Probing the early Universe with 21cm line

FAPESP-JSPS workshop on Dark Energy, Dark Matter and Galaxies

February 18, 2019 @ Saõ Paulo

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Probing the early (inflationary) Universe with 21cm

- Probing the early Universe with 21cm global signal

  - Running(s) of primordial power spectrum [Yoshiura, K.Takahashi, TT 1805.11806]

  (- Primordial magnetic field) [Minoda, Tashiro, TT 1812.00730]

- Probing the inflationary Universe with 21cm fluctuations

  - Running(s) of primordial power spectrum
  [Sekiguchi, TT, Tashiro, Yokoyama 1705.00405]

  - Non-Gaussianities [Sekiguchi, TT, Tashiro, Yokoyama 1807.02008]

→ Toyokazu Sekiguchi's talk

How can we probe inflationary epoch?

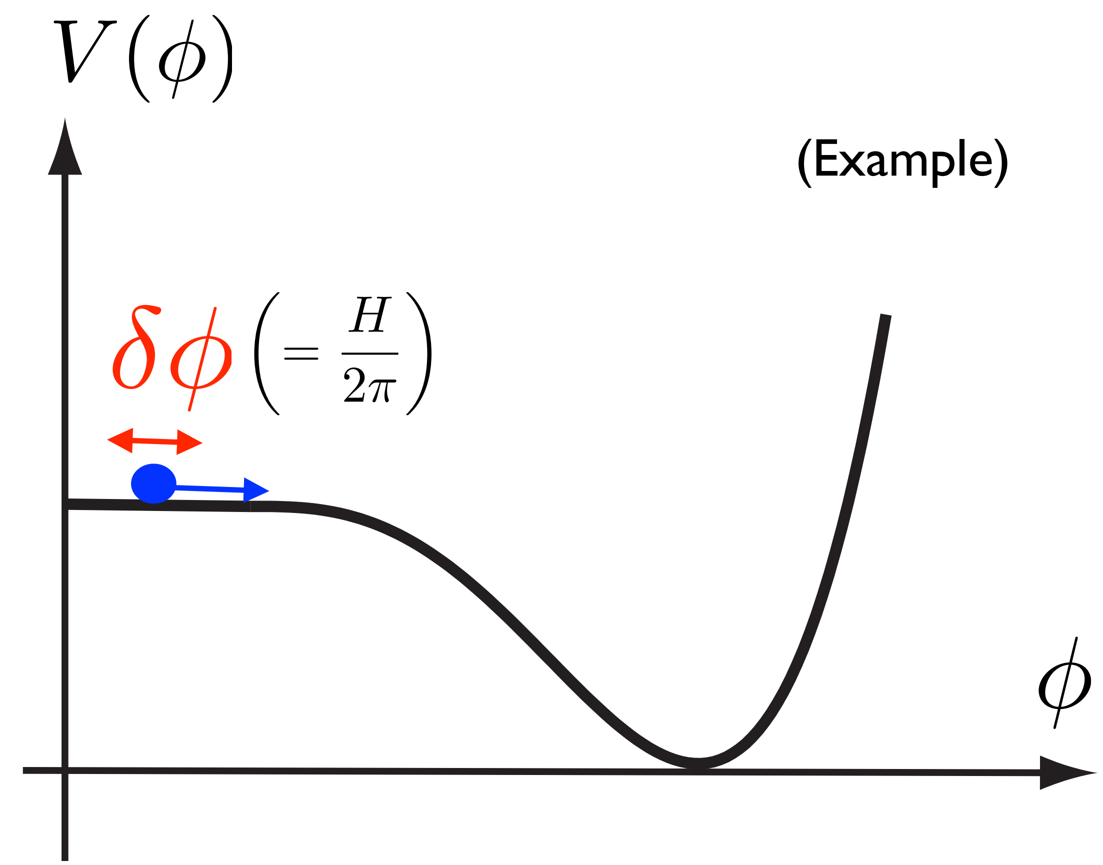
During inflation:

- Curvature perturbation (scalar mode) is generated.

  (Its amplitude depends on models and their model parameters.)

- Gravitational waves (tensor mode) are also generated.

  (Its amplitude depends on models and their model parameters.)



We can probe the nature of primordial perturbations with CMB, large scale structure and so on.

Power spectrum

- Curvature perturbation power spectrum (scalar mode)

$$\mathcal{P}_\zeta(k) = A_s(k_{\rm ref}) \left(\frac{k}{k_{\rm ref}}\right)^{n_s - 1} \quad \left(\sim \frac{1}{M_{\rm pl}^6}\frac{V^3}{(V')^2}\right)$$

V : inflaton potential, $\quad V' = dV/d\phi$

Curvature perturbation: $\zeta = -\dfrac{H}{\dot\phi}\delta\phi \qquad \left(\delta\phi = \frac{H}{2\pi}, \quad \dot\phi \simeq -\frac{V'}{3H}\right)$

- Gravitational wave power spectrum (tensor mode)

$$\mathcal{P}_T(k) = A_T(k_{\rm ref}) \left(\frac{k}{k_{\rm ref}}\right)^{n_T} \quad \left(\sim \frac{H_{\rm inf}^2}{M_{\rm pl}^2}\right)$$

➡ Tensor-to-scalar ratio: $r \equiv \dfrac{\mathcal{P}_T}{\mathcal{P}_\zeta}$

Characterizing the observables

- Scalar spectral index

$$n_s = 1 - 6\epsilon + 2\eta$$

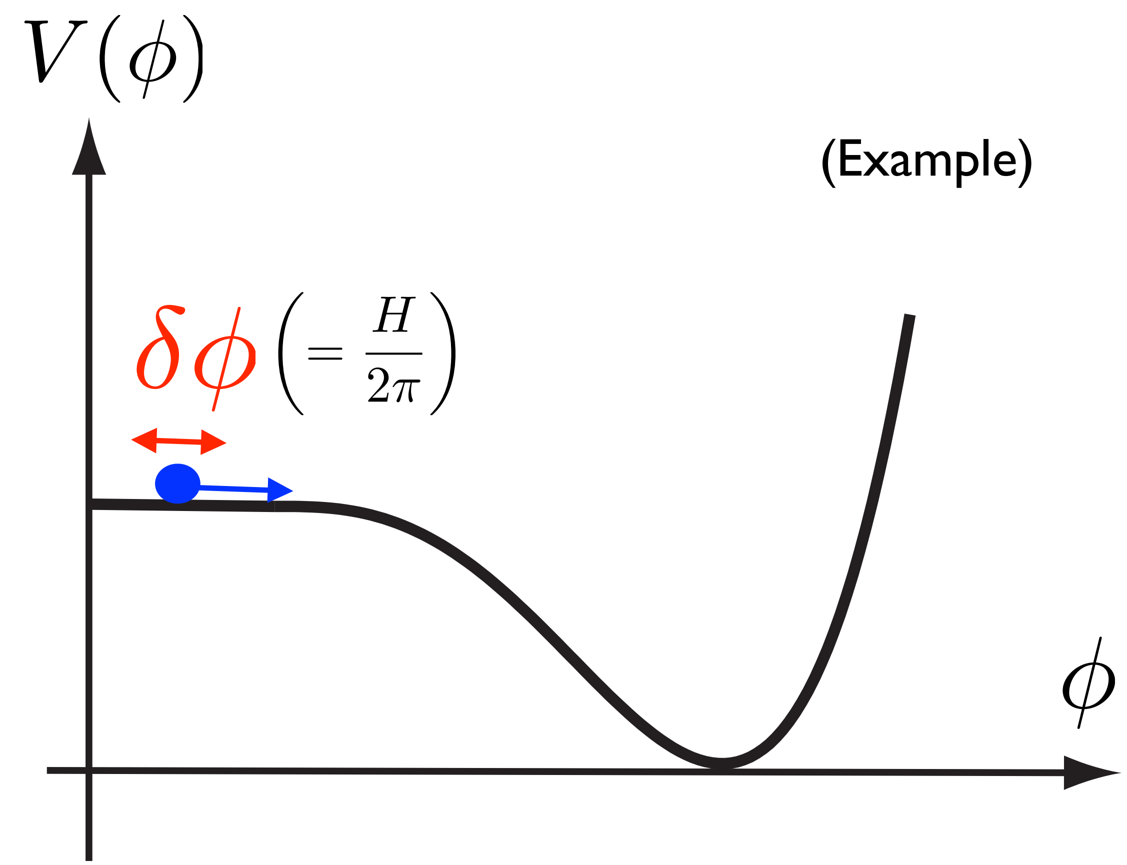
- Tensor-to-scalar ratio

$$r = 16\epsilon$$

(Slow-roll parameters)

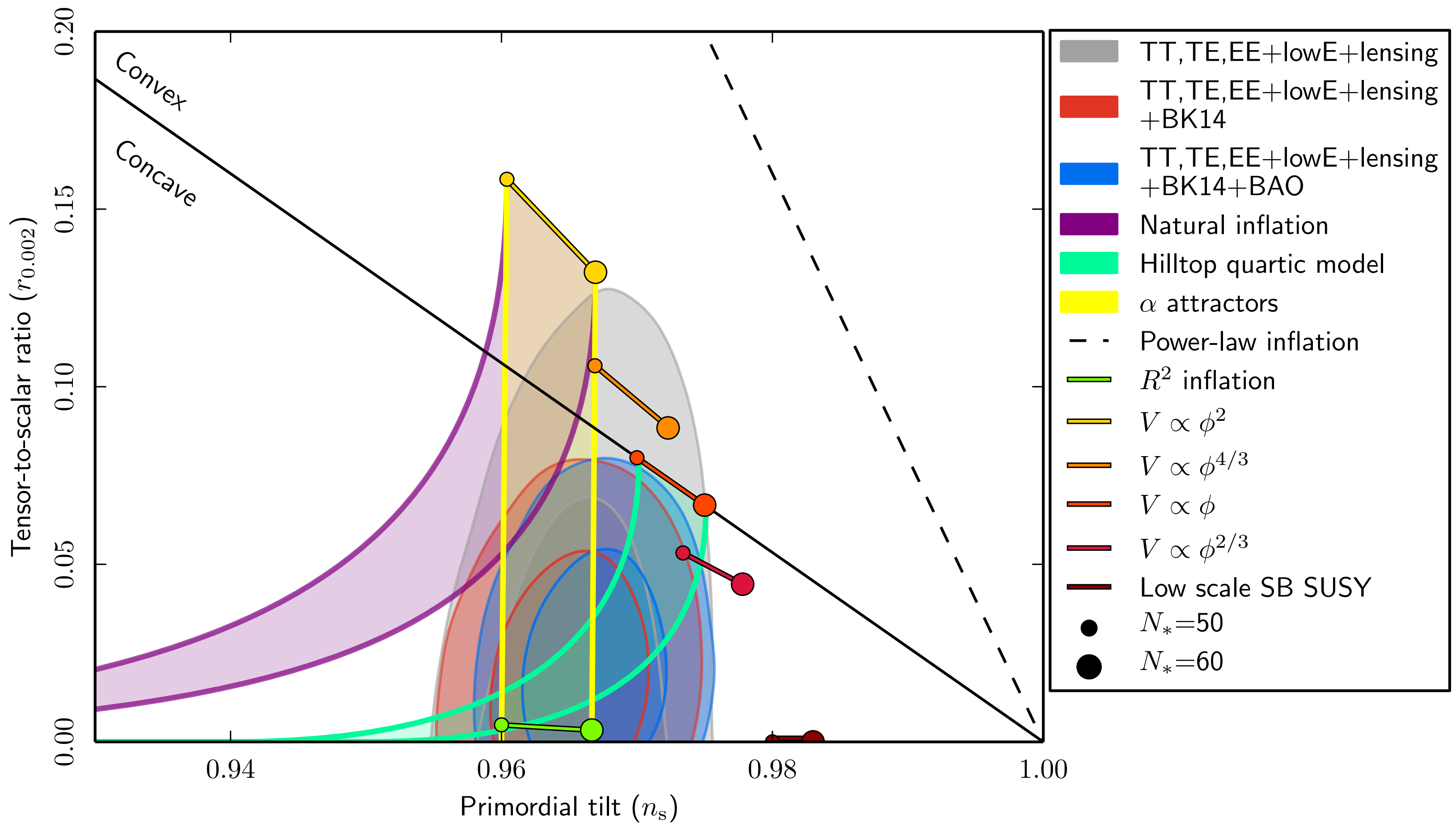
$$\epsilon = \frac{1}{2}M_{\rm pl}^2\left(\frac{V_\phi}{V}\right)^2 \qquad \eta = M_{\rm pl}^2\frac{V_{\phi\phi}}{V}$$

where $V_\phi \equiv \frac{dV}{d\phi}$

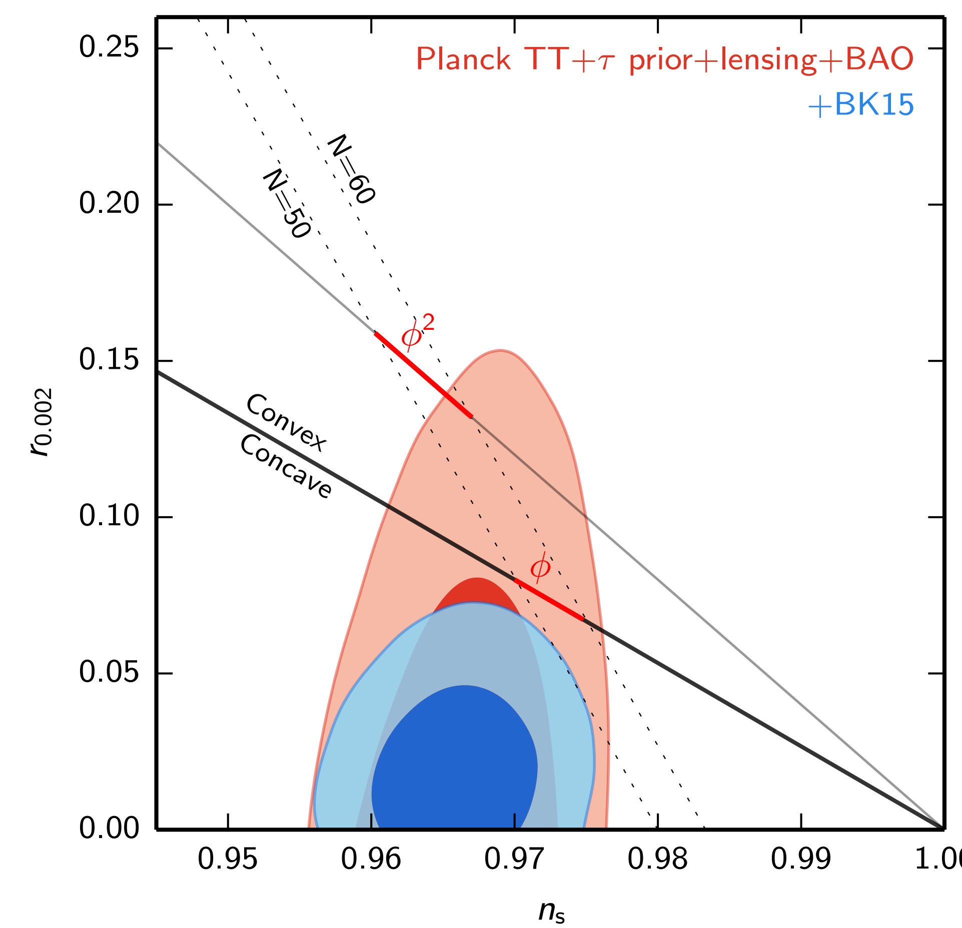


Spectral index and tensor-to-scalar ratio are discriminators of inflationary models.

Inflationary models: current status



[Planck collaboration 1807.06211]



[BICEP2/Keck Array 1810.05216]

Spectral index: $n_s = 0.9649 \pm 0.0042 \ (68\% \ \mathrm{CL})$ [Planck 2018]

Tensor-to-scalar ratio: $r_{0.05} < 0.06 \ \ (95\% \ \mathrm{CL})$ [Planck + BK15+ …]

Many inflation models are now ruled out, but …

A wide “variation” of inflation models

- Single-field models

- Extension of gravity

  (Starobinsky model, non-minimally coupled models, …)

- Multi-field models

  (Curvaton model, modulated reheating, …)

$\vdots$

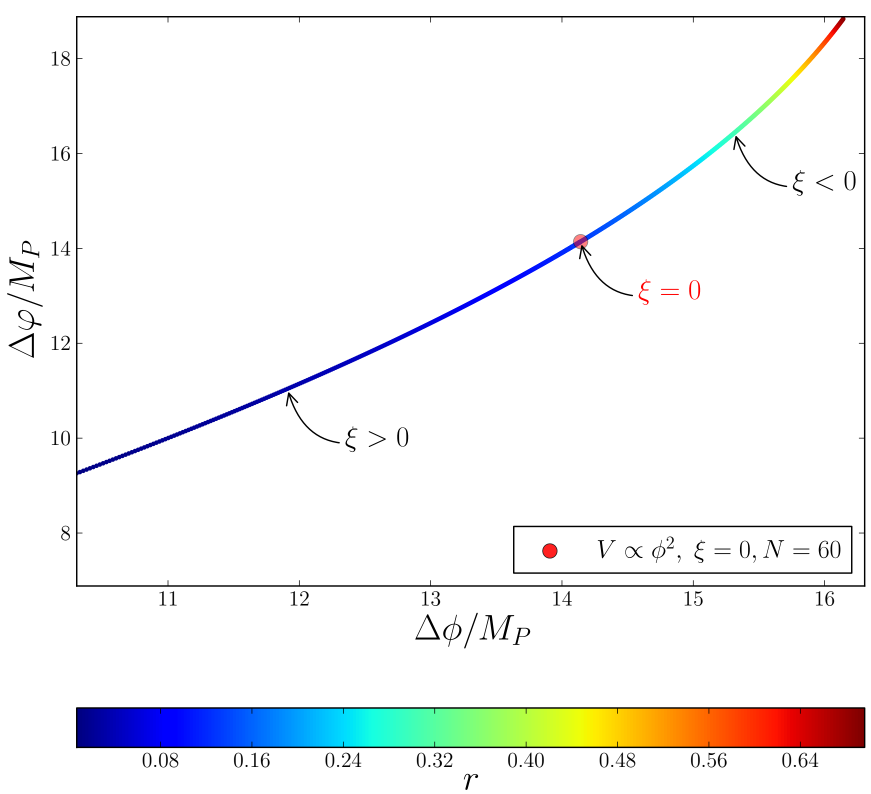
If you allow possibilities of wider class of models, you may be able cook up any models consistent with observations…

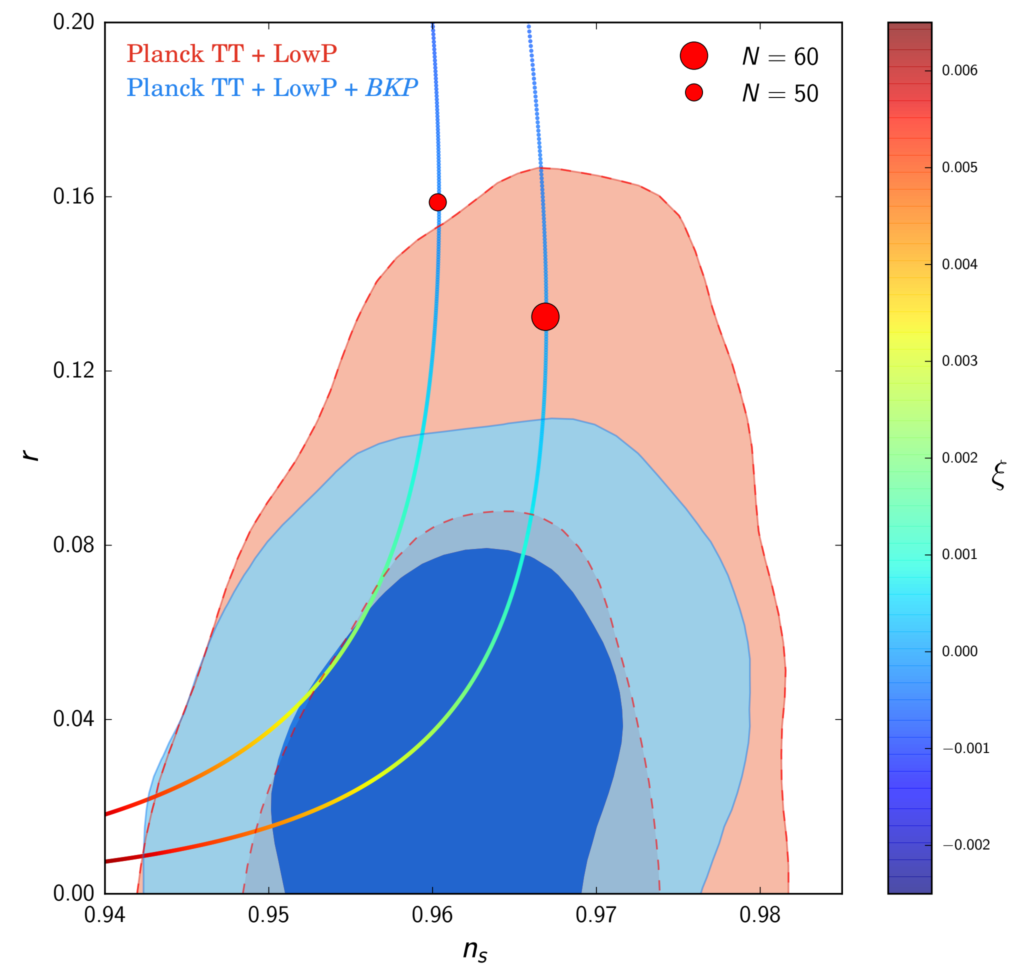
Predictions for ns and r in models w/non-minimal coupling

(example: quadratic potential w/non-minimal coupling)

$$S = \int dx^4 \sqrt{-g} \left[\frac{M_{\rm pl}^2}{2} R + \frac{\xi}{2} R \phi^2 - \frac{1}{2} (\partial\phi)^2 - \frac{1}{2} m^2 \phi^2 \right]$$

[Boubekeur, et al., 1502.05193]





For $\xi > 0$, r ↘

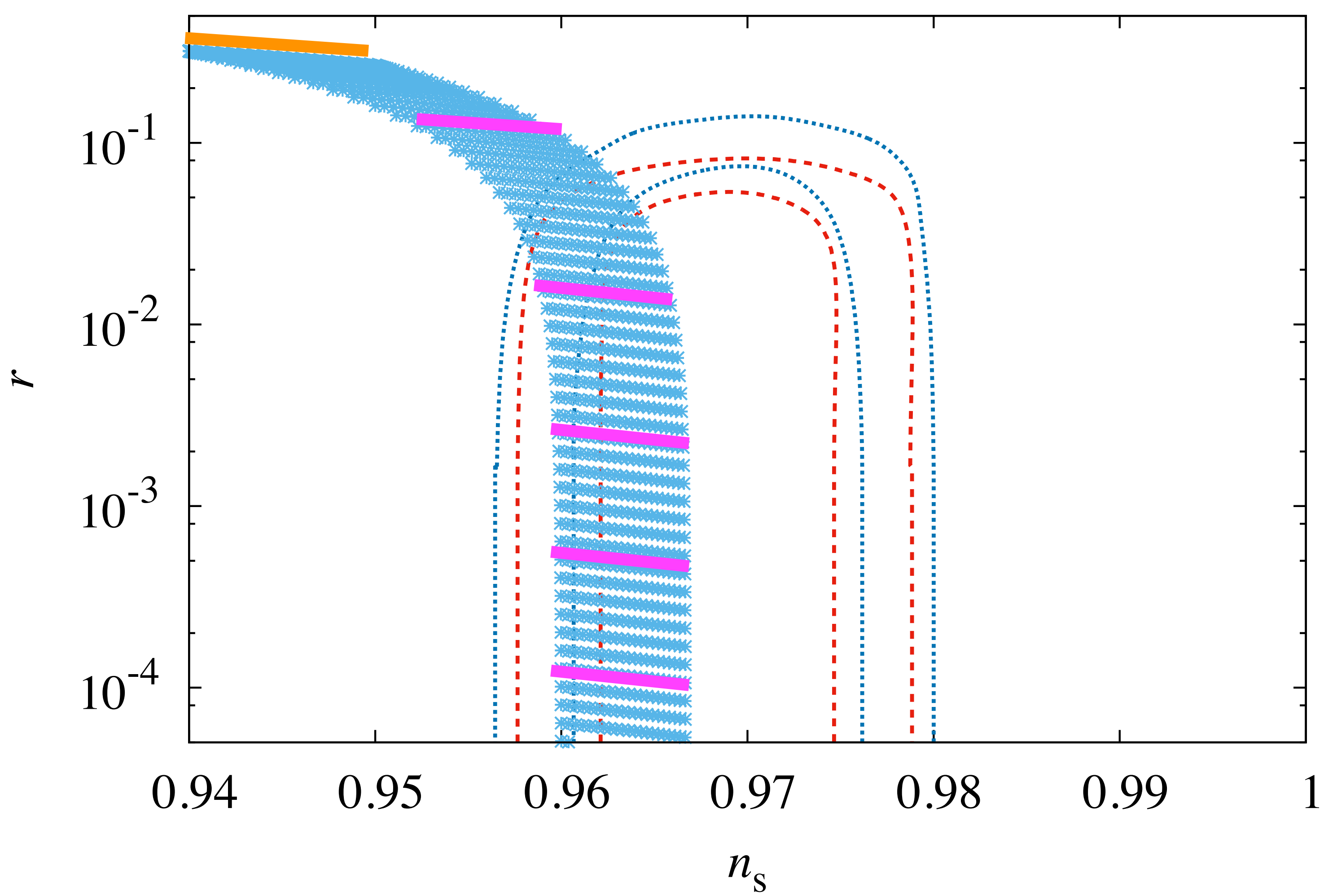
For $\xi < 0$, r ↗

Quadratic chaotic inflation model becomes viable w/non-minimal coupling.

Predictions for ns and r for multi-field models

(Example)

Chaotic inflation $\phi\left(V(\phi)=\frac{1}{4}\lambda\phi^4\right)$ + spectator field σ $\left(V(\sigma)=\frac{1}{2}m_\sigma^2\sigma^2\right)$

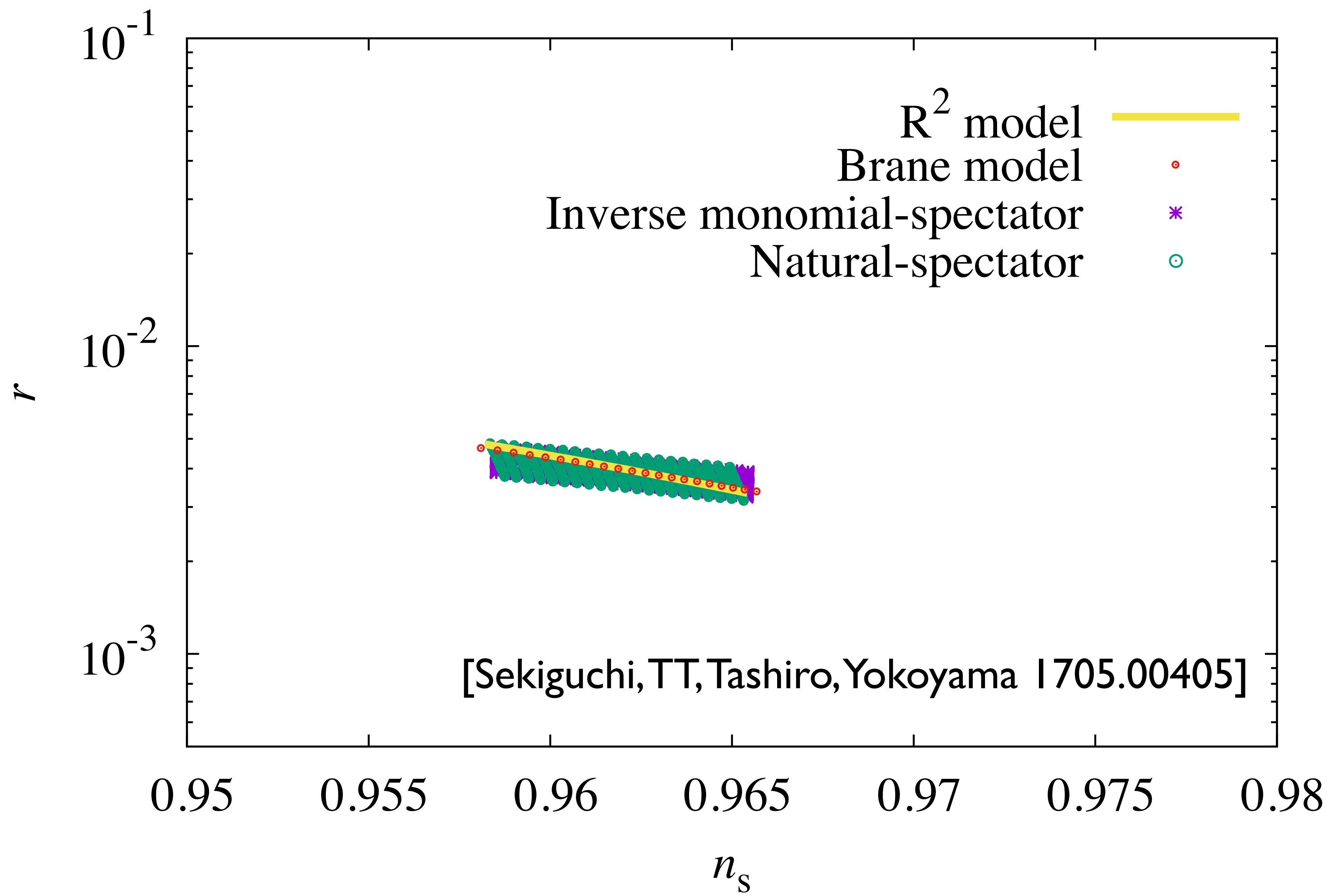


[See Enqvist, TT 1306.5958; Vennin, Koyama, Wands1507.07575]

By changing the fraction of the contribution from the spectator field, the predictions for ns and r are affected.

Predictions for n_s and r in some models…

- Some models may be degenerate in the ns-r plane…



Brane inflation

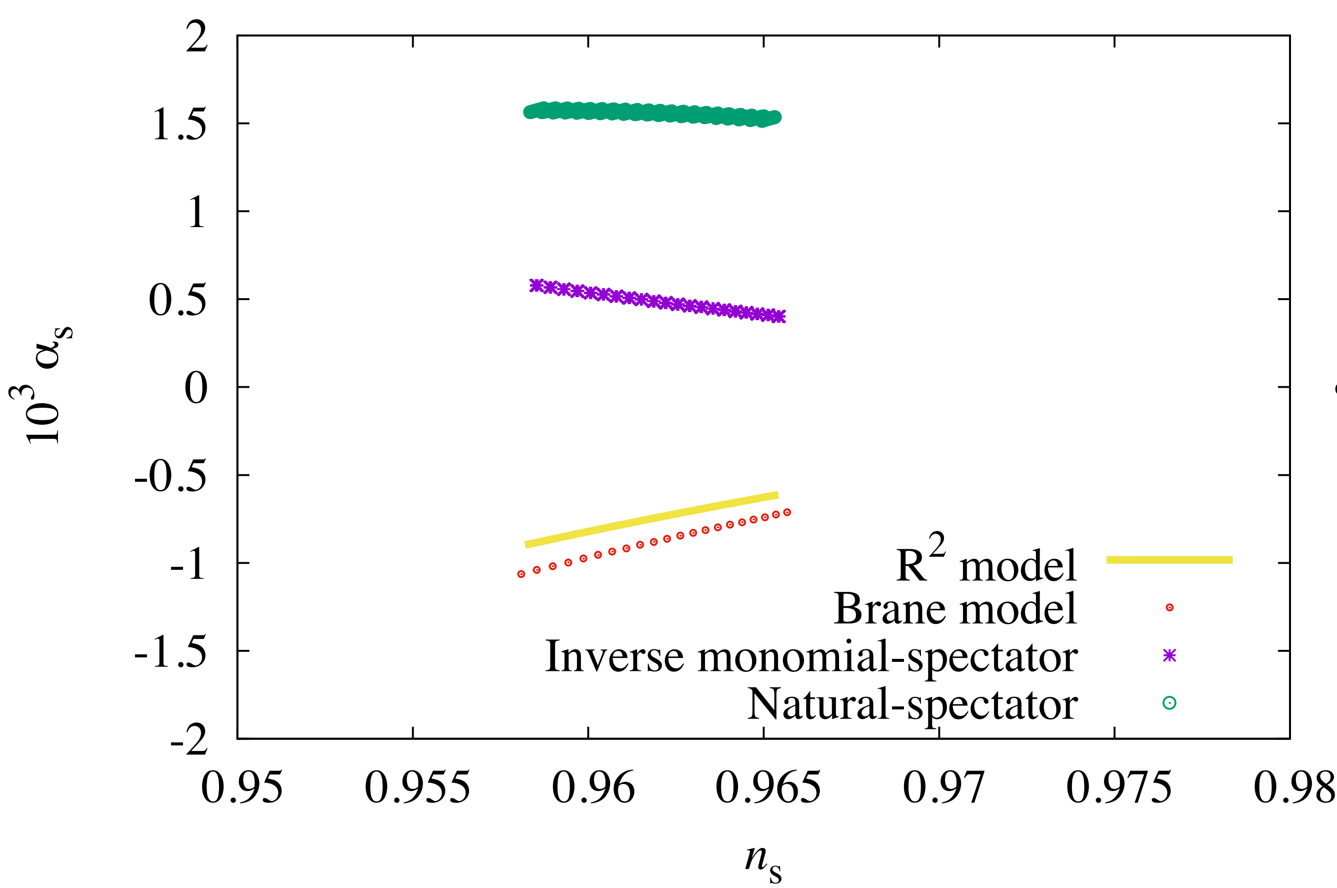
$$V(\phi) = V_0 \left[1 - \left(\frac{\phi}{\mu} \right)^{-p} \right]$$

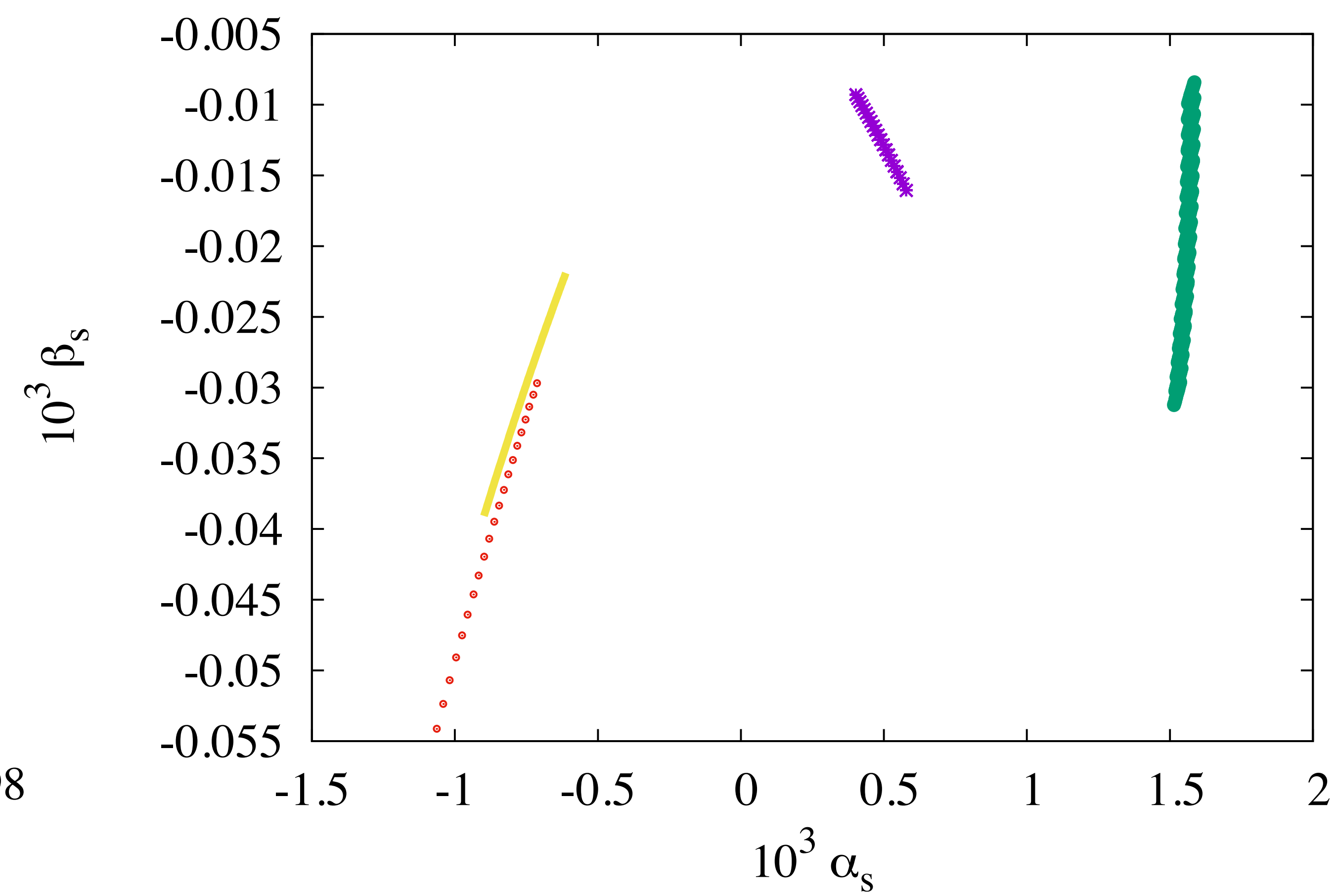
Inverse monomial inflation

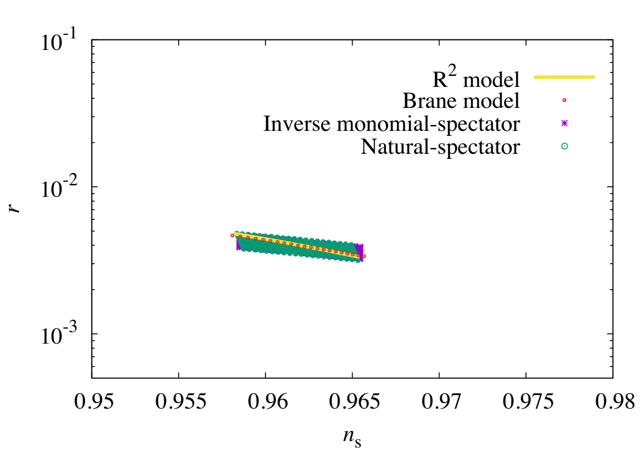
$$V(\phi) = V_0 \left(\frac{\phi}{M_{\rm pl}} \right)^{-p}$$

Predictions for ns and runnings

- Predictions for runnings are separated even for degenerate ns and r.







[Sekiguchi, TT, Tashiro, Yokoyama 1705.00405]

some typical size of the runnings:

$$\alpha_s \sim \mathcal{O}(10^{-3}), \quad \beta_s \sim \mathcal{O}(10^{-4})$$

Observables to probe the inflationary Universe

	Amplitude	scale dependence (ns, nT, nfNL, ..)	running(s)
Scalar power spectrum	A_s	n_s	α_s, β_s
Tensor (GW) power spectrum	r	n_T	
(scalar) Non-Gaussianity (bispectrum)	$f_{\rm NL}$	$n_{f_{\rm NL}}$	
(scalar) Non-Gaussianity (trispectrum)	$g_{\rm NL}, \tau_{\rm NL}$		

well measured

relatively well constrained

poorly constrained

(currently) no constraint

Observables which may should be more explored

- (scalar) spectral running(s) $\alpha = \frac{dn_s}{d\ln k}$ $\beta = \frac{d^2 n_s}{d\ln k^2}$

- Scale-dependence of non-Gaussianity $n_{f_{\rm NL}}$

- Tensor spectral running n_T

- Higher order non-Gaussianity (scalar) $g_{\rm NL}, \tau_{\rm NL}, \cdots$

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Probing runnings with future observations

- Galaxy surveys (+CMB)

  - Euclid, LSST, WFIRST

  [Basse et al., 1409.3469; Muñoz et al, 1611.05883; Li et al, 1806.02515, …]

- 21 cm fluctuations/global signal

  - Signals from minihalos [Sekiguchi, TT, Tashiro, Yokoyama 1705.00405]

  - Signals from intergalactic medium (IGM) [Kohri, Oyama, Sekiguchi, TT 1303.1688]

  - Intensity mapping (IM) [Pourtsidou 1612.05138]

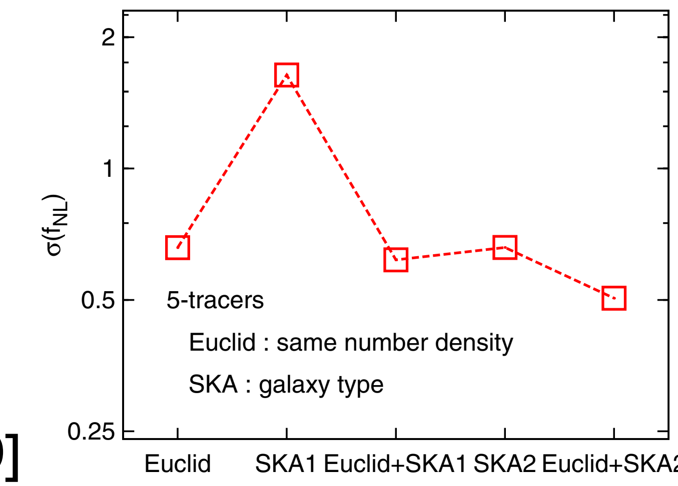
  - EDGES [Yoshiura, K.Takahashi, TT 1805.11806]

⋮

Probing non-Gaussianities with future observations

- Scale-dependent bias

[Dalal et al. 0710.4560; Smith et al. 1106.0503]



[Yamauchi et al 1407.5453]

- Multi-tracer (SKA+Euclid)

[Yamauchi et al 1407.5453; 1509.07585; 1611.03590]

fNL ~ O(0.1), τNL ~ O(10) can be probed with SKA/Euclid.

- Minihalo (angular power spectrum) [Sekiguchi, TT, Tashiro, Yokoyama 1807.02008]

fNL ~ O(1), τNL ~ O(10), gNL ~ O(10^3) can be probed with SKA.

(fNL ~ O(0.1), τNL ~ O(1), gNL ~ O(100) in futuristic obs.)

- 21cm fluctuations

In principle (in ideal case), 21cm survey can reach fNL ~O(0.01).

[Cooray astro-ph/0610257; Munos et al 1506.04152]

Observables which may should be more explored

- (scalar) spectral running(s) $\alpha = \frac{dn_s}{d\ln k}$ $\beta = \frac{d^2 n_s}{d\ln k^2}$

- Scale-dependence of non-Gaussianity $n_{f_{\rm NL}}$

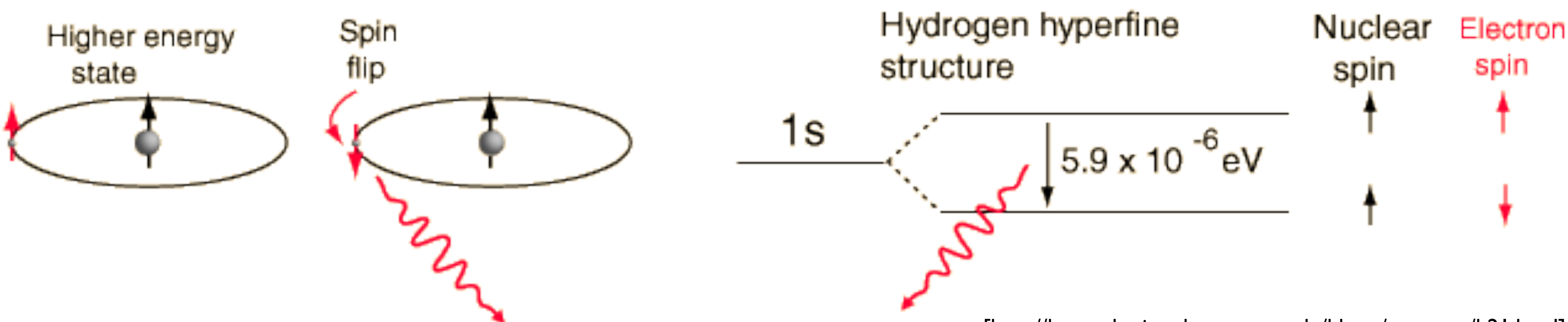
- Tensor spectral running n_T

- Higher order non-Gaussianity (scalar) $g_{\rm NL}, \tau_{\rm NL}, \cdots$

21cm line may would be very useful to probe the early (inflationary) Universe.

Probing the early Universe with 21cm global signal

What is 21cm?

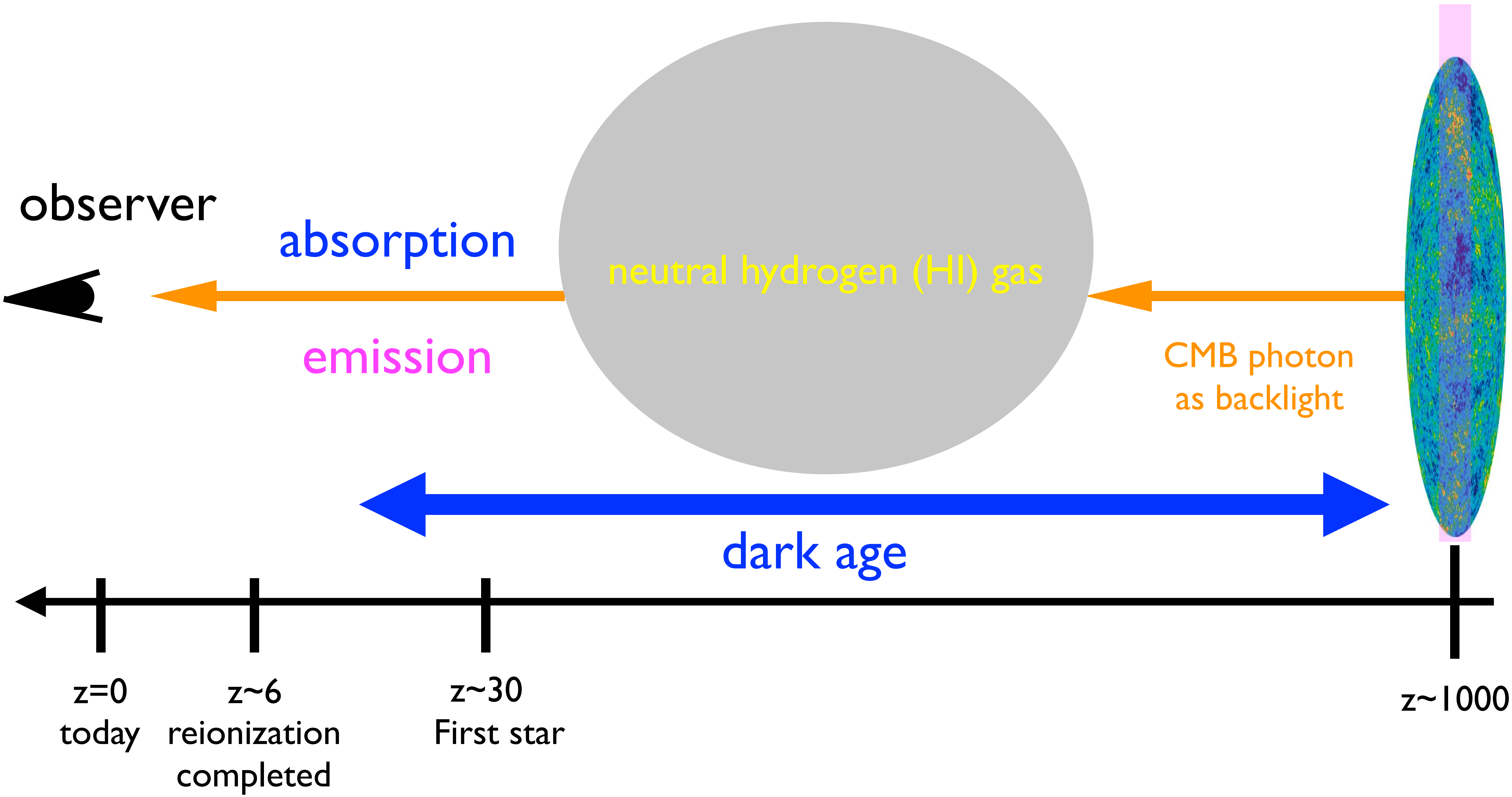


[http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/h21.html]

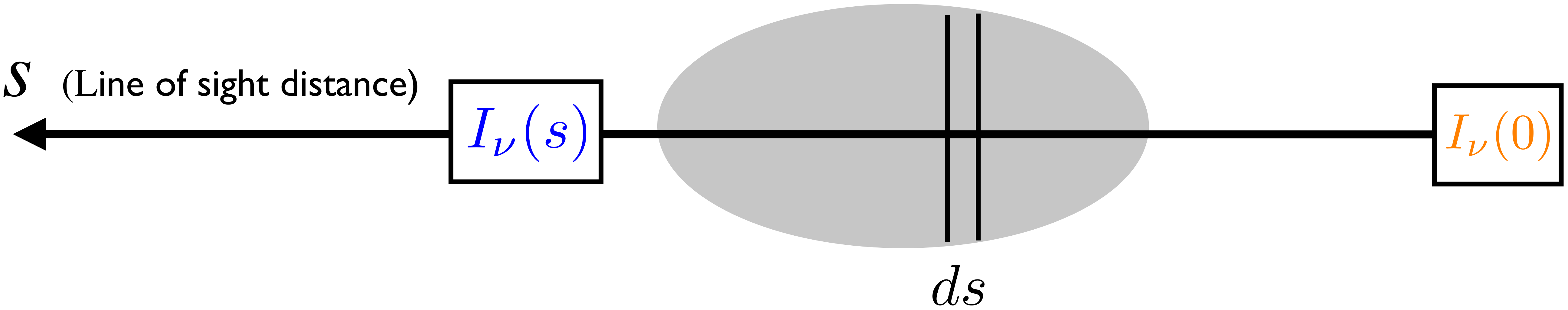
$$\nu_0 = 1420.4057517 \text{ MHz}$$
$$\lambda_0 = 21.106114 \text{ cm}$$

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

21cm from neutral hydrogen



Evolution of the intensity (radiative transfer eq.)



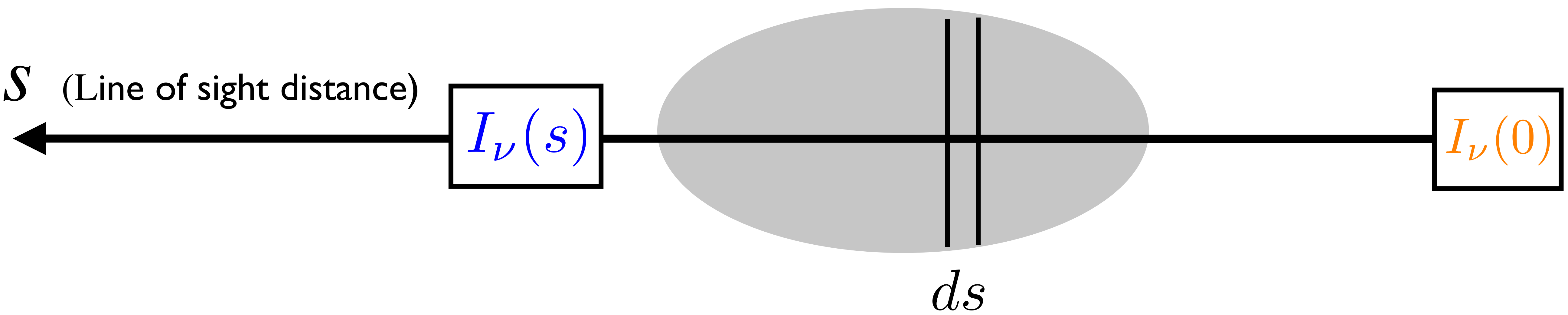
- Rewriting this equation with the optical depth τ_ν

$$\boxed{\text{optical depth: } d\tau_\nu = \alpha_\nu ds} \quad \left(\tau_\nu = \int_{s_0}^{s} \alpha_\nu(s') ds' \right)$$

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

Source function

Evolution of the intensity (radiative transfer eq.)



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

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

assuming $\tau_\nu \ll 1$

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

- $I_\nu(s) - I_\nu(0) < 0$: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

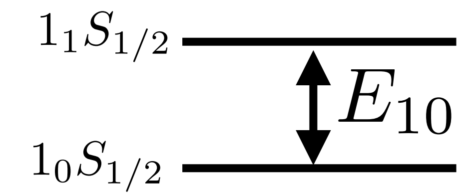
- In Rayleigh-Jeans (low frequency) region,

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

(brightness temperature = intensity)

Differential brightness temperature

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



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

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

Spin temperature

$$\frac{n_1}{n_0} \equiv \frac{g_1}{g_0}e^{-E_{10}/k_BT_s} = 3e^{-T_*/T_s}$$

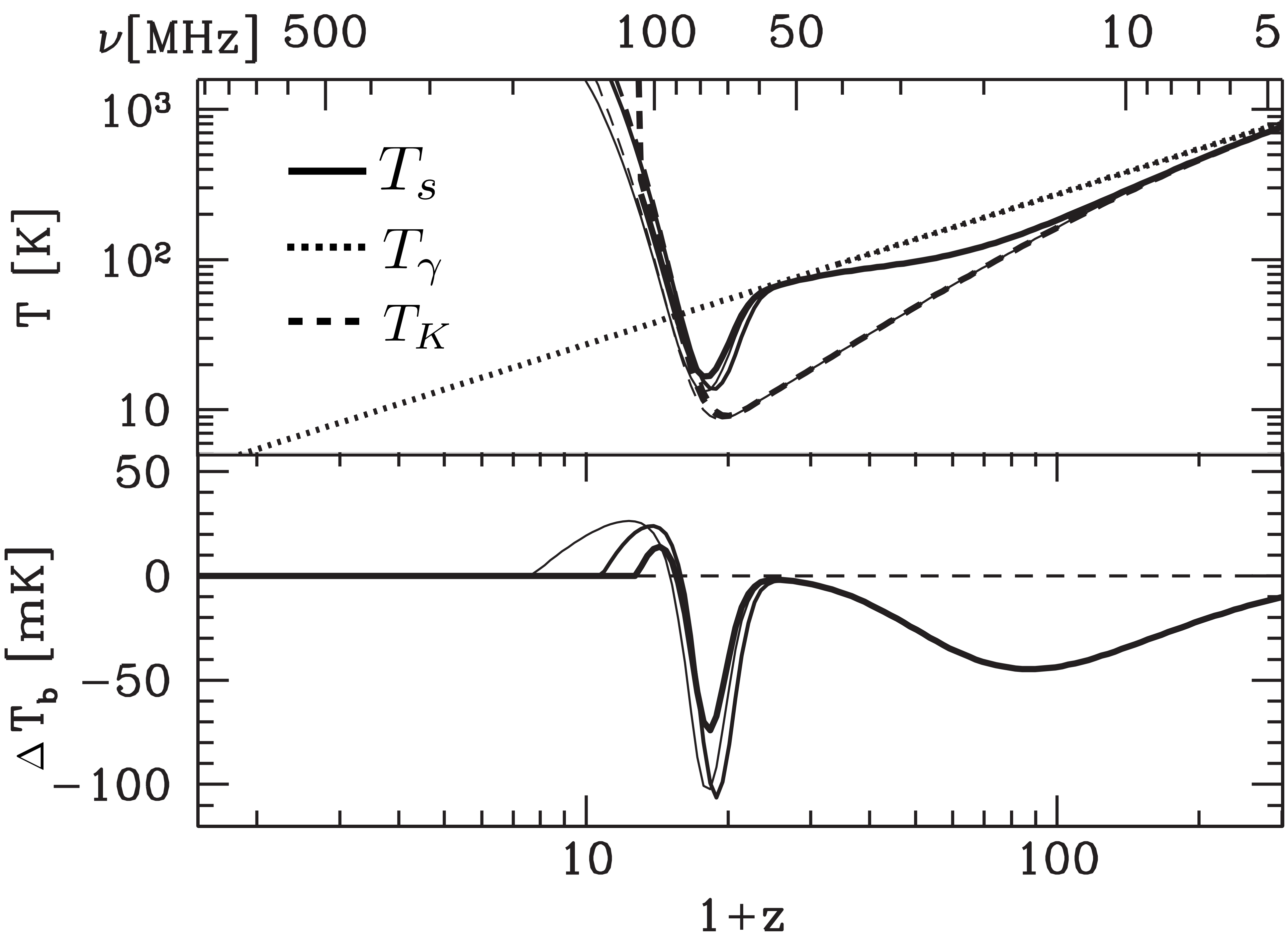
$$(T_* = E_{10}/k_B = 68 \text{ mK})$$

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

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

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

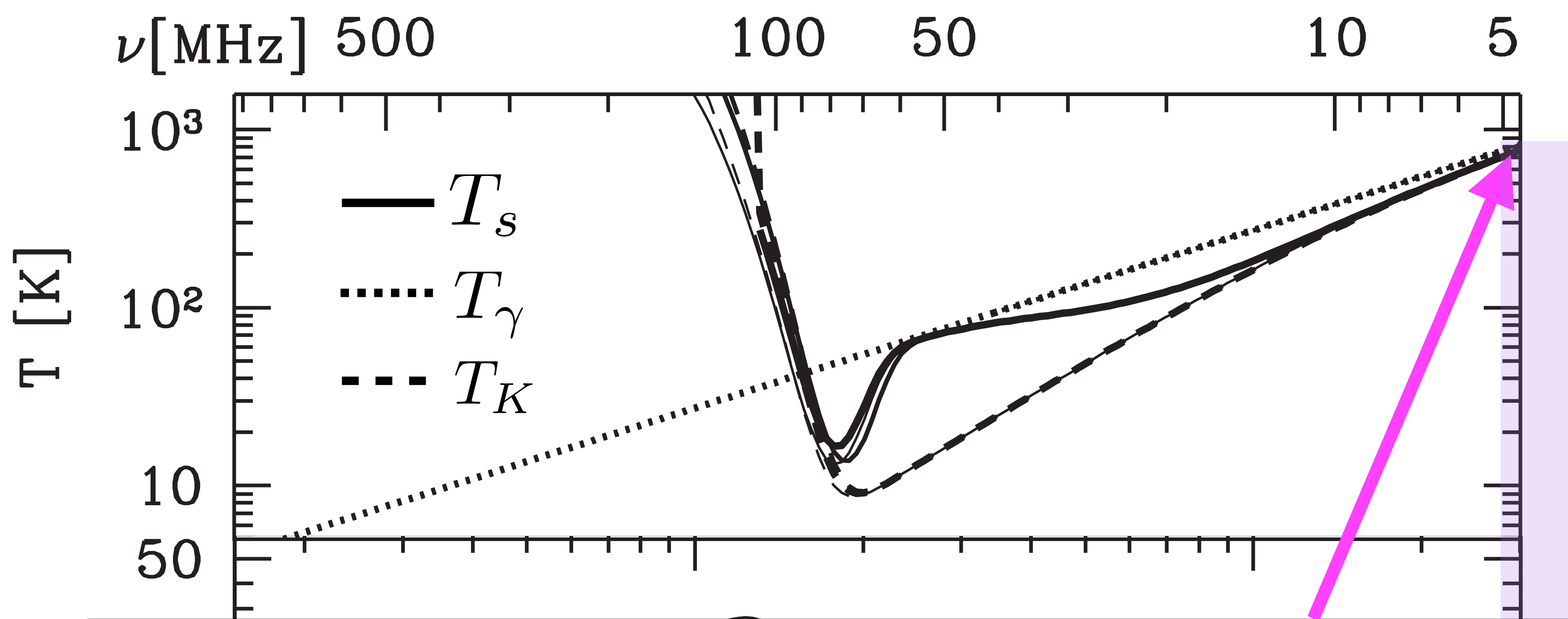
Evolution of ΔTb (after first astrophysical sources switched on)



[From Pritchard, Loeb 0802.2102]

Evolution of ΔTb

(after first astrophysical sources switched on)



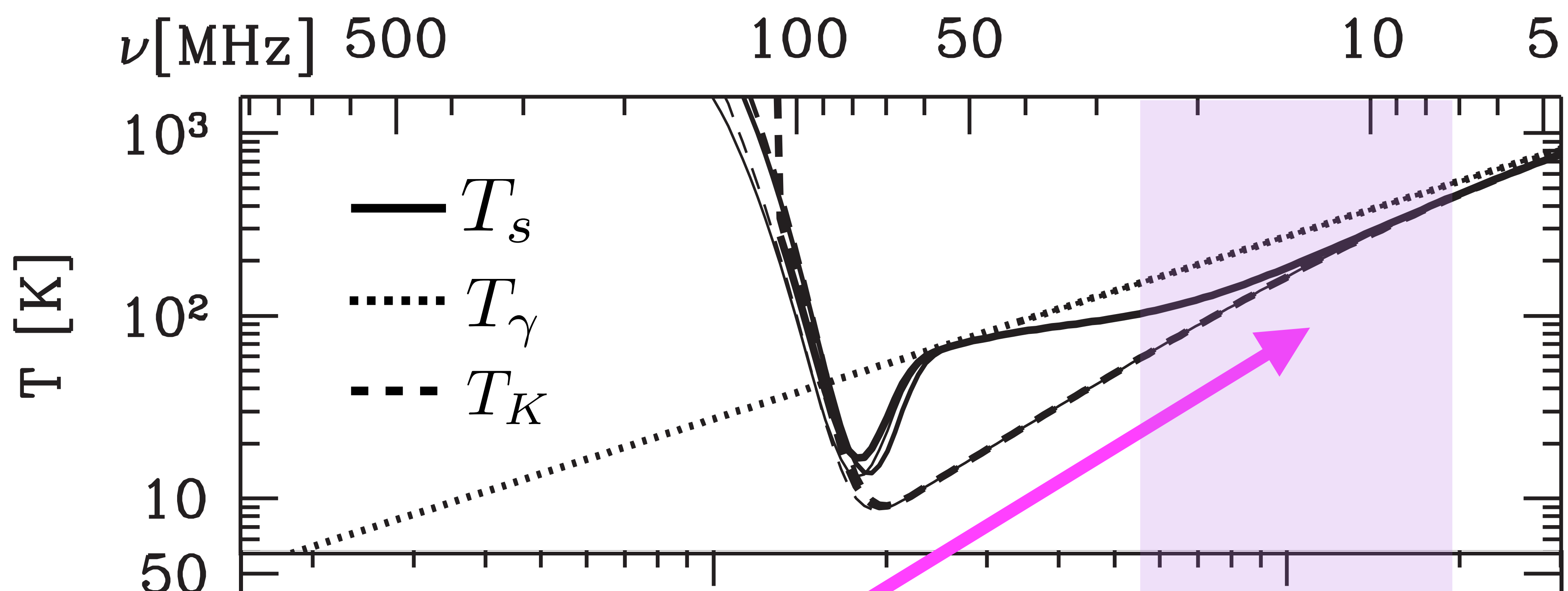
- After recombination, there remains residual free electrons to keep T_γ and T_K via Compton scattering.
- Collisional couplings are strong: $T_K = T_s$

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

[From Pritchard, Loeb 0802.2102]

Evolution of ΔTb

(after first astrophysical sources switched on)



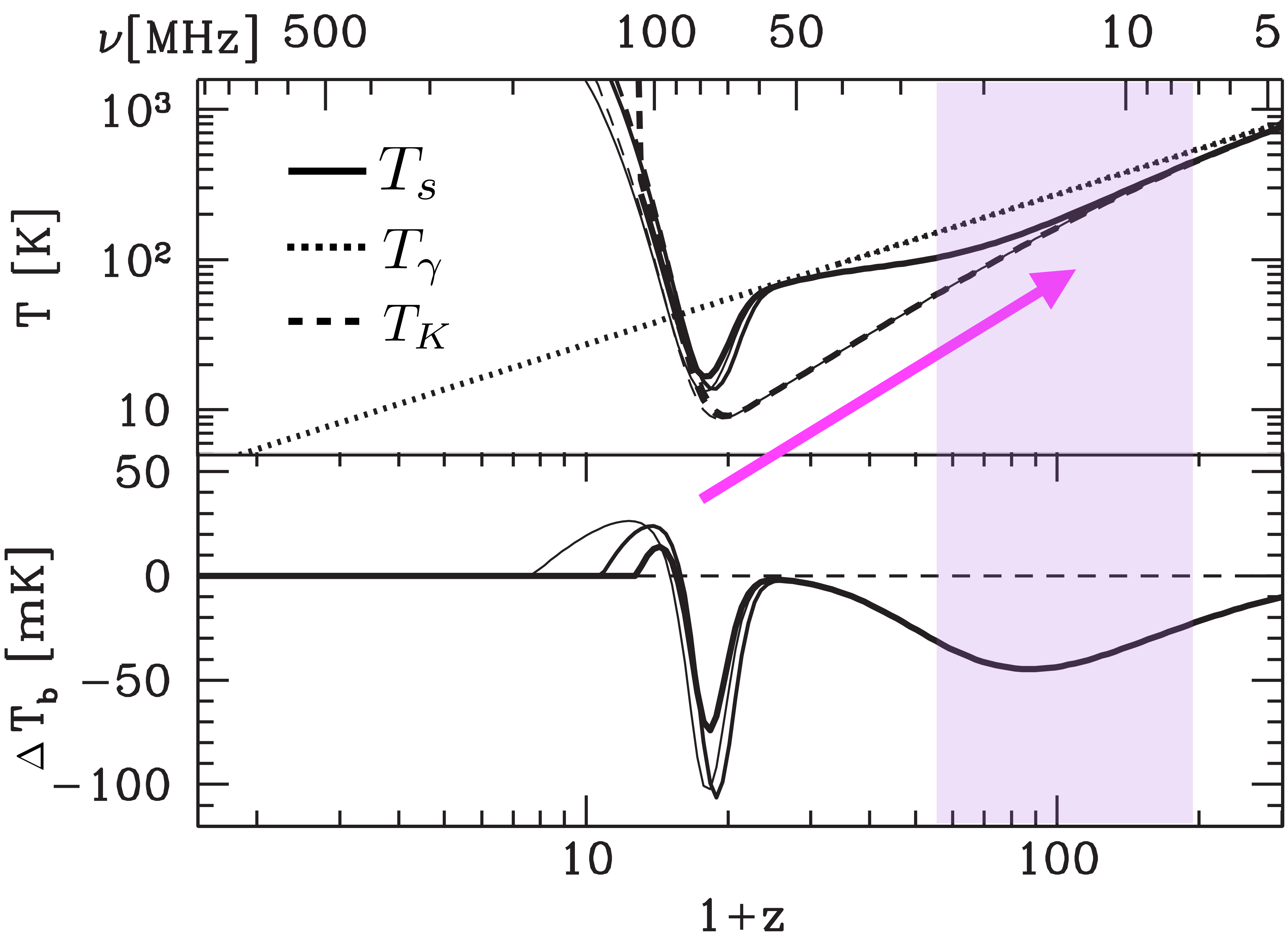
- Coupling between CMB photon and the gas becomes ineffective (collisional couplings are effective).
- T_K CMB cools down adiabatically: $T_K \propto (1+z)^2$

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

[From Pritchard, Loeb 0802.2102]

Evolution of ΔTb

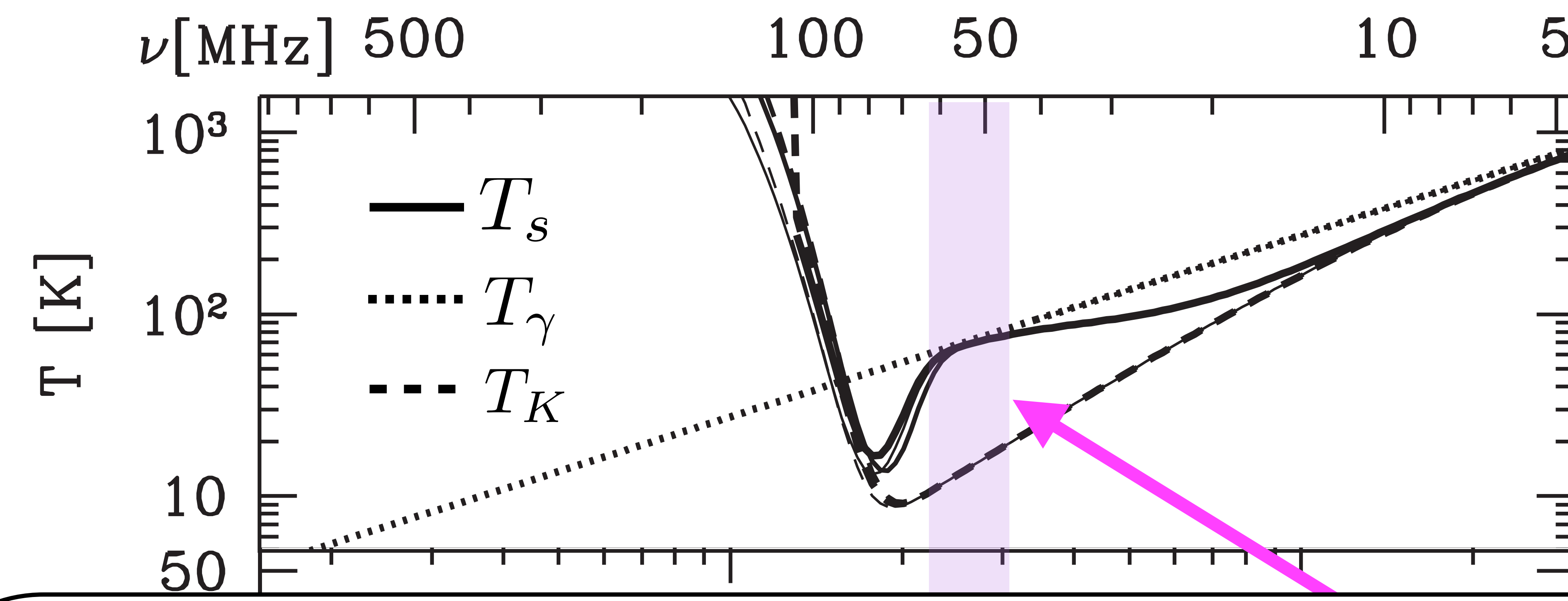
(after first astrophysical sources switched on)



[From Pritchard, Loeb 0802.2102]

Evolution of ΔTb

(after first astrophysical sources switched on)



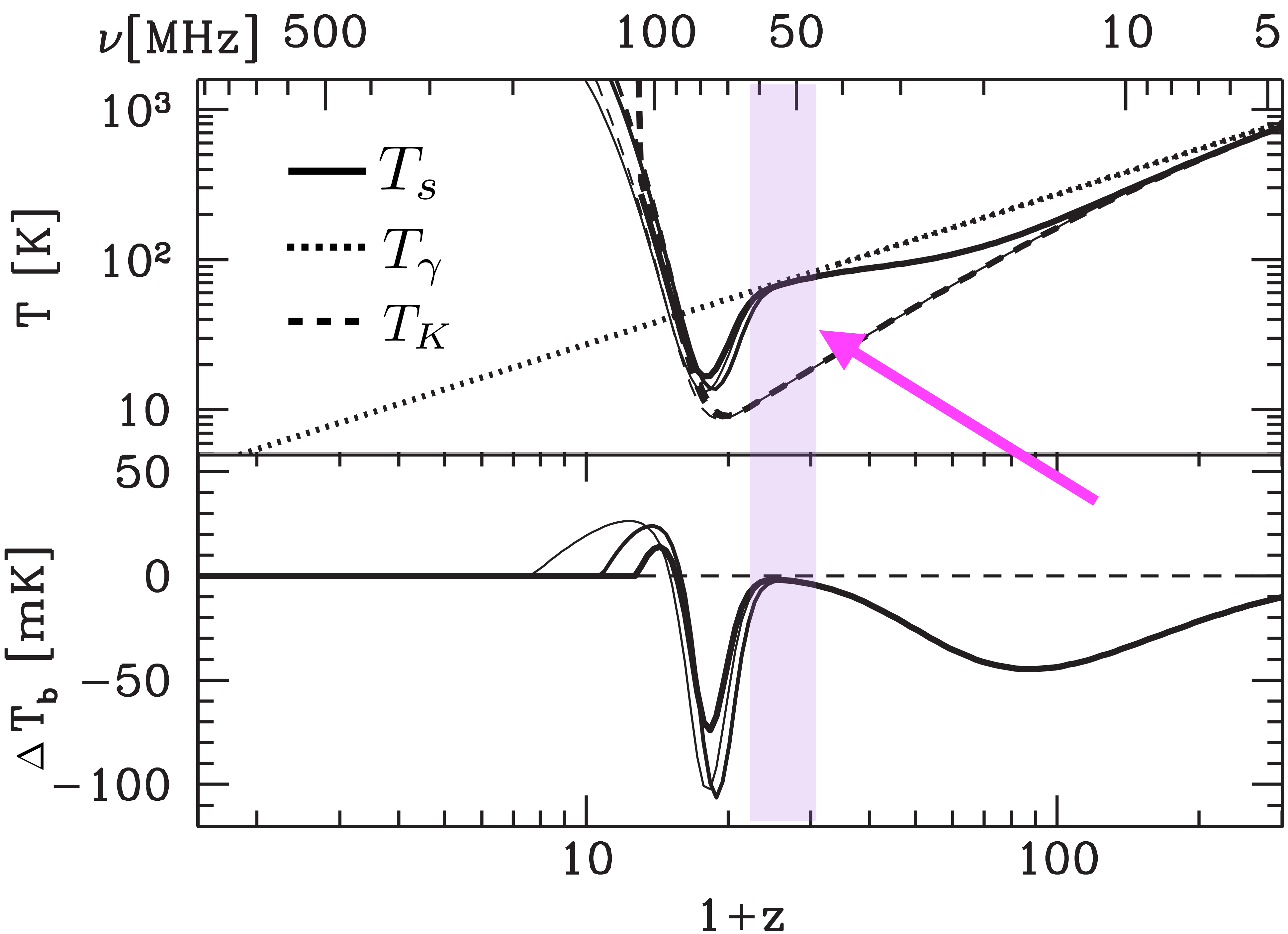
- As the gas density decreases, the collisional coupling between T_s and T_K becomes ineffective.
- Relatively, coupling between T_s and T_α becomes bigger to give $Ts = T\gamma$.

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

[From Pritchard, Loeb 0802.2102]

Evolution of ΔTb

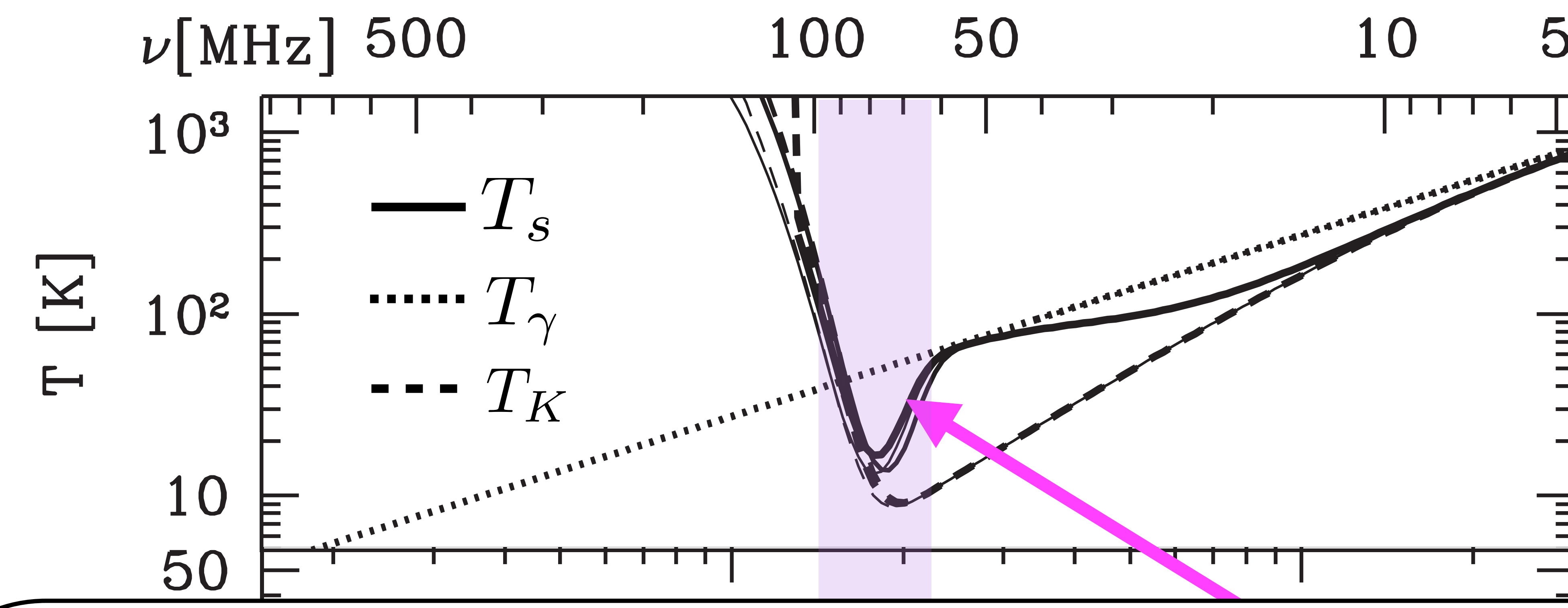
(after first astrophysical sources switched on)



[From Pritchard, Loeb 0802.2102]

Evolution of ΔTb

(after first astrophysical sources switched on)

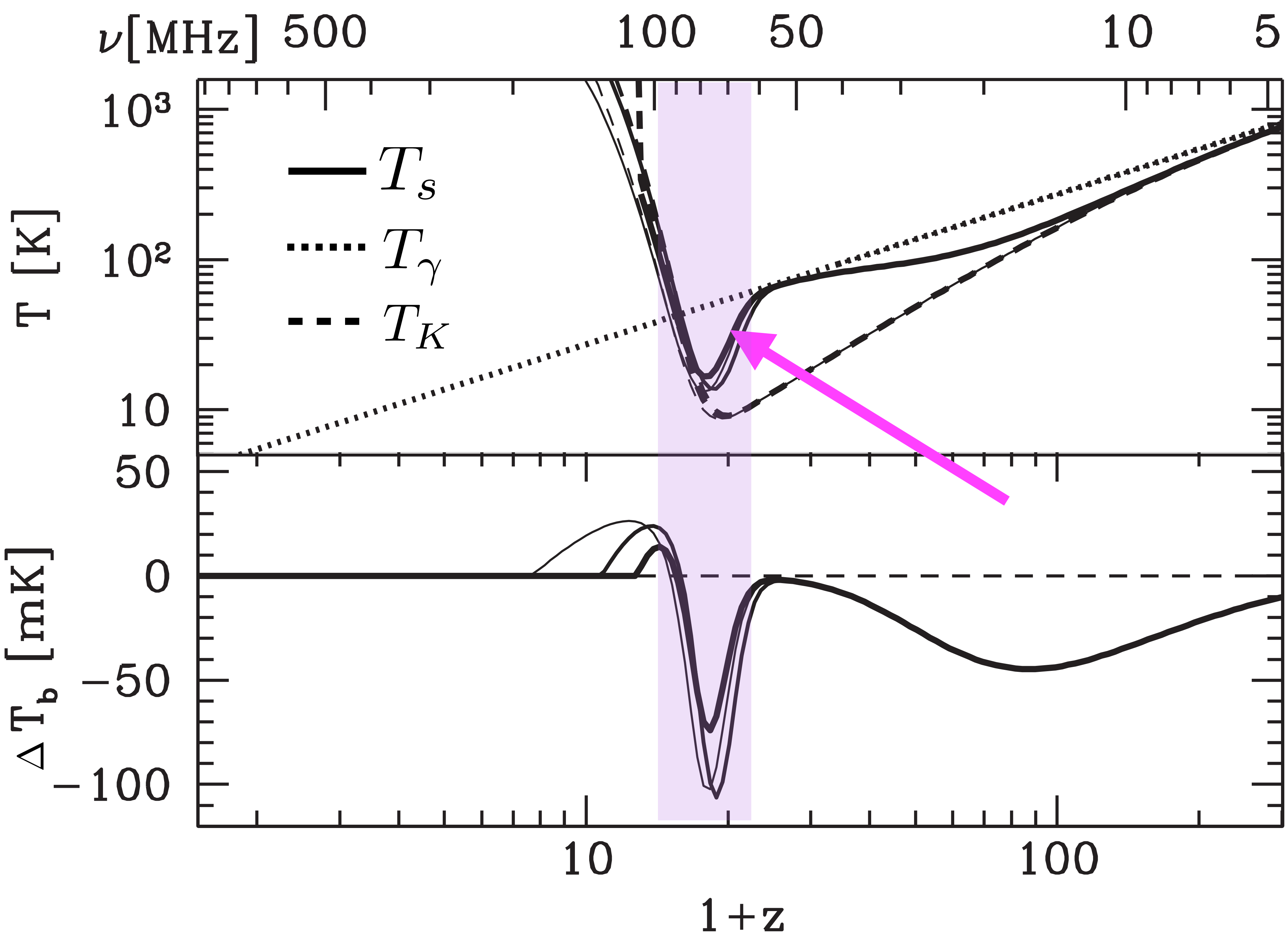


- After astrophysical sources are switched on, $T_s \sim T_K$.
- Heating is not enough to reach $T_K > T_\gamma$

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

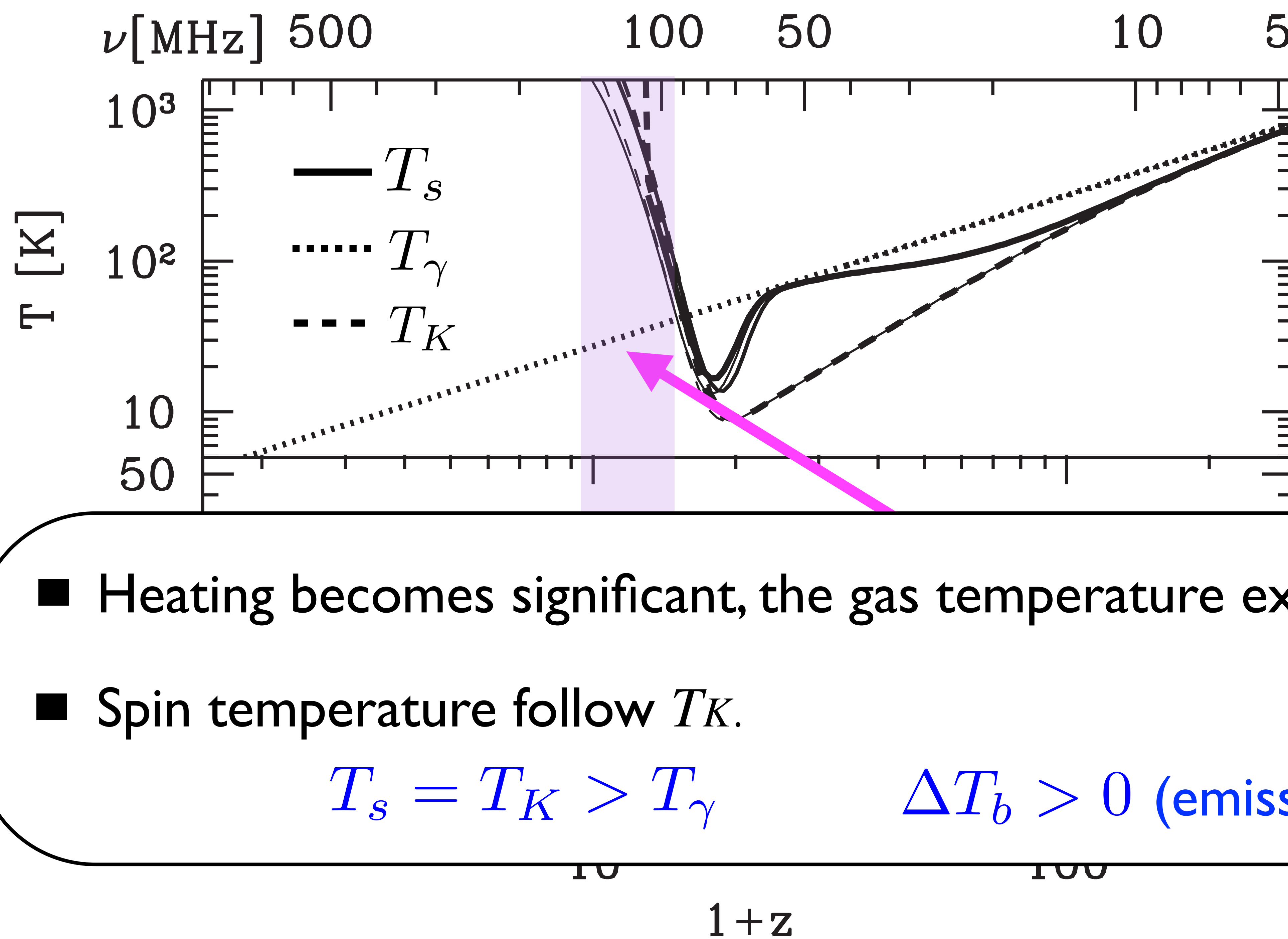
[From Pritchard, Loeb 0802.2102]

Evolution of ΔTb (after first astrophysical sources switched on)



[From Pritchard, Loeb 0802.2102]

Evolution of ΔTb (after first astrophysical sources switched on)

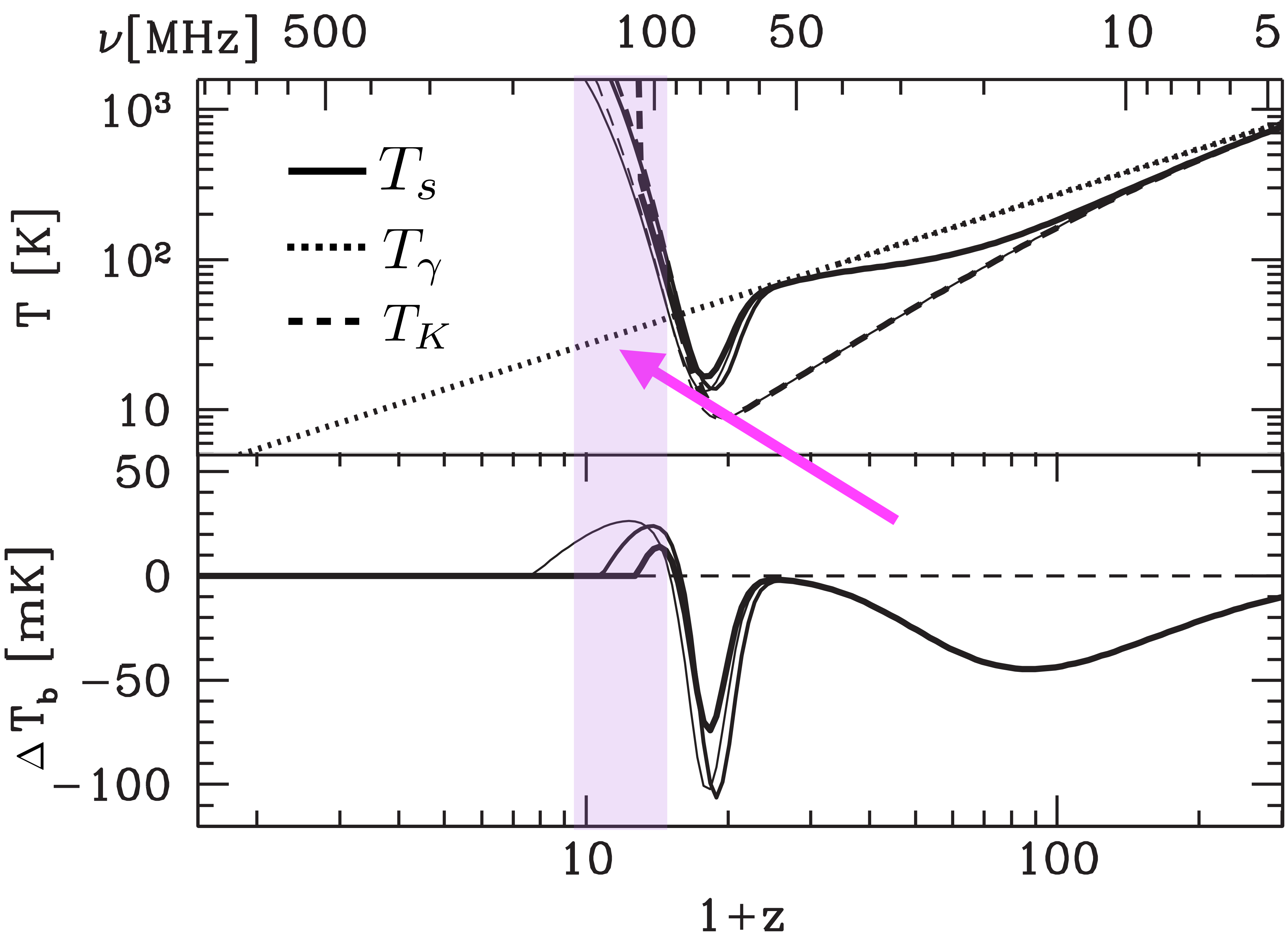


- Heating becomes significant, the gas temperature exceed $T\gamma$.
- Spin temperature follow T_K.

$$T_s = T_K > T_\gamma \qquad \Delta T_b > 0 \text{ (emission signal)}$$

[From Pritchard, Loeb 0802.2102]

Evolution of ΔTb (after first astrophysical sources switched on)



[From Pritchard, Loeb 0802.2102]

Probing runnings with future observations

- Galaxy surveys (+CMB)
    - Euclid, LSST, WFIRST

  [Basse et al., 1409.3469; Muñoz et al, 1611.05883; Li et al, 1806.02515, …]

- 21 cm fluctuations/global signal
    - Signals from minihalos [Sekiguchi, TT, Tashiro, Yokoyama 1705.00405]
    - Signals from intergalactic medium (IGM) [Kohri, Oyama, Sekiguchi, TT 1303.1688]
    - Intensity mapping (IM) [Pourtsidou 1612.05138]
    - EDGES [Yoshiura, K.Takahashi, TT 1805.11806]

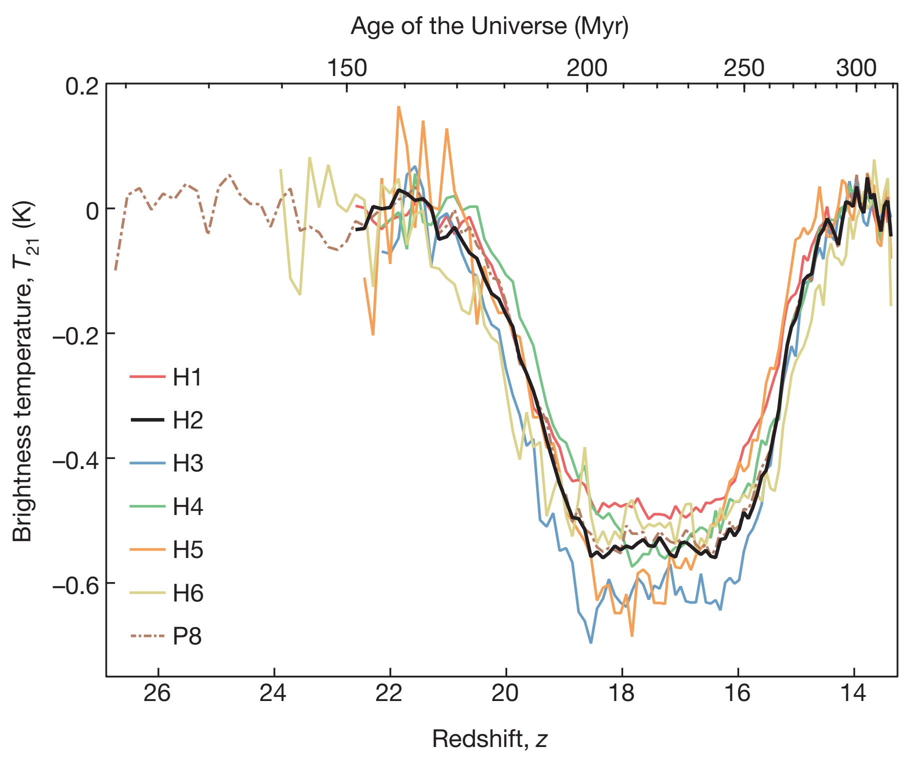
⋮

Detection of 21cm absorption line by EDGES

- EDGES (Experiment to Detect the Global Epoch of Reionization Signature) has reported the detection of 21cm absorption trough at z ~ 17.

- Brightness temperature: [Bowman et al. Nature 555, 67 (2018)]

$$T_b = -500^{+200}_{-500}\ \mathrm{mK} \quad (99\ \%\ \mathrm{C.L.})$$



- This signal is too low to be explained by standard scenarios.

→ Motivated a lot of works

NB:

(- foreground modeling should be more carefully investigated?) [Hill et al. 1805.01421]

(- the ground plane artifact?) [Bradley et al. 1810.0901]

Constraining primordial power spectrum

[Yoshiura, K.Takahashi, TT 1805.11806]

- We can constrain the primordial power spectrum, particularly the running parameters by the EDGES result.

$$P_\zeta(k) = A_s(k_{\rm ref}) \left(\frac{k}{k_{\rm ref}}\right)^{n_s - 1 + \frac{1}{2}\alpha_s \ln(k/k_{\rm ref}) + \frac{1}{3!}\beta_s \ln^2(k/k_{\rm ref})}$$

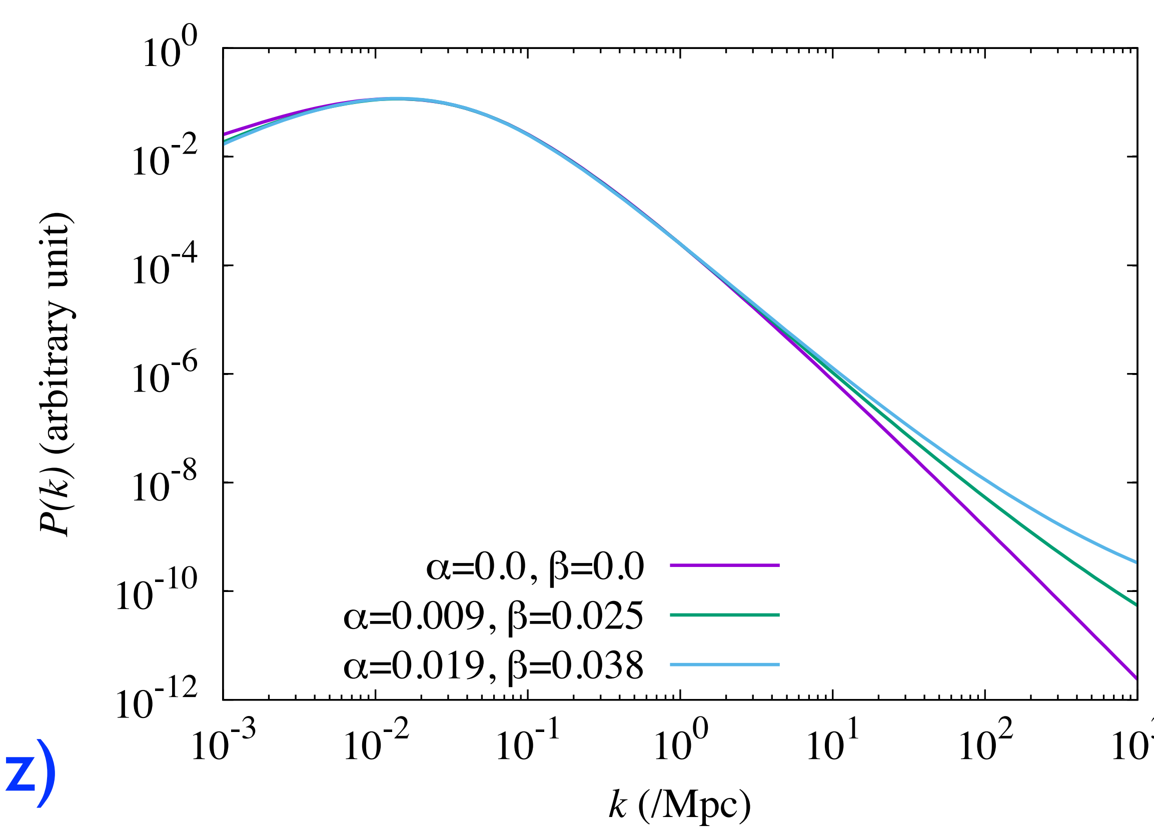
where $\boxed{\alpha_s = \frac{dn_s}{d\ln k}, \qquad \beta_s = \frac{d^2 n_s}{d\ln k^2} \quad \text{: running parameters}}$

Larger (smaller) the runnings

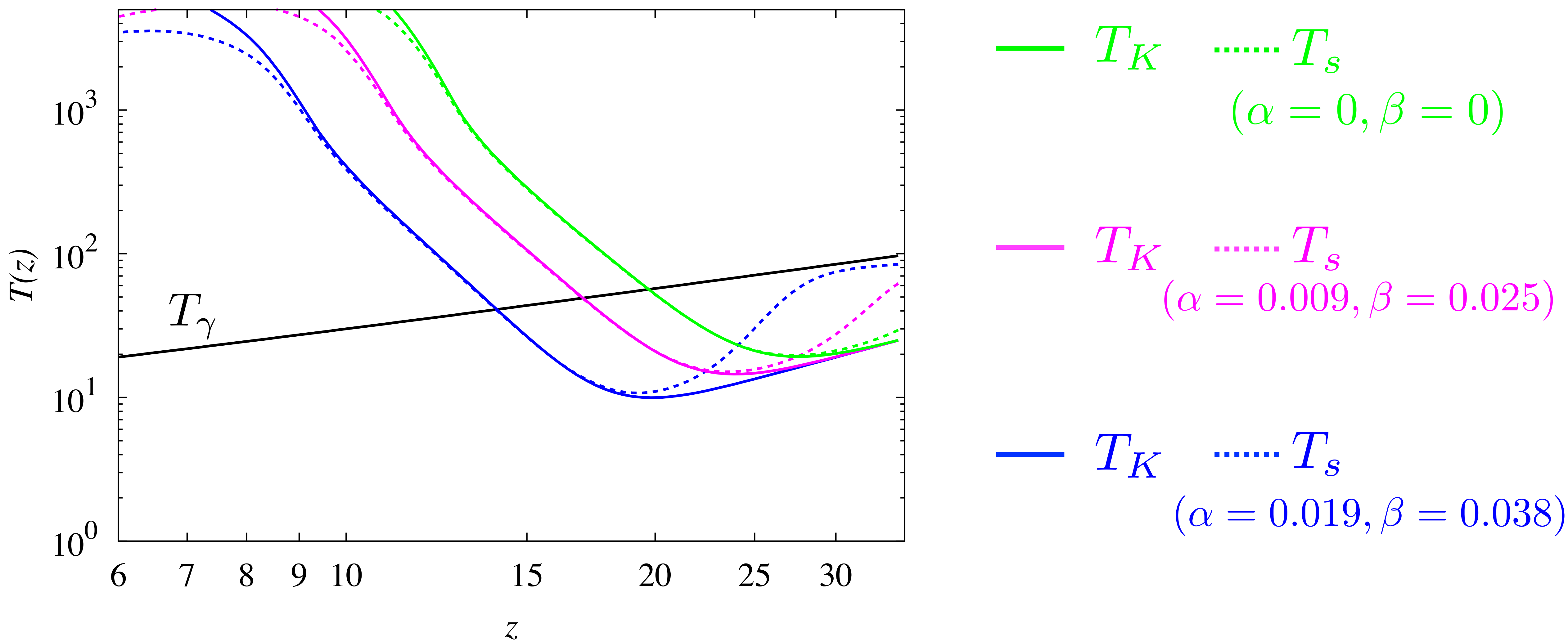
➡ faster (slower) structure formation

➡ switches on Lyα sources earlier (later)

➡ affects 21cm global signal (absorption line shifted to higher (lower) z)



Evolutions of the temperatures



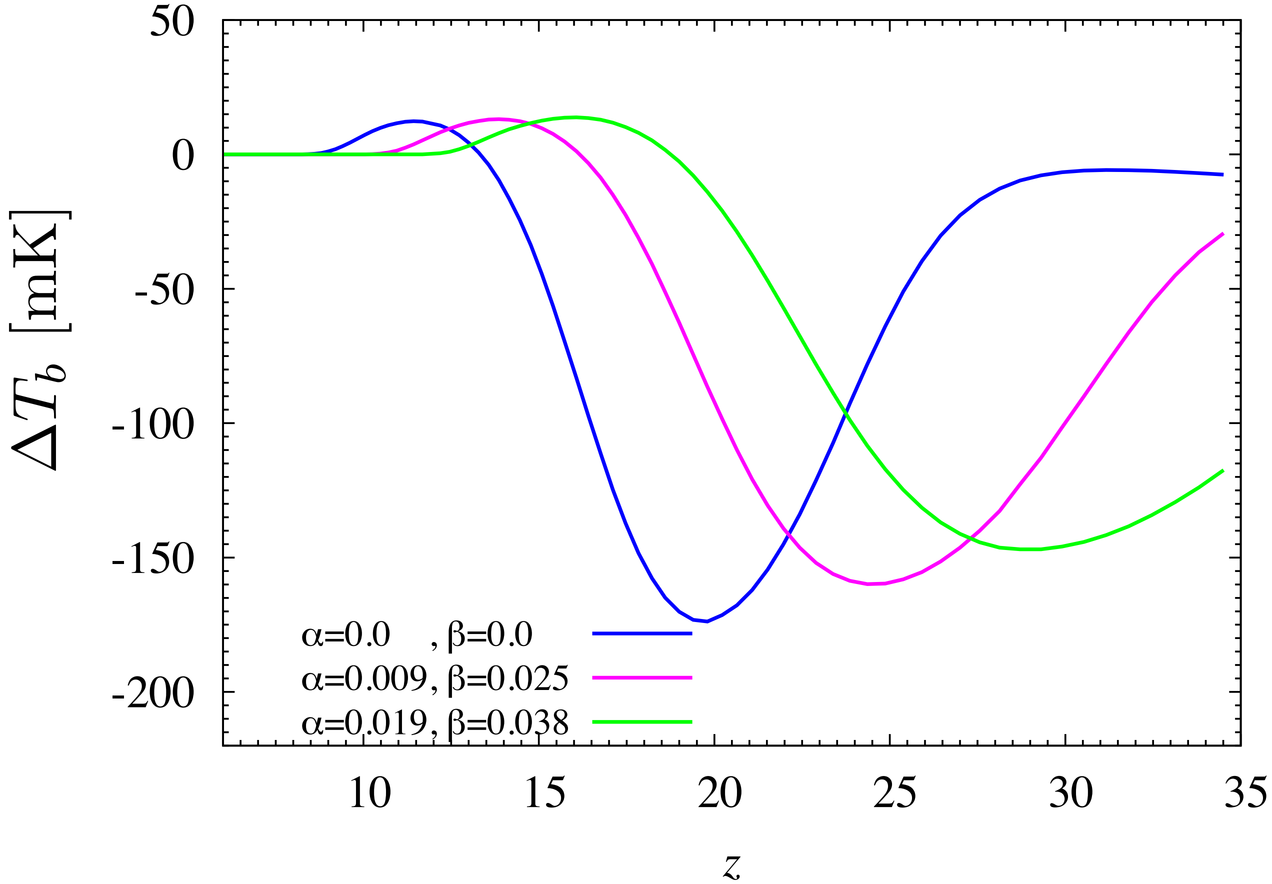
Larger (smaller) the runnings

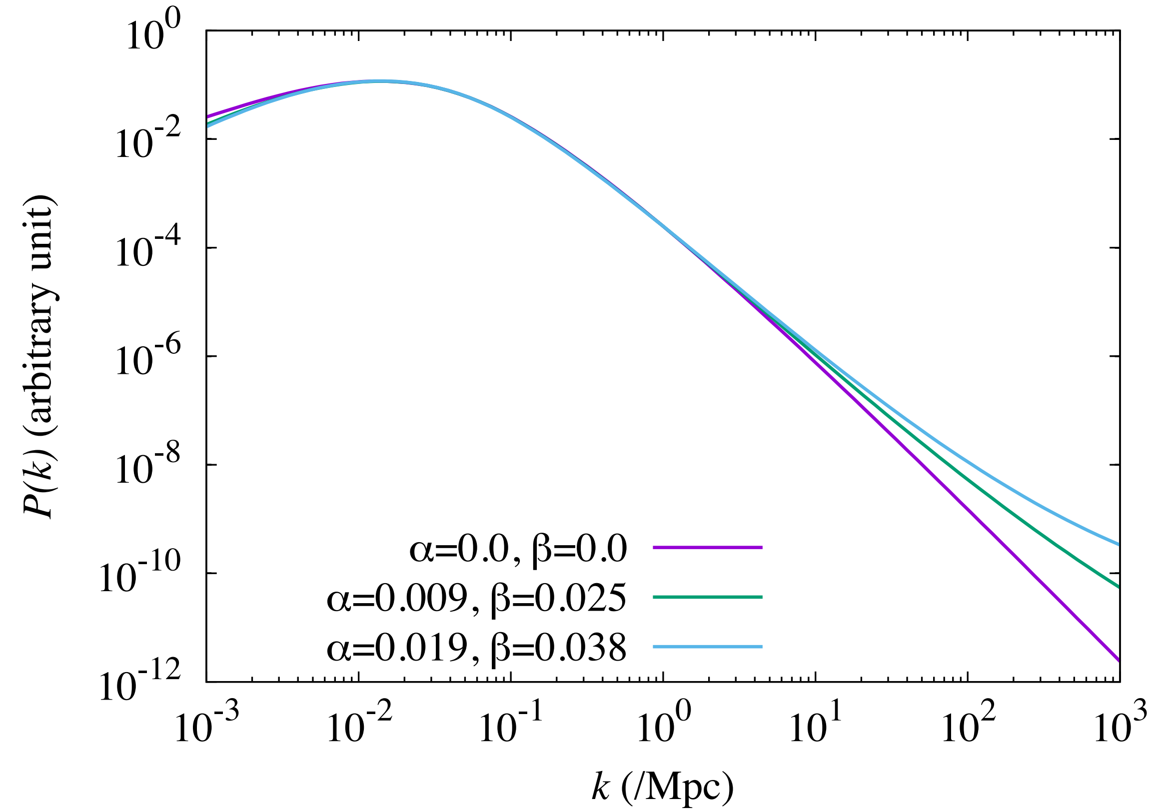
→ faster (slower) structure formation

→ switches on Lyα sources earlier (later)

→ affects 21cm global signal

Evolution of ΔTb





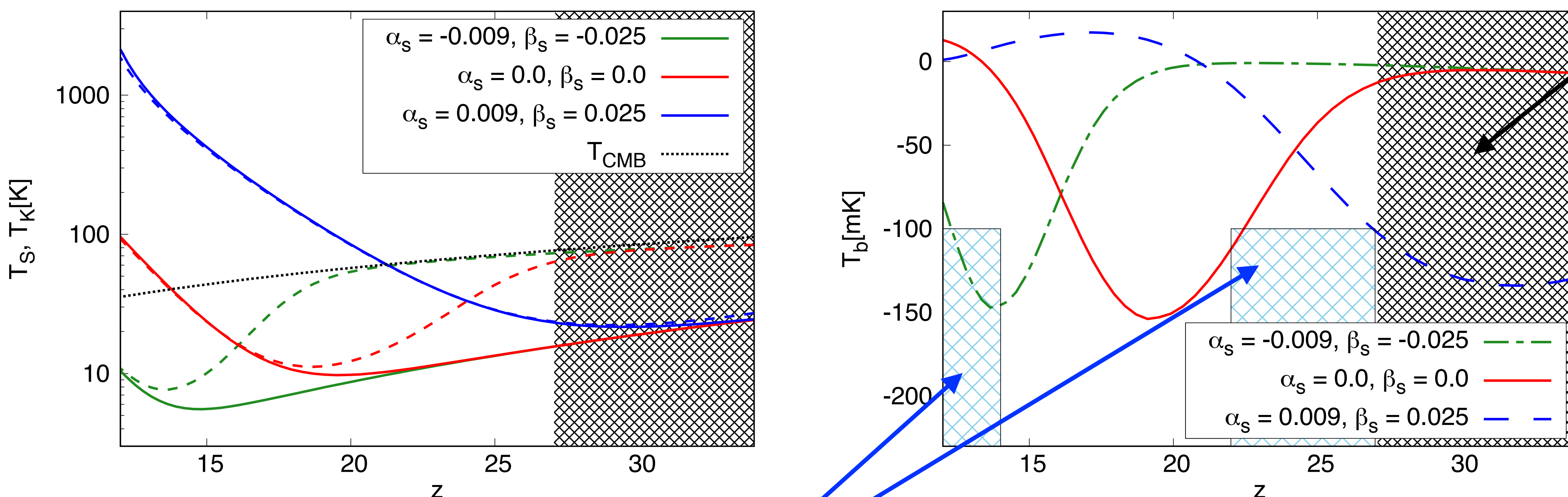
21cm global signal is affected by small scale fluctuations.

Constraining primordial power spectrum

[Yoshiura, K.Takahashi, TT 1805.11806]

- Effects of the running parameters on 21cm global signal

No data



EDGES suggests no signal in these redshifts

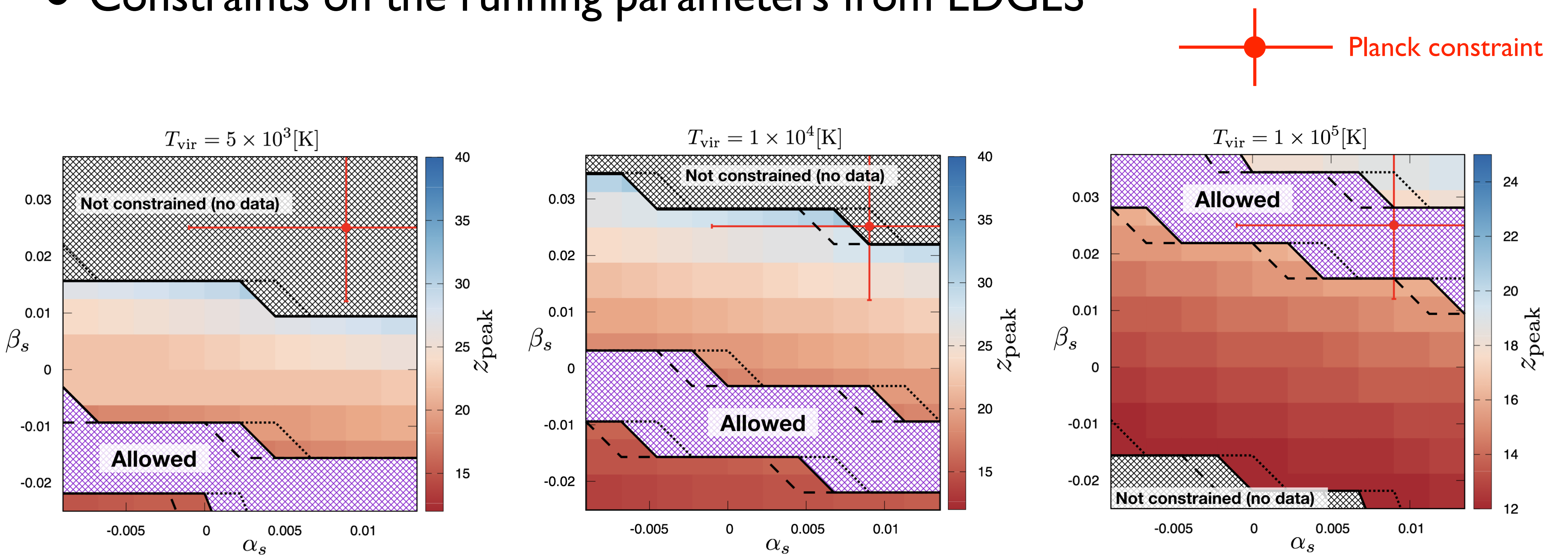
Demanding that the absorption line should not appear z < 14, 22 < z, we can constrain the running parameters

(Just using the information of the position of the absorption trough.)

Constraining primordial power spectrum

[Yoshiura, K.Takahashi, TT 1805.11806]

- Constraints on the running parameters from EDGES



- Only with the position of the absorption trough, the runnings can be constrained and check with Planck constraint.

- Uncertainties in astrophysics would affect the constraints.

Summary

- Current cosmological observations now severely constrain primordial fluctuations.

- However, they are not enough to pin down the inflationary model.

- We need to probe yet other quantities more precisely to test the inflationary models.

- Future observations of 21cm line may be able to give a critical test to models of inflations.