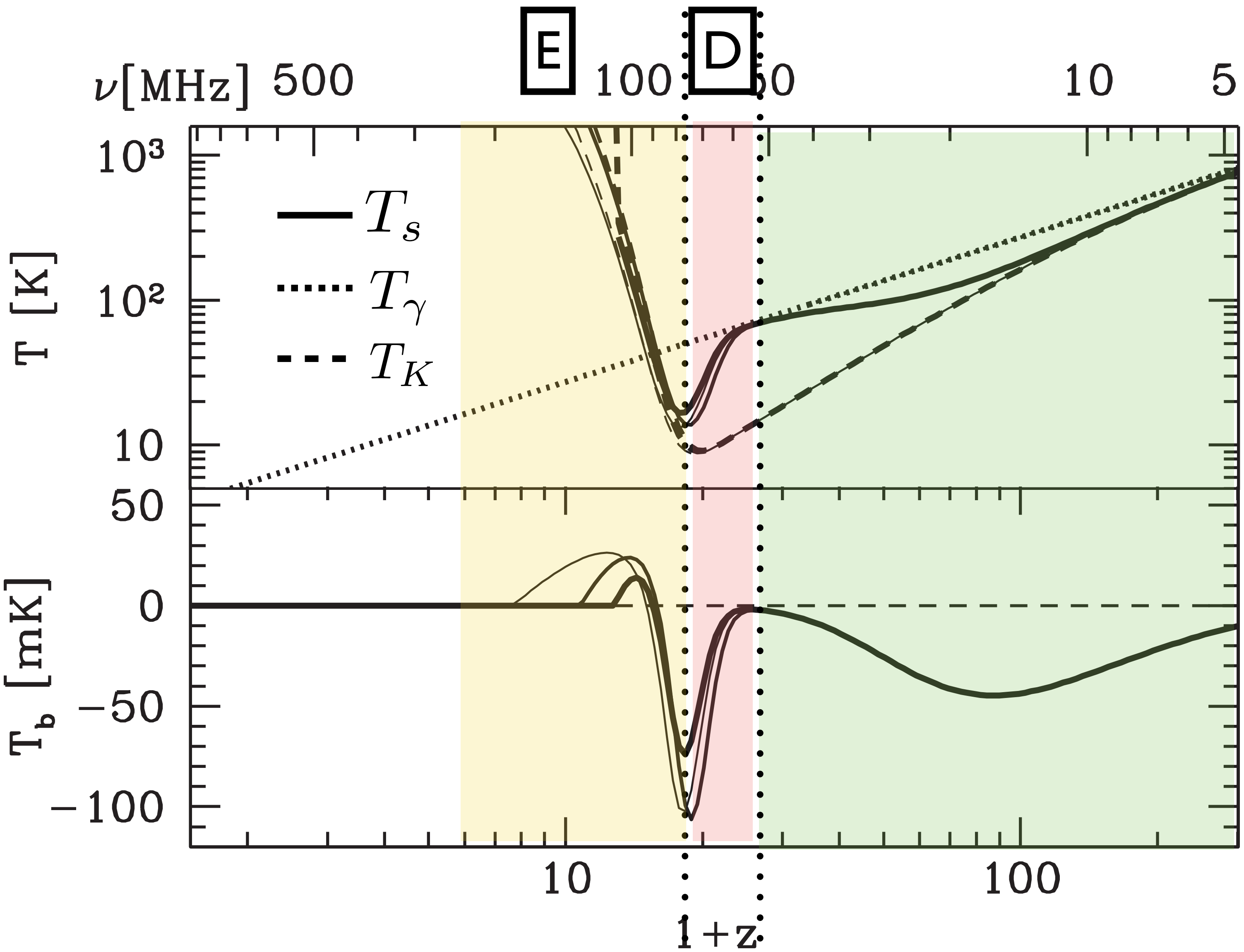
$T_\gamma = T_s$ $(T_\gamma > T_K)$ $\Delta T_b = 0$ (no 21cm signal)

Evolution of ΔT_b (assuming no astrophysical sources)



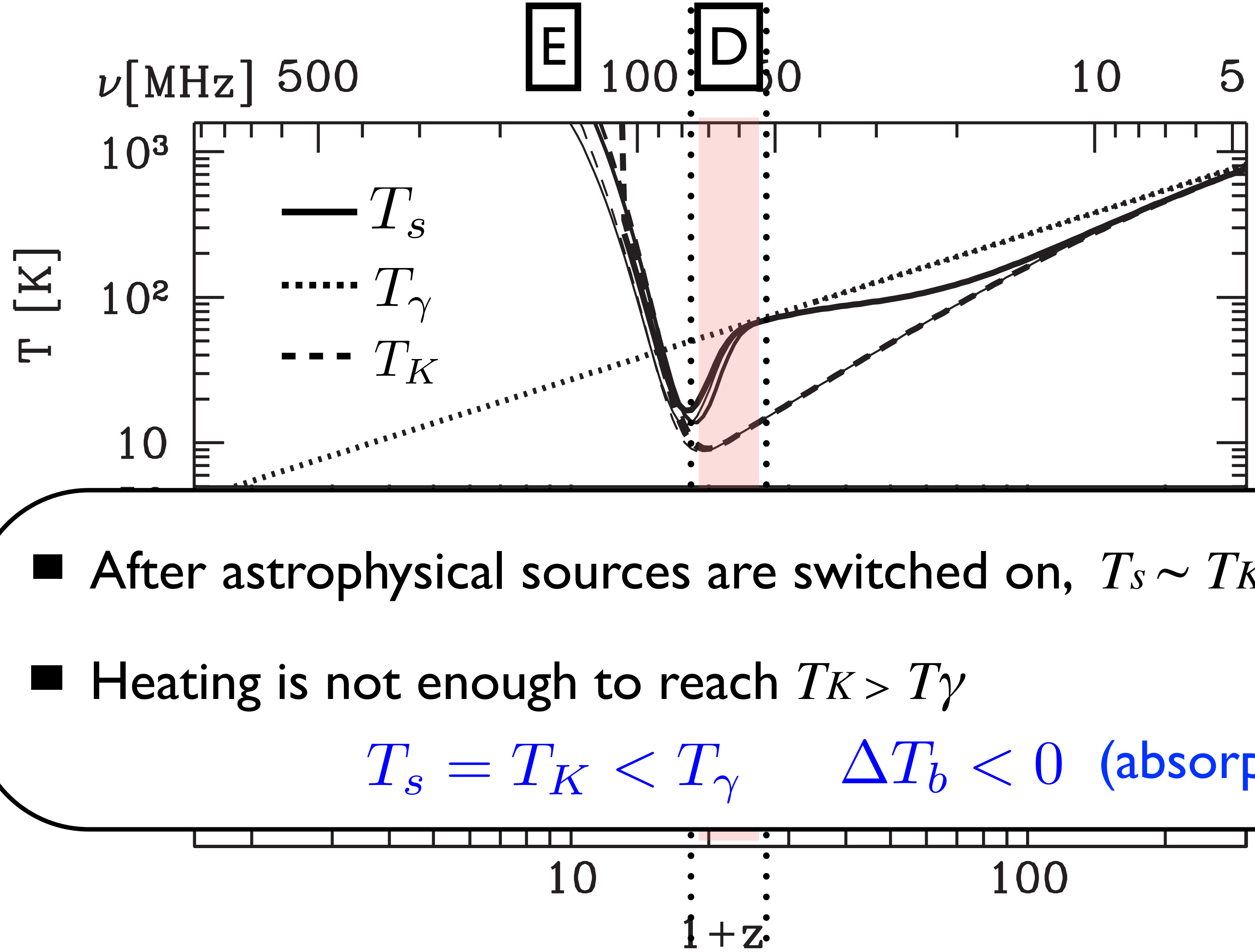
[Furlanetto, Oh, Briggs astro-ph/0608032]

Evolution of ΔT_b (after first astrophysical sources switched on)



[From Pritchard, Loeb 0802.2102]

Evolution of ΔT_{b} (after first astrophysical sources switched on)



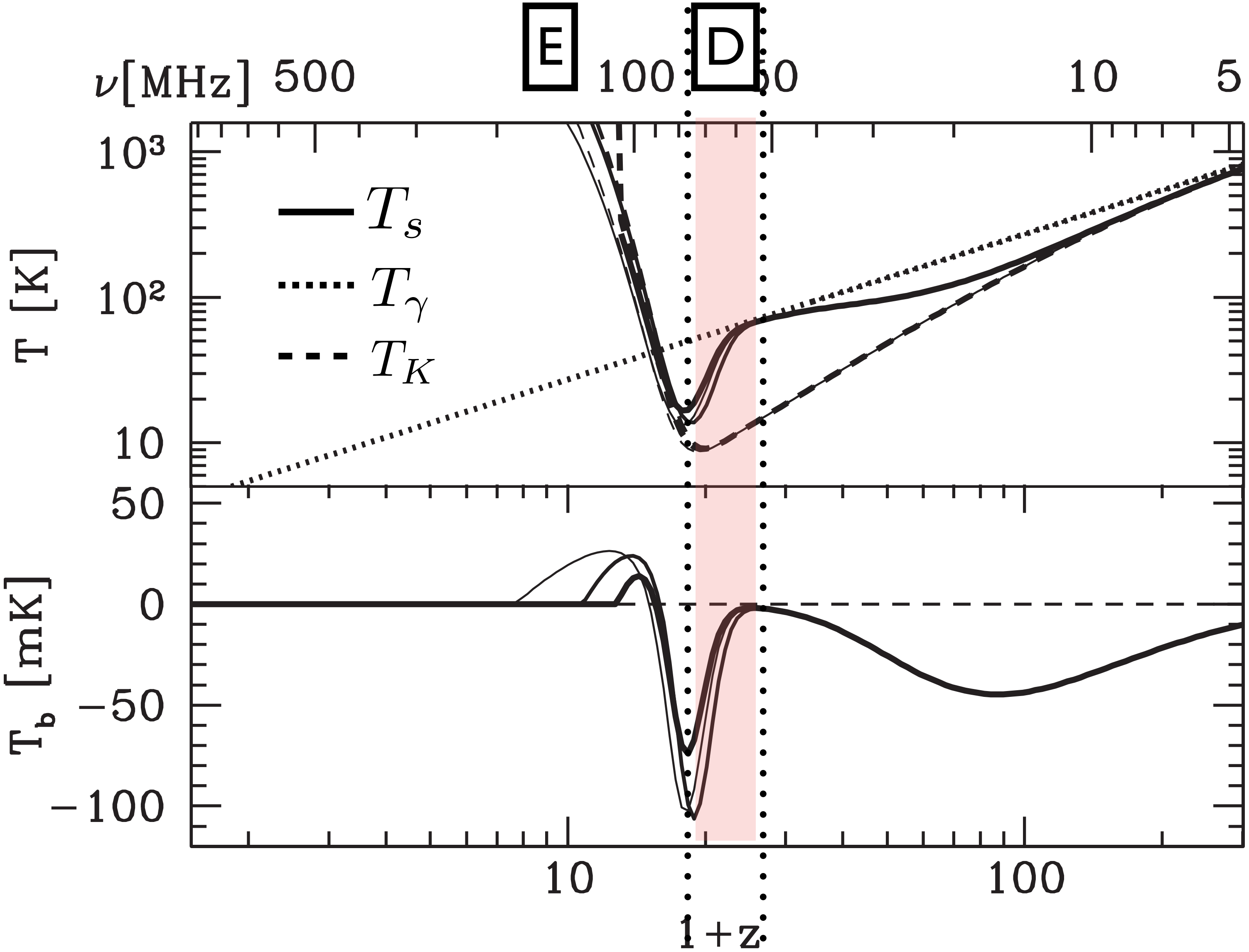
D

- After astrophysical sources are switched on, $T_s \sim T_K$.
- Heating is not enough to reach $T_K > T_\gamma$

$T_s = T_K < T_\gamma$ $\quad \Delta T_b < 0$ (absorption signal)

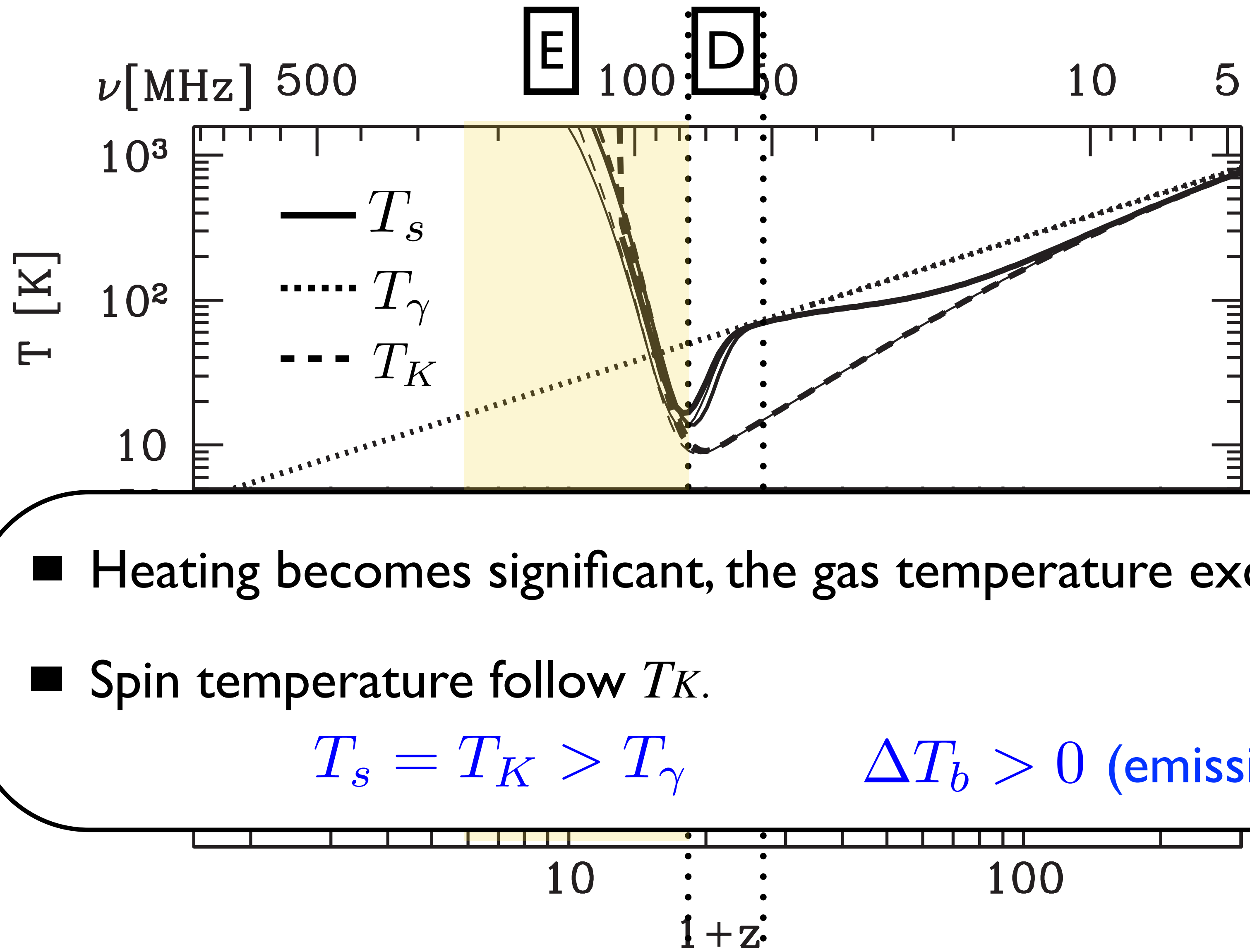
[From Pritchard, Loeb 0802.2102]

Evolution of $\Delta T_{\rm b}$ (after first astrophysical sources switched on)



[From Pritchard, Loeb 0802.2102]

Evolution of ΔT_b (after first astrophysical sources switched on)



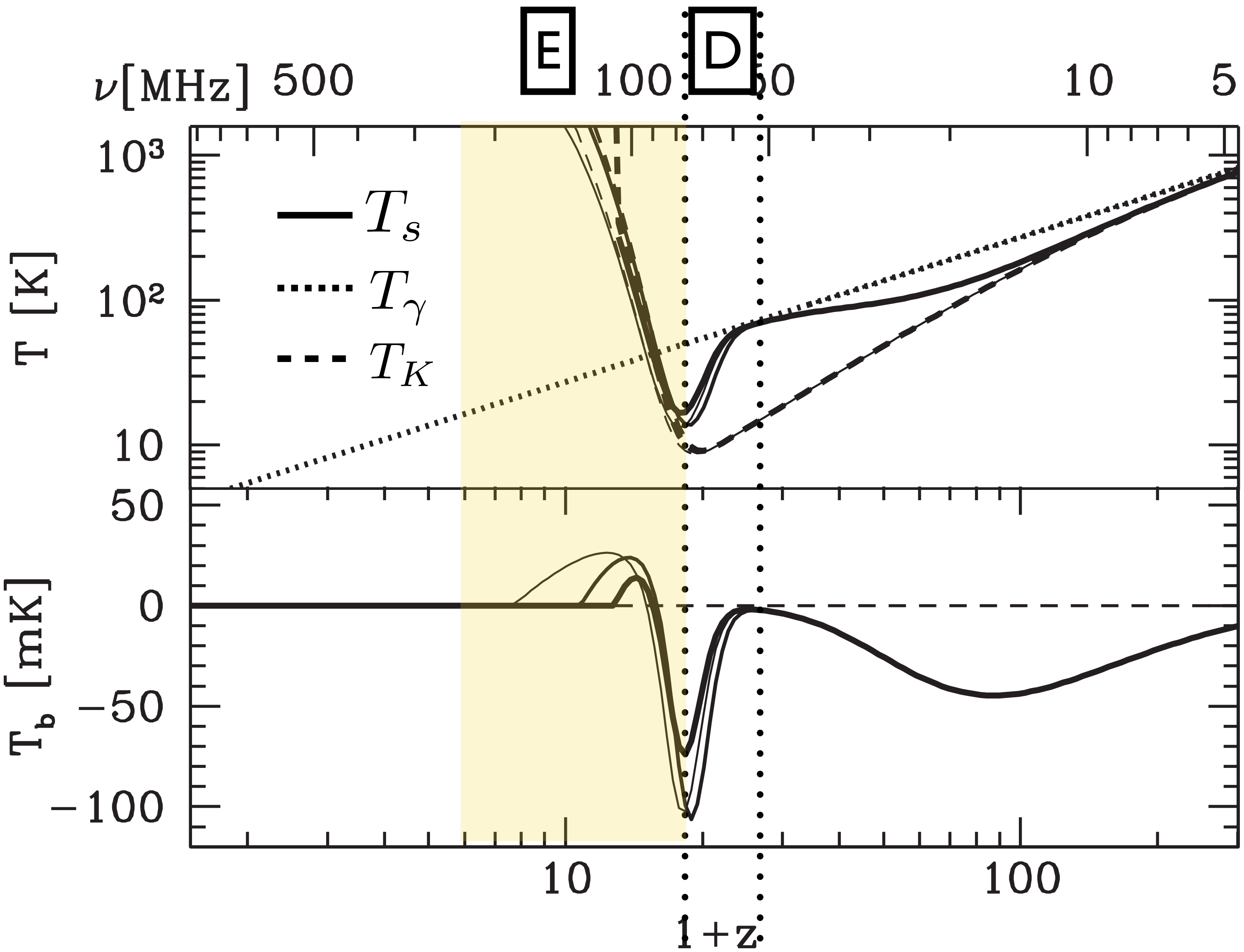
E

- Heating becomes significant, the gas temperature exceed $T\gamma$.
- Spin temperature follow T_K.

$T_s = T_K > T_\gamma$ $\quad\quad$ $\Delta T_b > 0$ (emission signal)

[From Pritchard, Loeb 0802.2102]

Evolution of ΔT_b (after first astrophysical sources switched on)

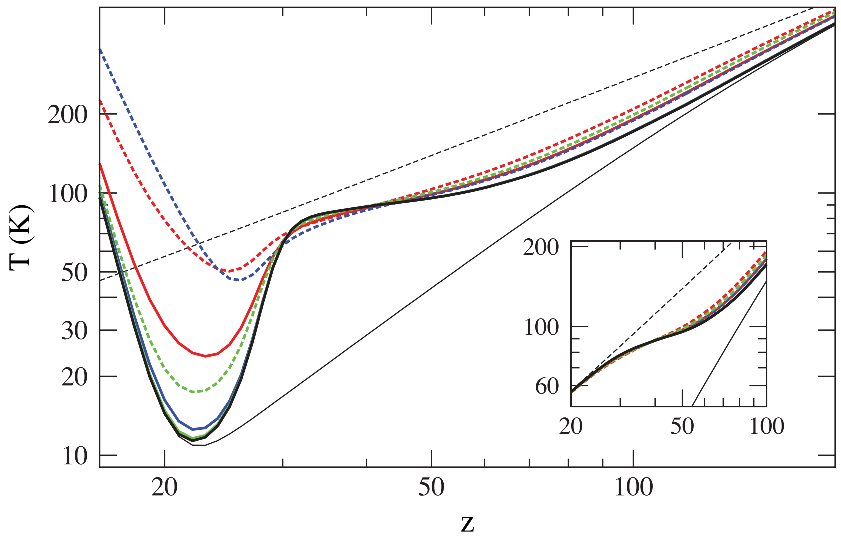


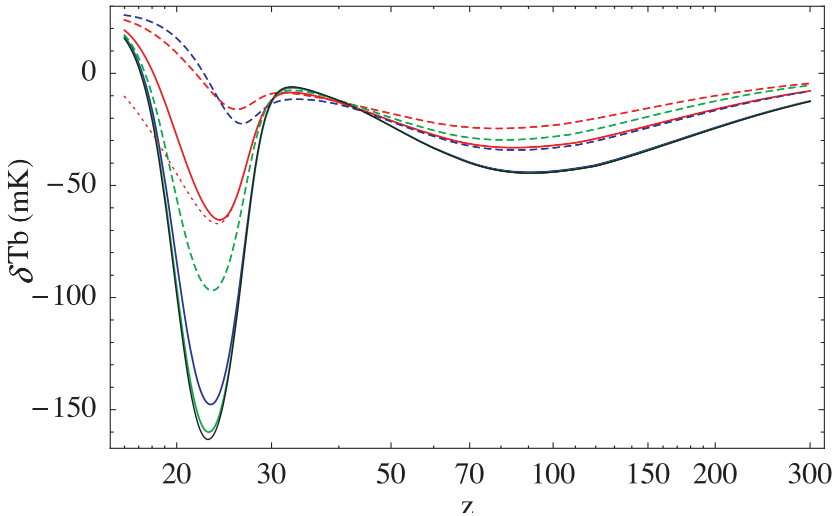
[From Pritchard, Loeb 0802.2102]

Dark Matter annihilation effect on 21cm signal

[Valdes et al 2013]

- Dark matter annihilation deposits energy into IGM.



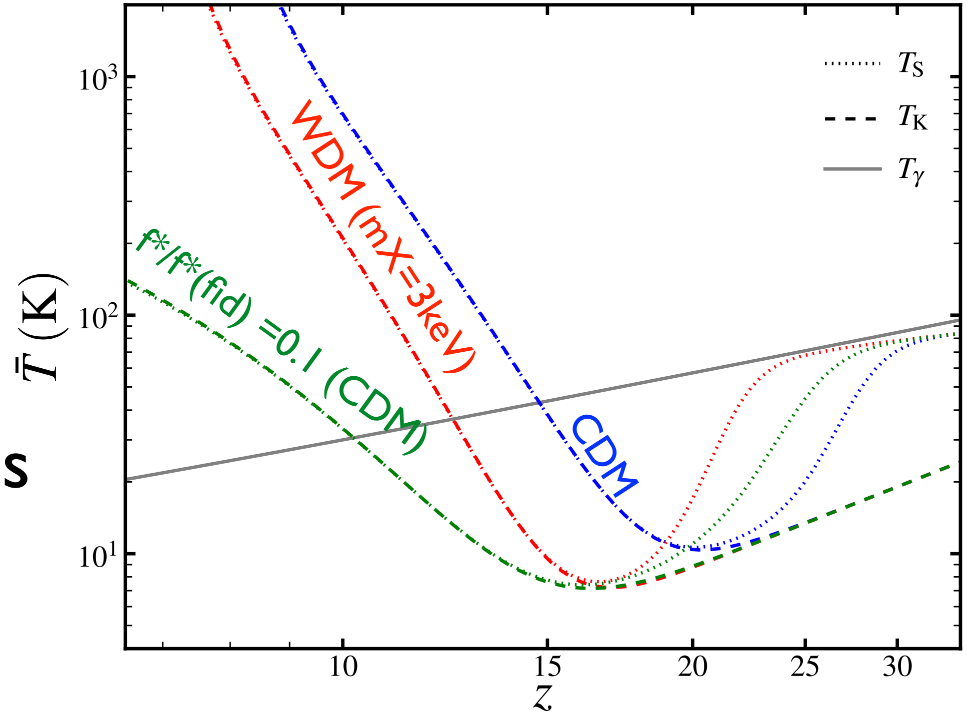


DM model	Mass (GeV)	$\langle\sigma v\rangle$ ($cm^3\ s^{-1}$)	ϵ_0 ($eV\ s^{-1}$)	$\delta\tau_e$	Line style
W^+W^-	200	$\langle\sigma v\rangle_{th} = 3.0 \times 10^{-26}$	5.35×10^{-25}	1.53×10^{-3}	Blue solid
W^+W^-	200	$\langle\sigma v\rangle_{max} = 1.2 \times 10^{-24}$	2.14×10^{-23}	6.09×10^{-2}	Blue dashed
$b\bar{b}$	10	$\langle\sigma v\rangle_{th} = 3.0 \times 10^{-26}$	1.07×10^{-23}	1.80×10^{-2}	Red solid
$b\bar{b}$	10	$\langle\sigma v\rangle_{max} = 1.0 \times 10^{-25}$	3.57×10^{-23}	5.76×10^{-2}	Red dashed
$\mu^+\mu^-$	1000	$\langle\sigma v\rangle_{th} = 3.0 \times 10^{-26}$	1.07×10^{-25}	1.42×10^{-4}	Green solid
$\mu^+\mu^-$	1000	$\langle\sigma v\rangle_{max} = 1.4 \times 10^{-23}$	4.99×10^{-23}	6.18×10^{-2}	Green dashed

Effects of warm DM

[Sitwell et al 2014]

- Non-negligible velocity by WDM suppresses the formation of low-mass halos.
- The star formation is delayed.
- The change in the early sources affects the 21 cm signal.



(f*: fraction of baryon incorporated into star)

Fluctuations of 21 cm

Fluctuations in ΔTb

- (Differential) brightness temperature can also fluctuate in space:

$$n_{HI} = x_H n_H$$
$$\sim (1 - x_i) n_b$$

$$\Delta T_b(z, \vec{x}) = \frac{\boxed{T_s} - T_\gamma(z)}{1+z} \frac{3}{32\pi} \frac{T_*}{\boxed{T_s}} \frac{A_{10}}{\nu_{21}^3} \frac{1}{1+z} \frac{\boxed{n_{HI}}}{\boxed{\partial v / \partial s}}$$

These parts can fluctuate

- Define fluctuation in ΔTb:

$$\delta_{T_b} \equiv \frac{\Delta T_b(z, \vec{x}) - \Delta \bar{T}_b(z)}{\Delta \bar{T}_b(z)}$$

Power spectrum

- 21cm fluctuations

cosmology

cosmology

$$\delta_{T_b} = \beta_b \boxed{\delta_b} + \beta_x \delta_x + \beta_\alpha \delta_\alpha + \beta_T \delta_T - \boxed{\delta_v}$$

baryon density

hydrogen neutral fraction (ionization fraction)

Lyα coupling (Ts)

gas temperature (Ts)

velocity gradient

- Power spectrum

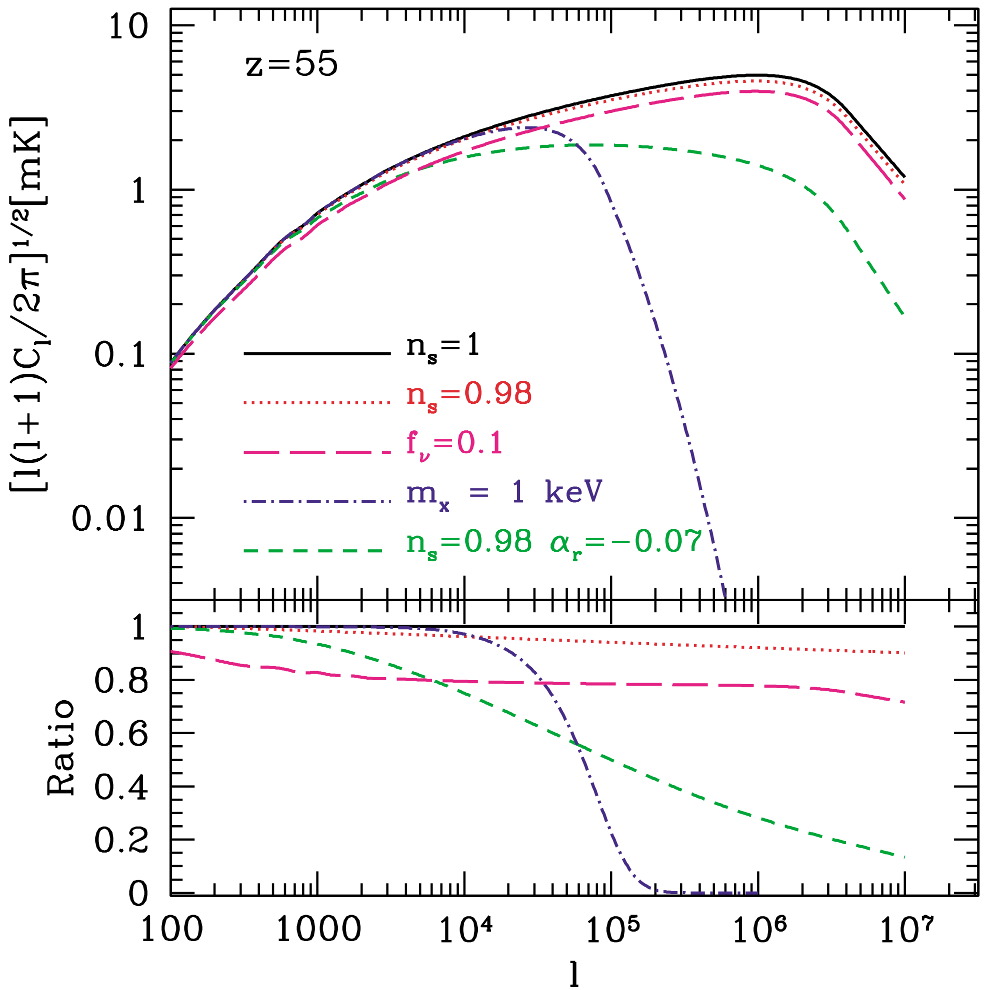
$$\langle \delta_{T_b}(\boldsymbol{k}, z)\delta^*_{T_b}(\boldsymbol{k}', z)\rangle \longrightarrow P_{T_b}(\boldsymbol{k}, z)$$

  - 21cm power spectrum can probe in 3D.

[For review, see Furlanetto, Oh, Briggs astro-ph/0608032; Pritchard, Loeb 1109.6012]

Power spectrum

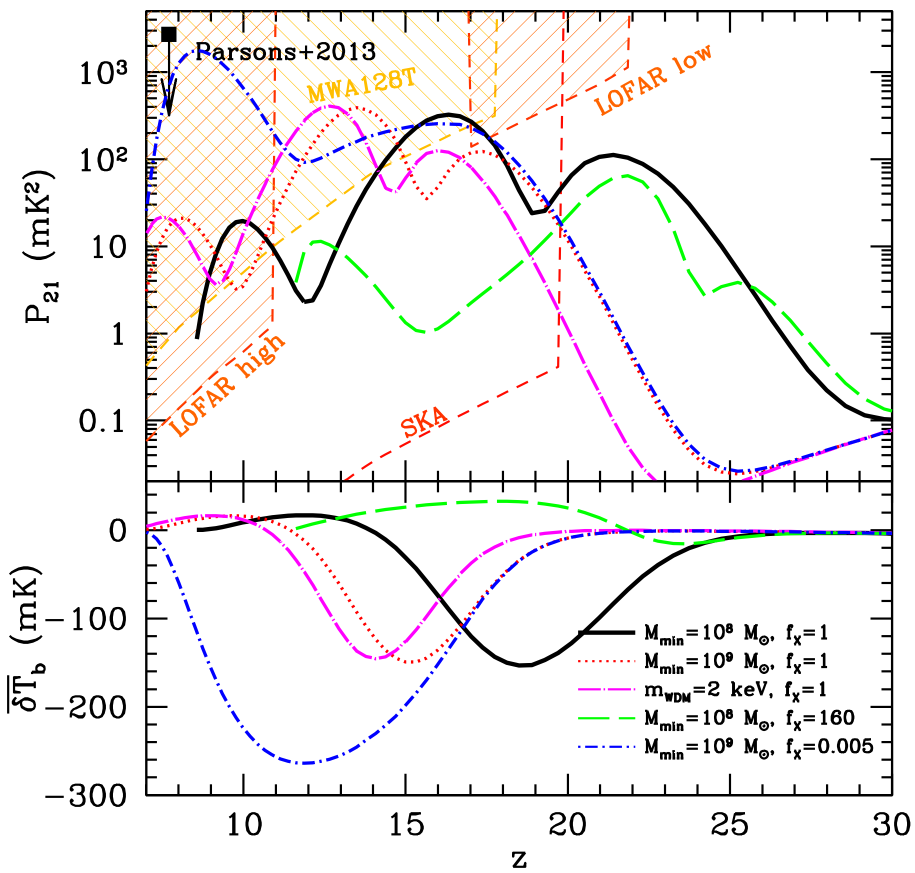
- Power spectrum as a function of multipole for a fixed z



[Loeb, Zaldarriaga 2004]

Power spectrum

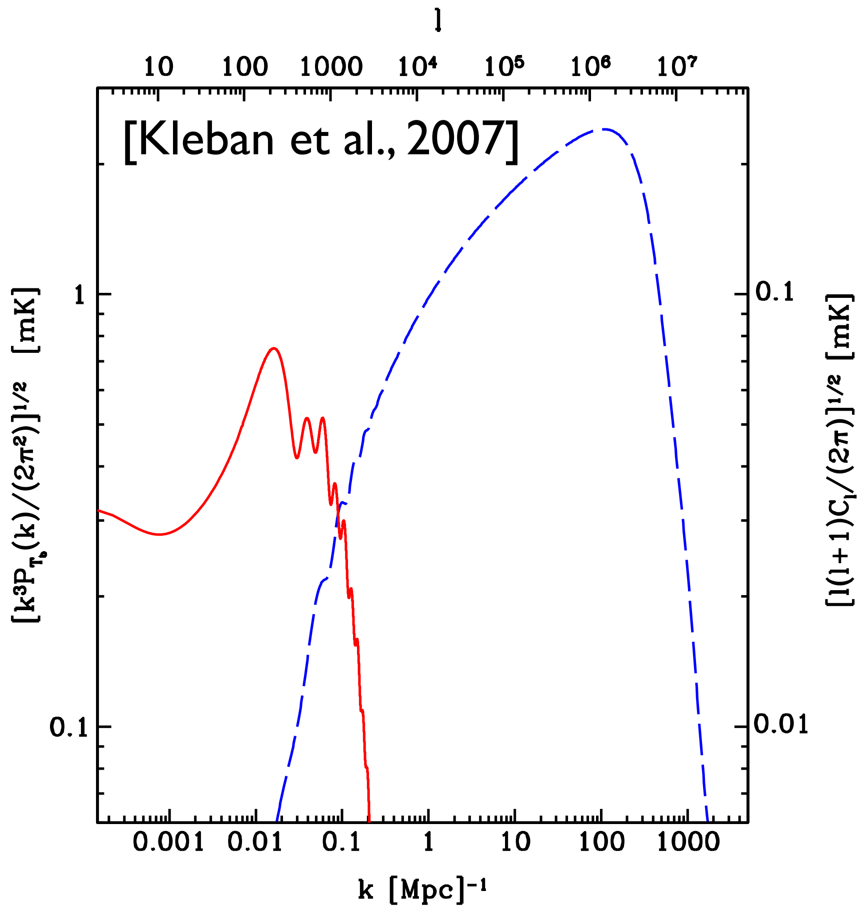
- Power spectrum as a function of z for a fixed k



$$k = 0.1\ \mathrm{Mpc}^{-1}$$

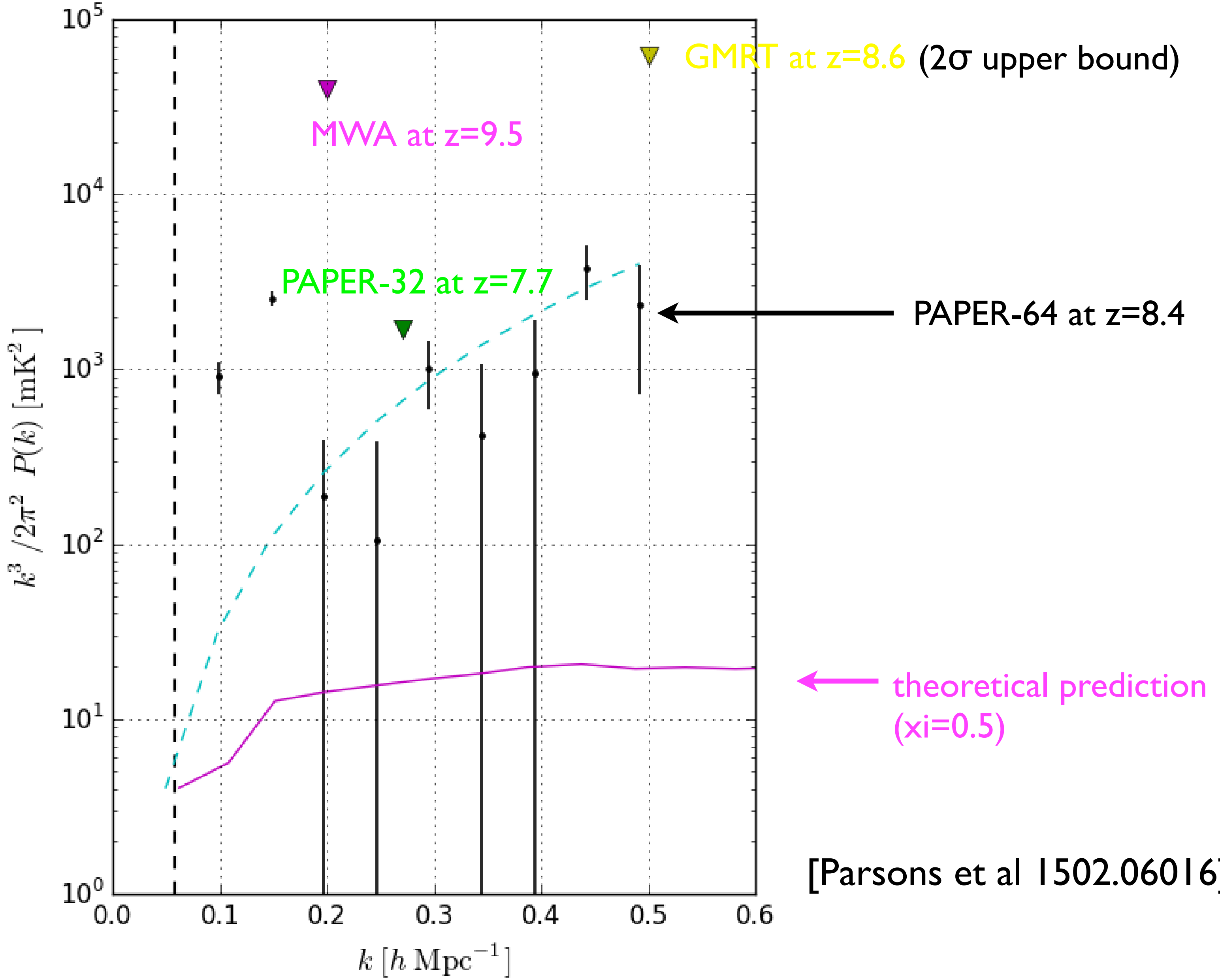
[Mesinger et al 2014]

Power spectrum



- 21cm can probe smaller scales than CMB.

Power spectrum: current data



[Parsons et al 1502.06016]

Observations of 21 cm line

On-going observations:

- LOFAR (LOw Frequency ARray) [Netherlands]

[http://www.lofar.org]

ν = 115 - 230 MHz,   30-80 MHz

- MWA (Murchison Widefield Array) [western Australia]

ν = 80 - 300 MHz

[http://www.mwatelescope.org/science]

- PAPER (Precision Array to Probe the Epoch of Reionization)

[South Africa]

ν = 100 - 200 MHz

[http://eor.berkeley.edu]

$\nu = 70 \text{ MHz} \longrightarrow z \sim 20$ $\nu = 200 \text{ MHz} \longrightarrow z \sim 6$

Future observation

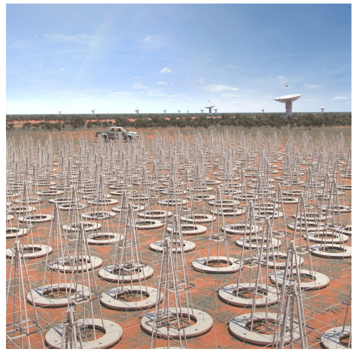
- SKA (Square Kilometer Array)

[South Africa & Australia]

  - SKA1 (Phase 1): 2018 - 2023 construction (2020+early science)

    SKA1-mid: 0.95-1.76 GHz, 4.6-14(24) GHz, 0.13-1.1 GHz [South Africa]

    SKA1-low: 50-350 MHz [Australia]



  - SKA2 (Phase 2): 2023 - 2030 construction

[https://www.skatelescope.org]

- Omniscope (next+1 generation) [Tegmark & Zaldarriaga, 2009]

Cosmology with 21 cm

Cosmology with 21 cm

■ Dark matter

- Dark matter annihilation [Furlanetto, Oh, Pierpaori 2006; Valdes et al., 2007; Natarajan, Dominik, Schwarz 2009; ....]

- Warm dark matter [Sitwell et al 2013; Sekiguchi, Tashiro 2014; Carucci et al 2015]

- Differentiating CDM and bayron isocurvature modes [Kawasaki, Sekiguchi, TT 2011]

⋮

■ Neutrino

- Neutrino masses [Pritchard, Pierpaoli 2008; Oyama, Shimizu, Kohri 2012]
- Lepton asymmetry [Kohri, Oyama, Sekiguchi, TT 2014]

Cosmology with 21 cm

- Inflation (primordial fluctuations)
  - Primordial non-Gaussianity [Cooray 2006; Pillepich et al 2007; Yokoyama et al 2011; Joudaki et al 2011; Chongchitnan, Silk 2012; Yamauchi et al 2014; Munos et al 2015…]
  - Precise measurement of power spectrum
    [Barger et al, 2009; Adshead et al 2010, Kohri, Oyama, Sekiguchi TT 2013]
  - Initial state for the inflation [Kleban et al, 2007]
  - Compensated isocurvature fluctuation [Gordon, Pritchard 2009]

Cosmology with 21 cm

- Cosmological parameter estimation

  [Mao et al 2008; McQuinn et al 2006, ….]

- Dark energy

  [Wyithe et al 2008; Archidiacono et al 2014; Bull et al 2014; Kohri, Oyama, Sekiguchi, TT in prep….]

- Cosmic string

  [Brandenberger et al 2006; Khatri, Wandelt 2008; Hernandez et al 2011, 2012, …]

⋮

Primordial Non-Gaussianity

- Primordial non-Gaussianity is one of the important observable to check the inflation.

Bispectrum

- Non-Gaussianity is usually characterized by fNL

$$\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \zeta_{\vec{k}_3} \rangle \quad = \quad (2\pi)^3 B_\zeta(k_1, k_2, k_3) \delta(\vec{k}_1 + \vec{k}_2 + \vec{k}_3).$$

(amplitude) x (shape dependent function)

$f_{\rm NL}$ $\qquad$ $F(k_1, k_2, k_3)$

$$\left(f_{\rm NL} \sim \frac{B_\zeta}{P_\zeta^2} \right)$$

If fluctuations are Gaussian, $f_{\rm NL} = 0$

Primordial Non-Gaussianity

- Primordial non-Gaussianity is one of the important observable to check the inflation.

- Planck has already obtained a severe constraint on fNL.

(Temperature+polarization)

$$f_{\rm NL}^{\rm (local)} = 0.8 \pm 5.0, \quad f_{\rm NL}^{\rm (equil)} = -4 \pm 43, \quad f_{\rm NL}^{\rm (ortho)} = -26 \pm 21$$

(68 % CL)

[Planck collaboration 2015]

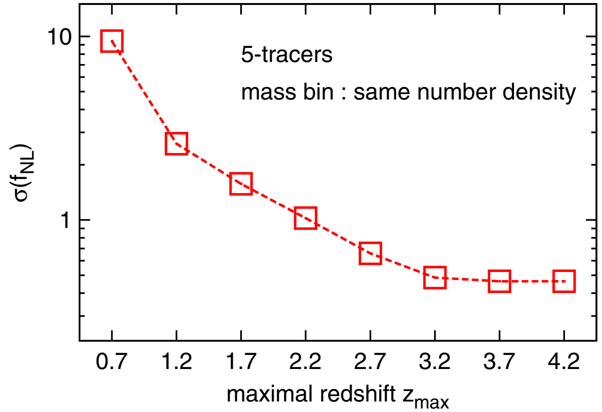
- Standard single-field inflation models predict fNL~O(0.01)

(Multi-field models can predict fNL~O(1).)

- Future CMB (e.g. CMBpol) can reach fNL~O(1).

Probing primordial Non-Gaussianity w/21cm

- SKA can reach fNL ~ O(0.1)
  (+Euclid)
  - Scale-dependent bias
  - Multi-tracer technique



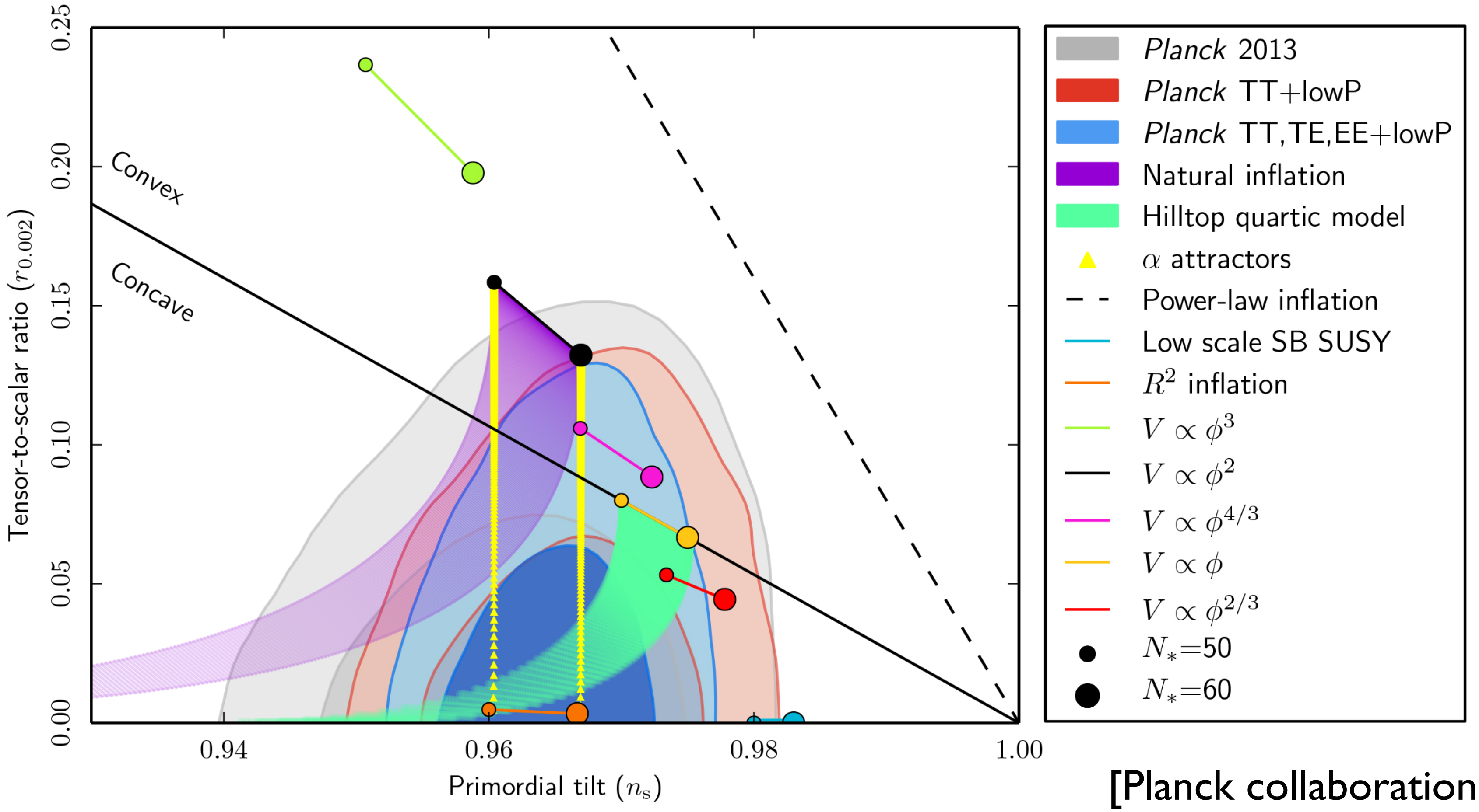
[Yamauchi et al 2014]

- In principle, 21cm can reach fNL ~ O(0.01)
  - Cosmic-variance-limited
  - 30 < z < 100

PNG type	$\sigma_{f_{NL}}$ (1 MHz)	$\sigma_{f_{NL}}$ (0.1 MHz)
Local	0.12	0.03
Equilateral	0.39	0.04
Orthogonal	0.29	0.03
$J = 1$	1.1	0.1
$J = 2$	0.33	0.05
$J = 3$	0.85	0.09

[Munos et al 2015]

Constraints on inflationary models



[Planck collaboration 2015]

Spectral index: $n_s = 0.968 \pm 0.006$ (68 % CL)

Tensor-to-scalar ratio: $r < 0.12$ (95 % CL) (Planck/BICEP2/Keck)

Precise measurement of power spectrum

- Inflation models can be probed with spectral index ns and the tensor-to-scalar ratio r.

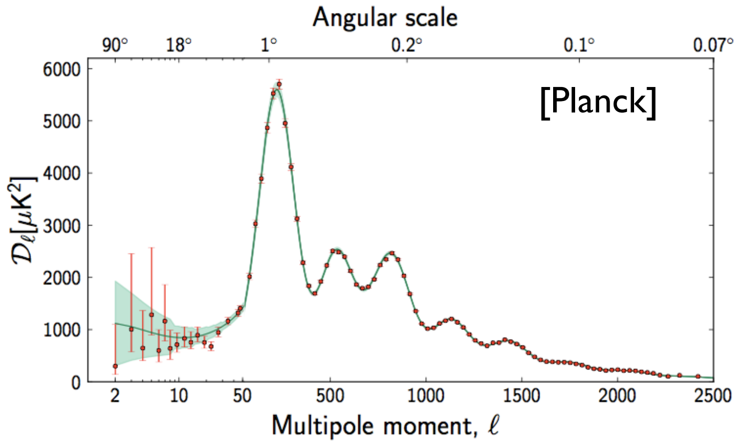
- To test inflationary models, more information would be necessary.

  (Non-Gaussianity does not help for standard single-field inflation models.)

- More precise measurements of power spectrum may be very useful.

  → higher order scale-dependence might help

Power spectrum



Primordial (scalar) power spectrum:

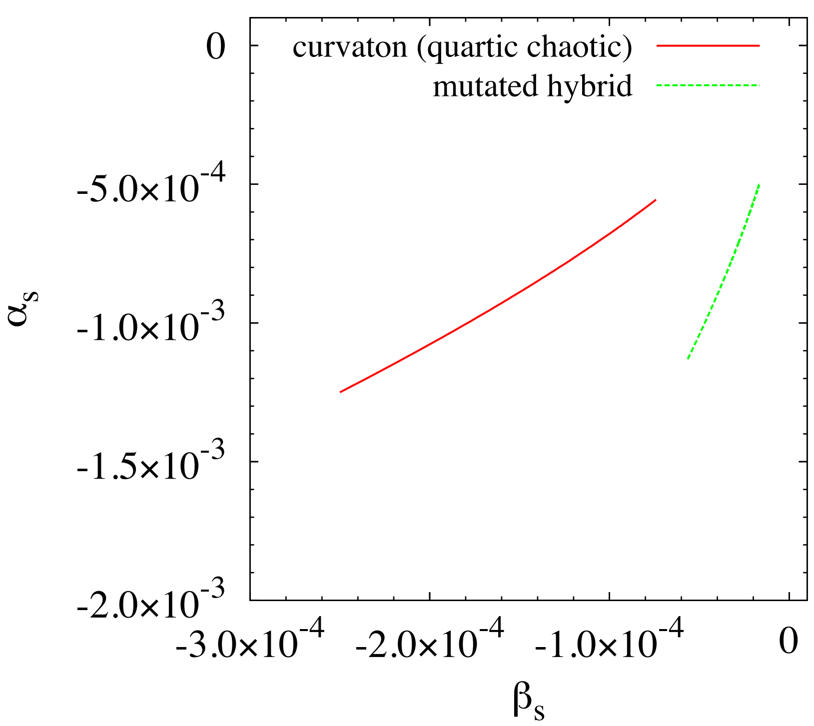
$$\mathcal{P}_\zeta(k) = A_s(k_{\rm ref}) \left(\frac{k}{k_{\rm ref}}\right)^{n_s - 1 + \frac{1}{2}\alpha \ln(k/k_{\rm ref}) + \frac{1}{6}\beta \ln^2(k/k_{\rm ref})}$$

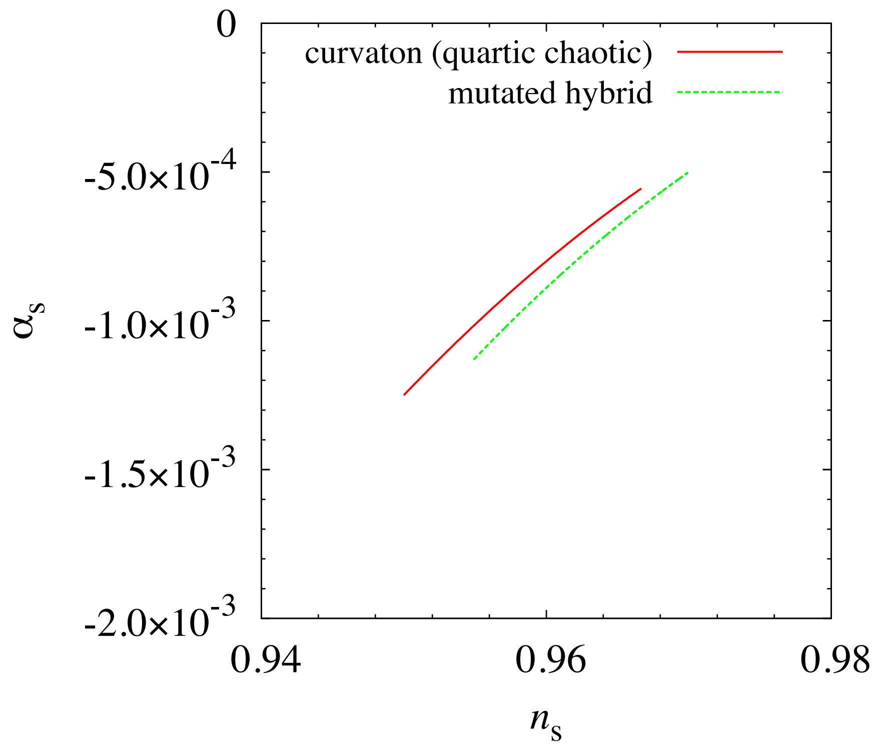
- Spectral index: $n_s = 0.9586 \pm 0.0056$
- Running of ns: $\alpha = 0.009 \pm 0.010$ ~O(SR^2)
- Running of the running of ns: $\beta = 0.025 \pm 0.013$ ~O(SR^3)

(68% CL) [Planck TT+TE+EE+lowP, Planck collaboration 2015]

→ futuristic 21cm observations can probe more

Running of running: useful ?





(mutated hybrid)

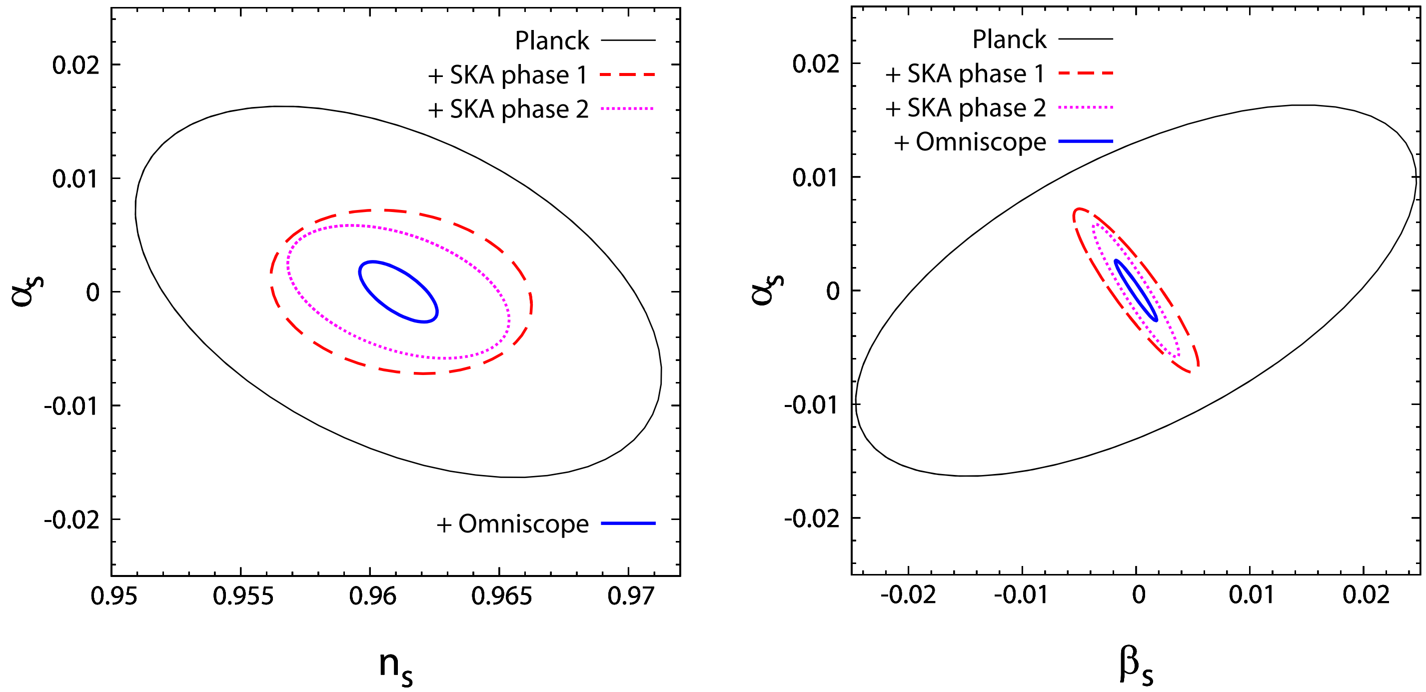
[Kohri, Oyama, Sekiguchi, TT 2013]

$$V(\phi) = V_0 \left[1 - \left(\frac{\mu}{\phi} \right)^q + \cdots \right]$$

Running of running may be useful in some cases

Precise measurement of power spectrum

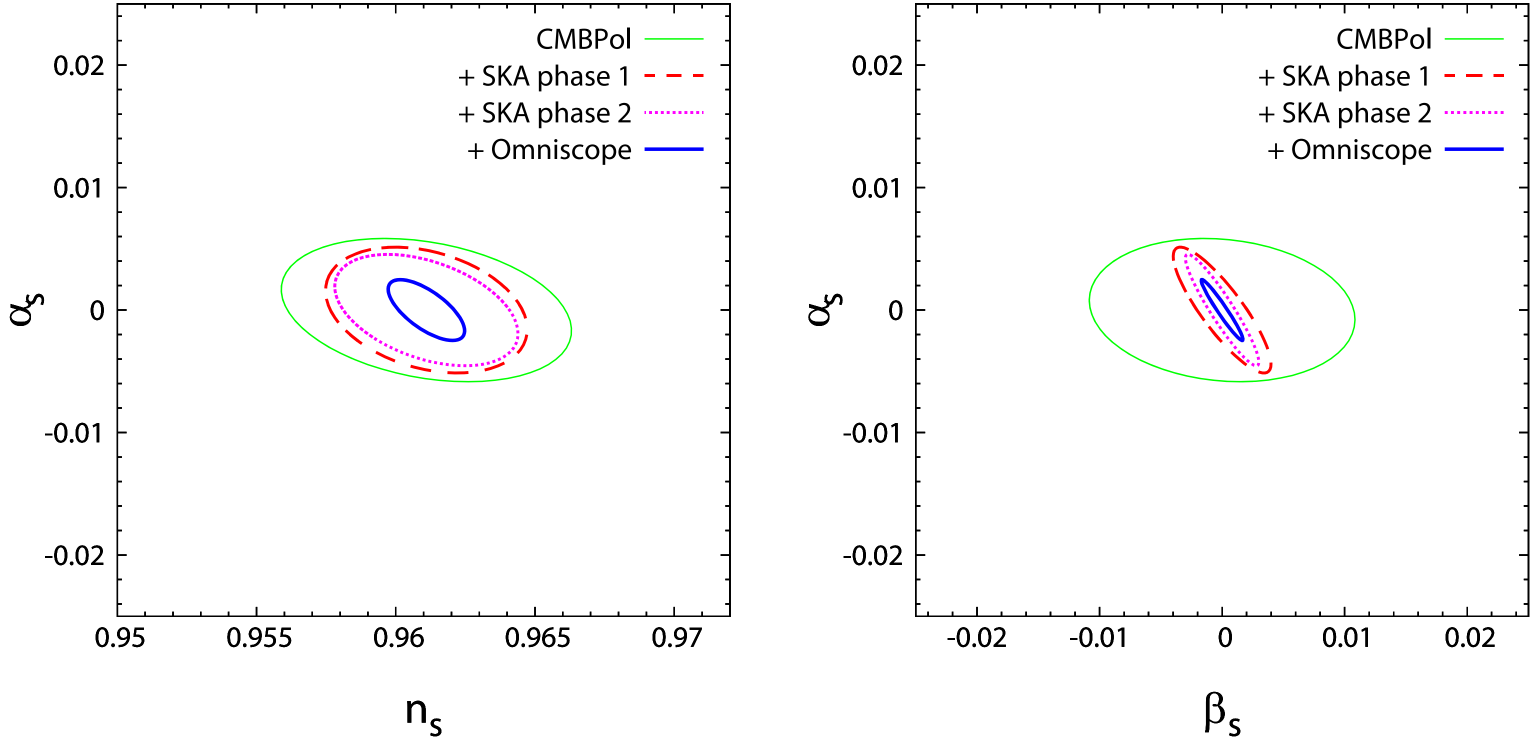
- Planck + 21cm



[Kohri, Oyama, Sekiguchi, TT 2013]

Precise measurement of power spectrum

- CMBPol + 21cm



[Kohri, Oyama, Sekiguchi, TT 2013]

→ future 21cm observations can probe $\beta \sim \mathcal{O}(10^{-4})$

Summary

- 21cm line of neutral hydrogen can probe the dark age which cannot be seen with any other observations.
- 21cm line can probe various aspects of cosmology. (inflation, dark matter, neutrino, …)
- SKA will operate in 2020s.
- 21cm cosmology will bring us a lot of information which cannot be probed with other cosmological observations.