How to See the Dark?

Signatures of strings and other things in the 21 cm radiation from high-redshift hydrogen.

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ASU-Tufts Cosmic String Workshop 2014

Outline

- Dark Ages and 21 cm radiation
- Radiative Transfer
- Brightness Temperature diff. Cosmic Gas vs. String Wake
- Strings and Their Signatures around z=20
- Strings and Their Signatures just before reionization.

- The 21 cm Signature of Cosmic String Wakes,
  R. Brandenberger, R. Danos, O.H., G. Holder , JCAP 1012 (210) 028,2010, arXiv:1006.2514.
  Angular 21 cm Power Spectrum of a Scaling Distribution of Cosmic String Wakes,
  O.H., Y. Wang, R. Brandenberger, J. Fong, JCAP 1108 (2011) 014, arXiv:1104.3337. The High-Redshift Neutral Hydrogen Signature of an Anisotropic Matter Power Spectrum,
  O.H., G.P.Holder, JCAP 1109 (2011) 031, arXiv:1104.5403.
  The 21 cm Signature of Shock Heated and Diffuse Cosmic String Wakes,
  O.H., R. Brandenberger, JCAP 1207 (2012) 032, arXiv:1203.2307.
  Wouthuysen–Field coupling in Cosmic Strings Wakes.
  work in progress.

Observations during Dark Ages can directly constrain cosmology

- During Dark Ages, 1100 < z < 20, the 10^{-5} density fluctuations present at recombination grow to form structure.
- Physics is simple then, calculations can be done, an observed deviation from expected evolution would be a clean signature of new physics, e.g. cosmic strings

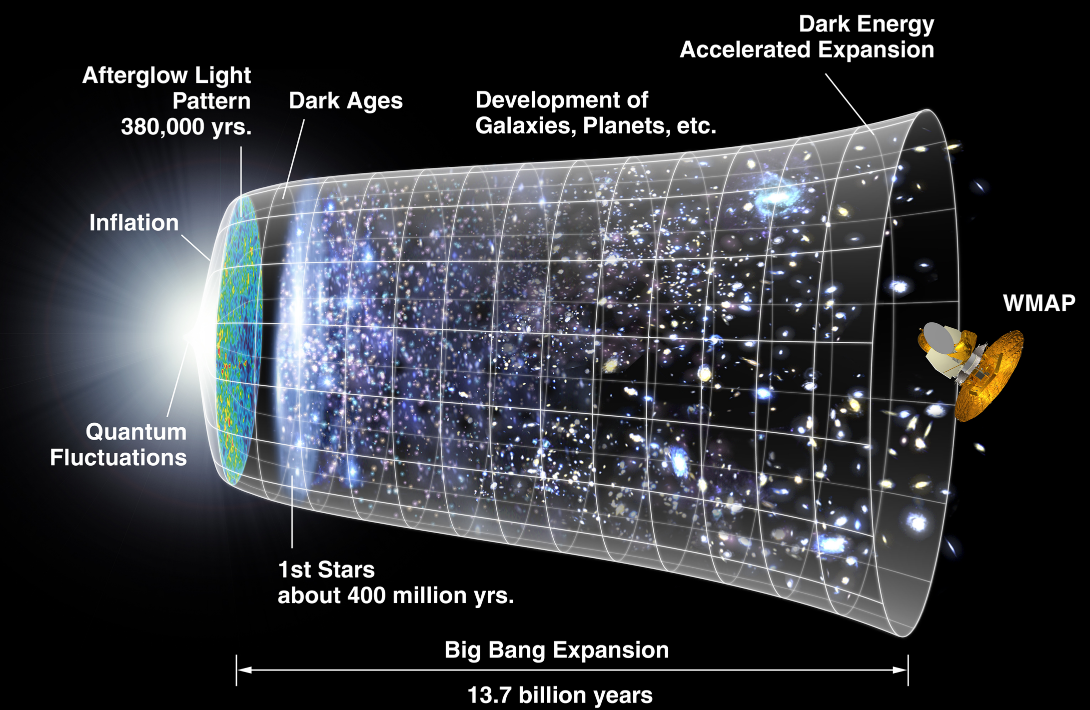
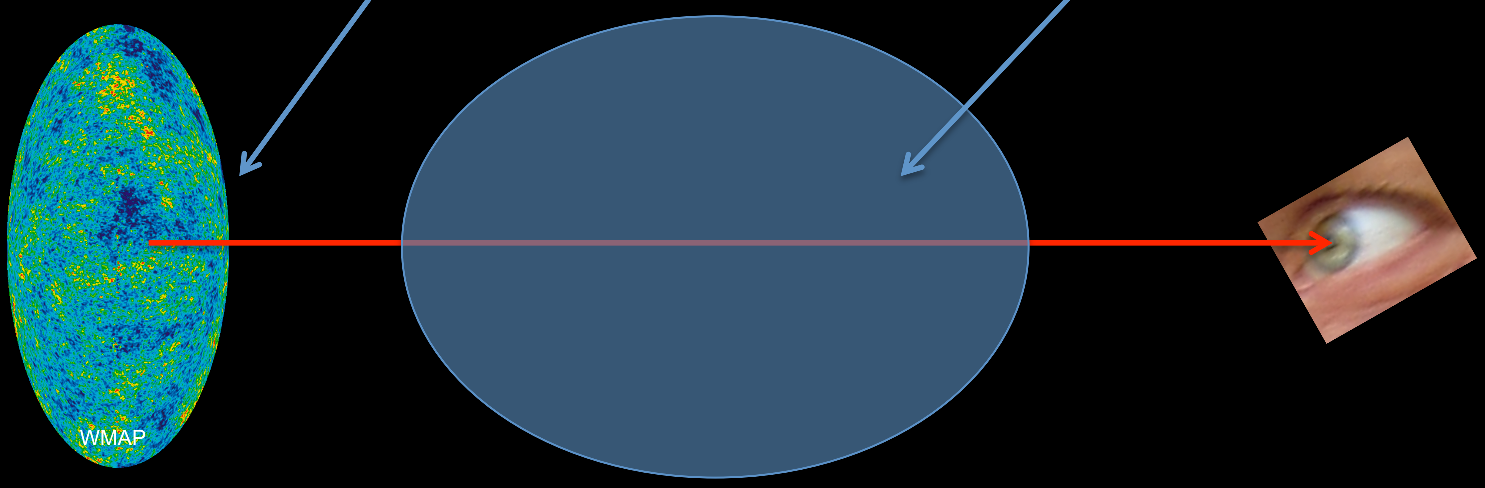


image from the WMAP http://map.gsfc.nasa.gov/media/060915/index.html

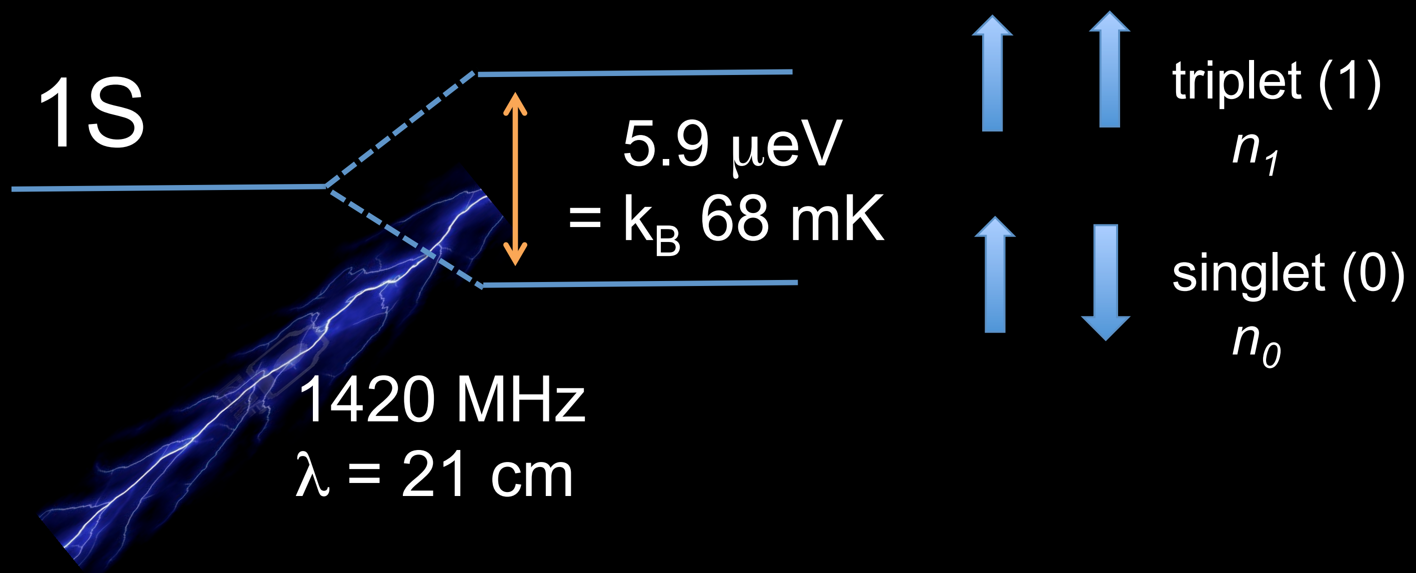
How to see the Dark

- Use the CMB light released at recombination as a backlight for the Cosmic Hydrogen Gas.



Neutral hydrogen cloud can absorb or emit 21 cm radiation

through the spin flip transition of the hyperfine split ground state

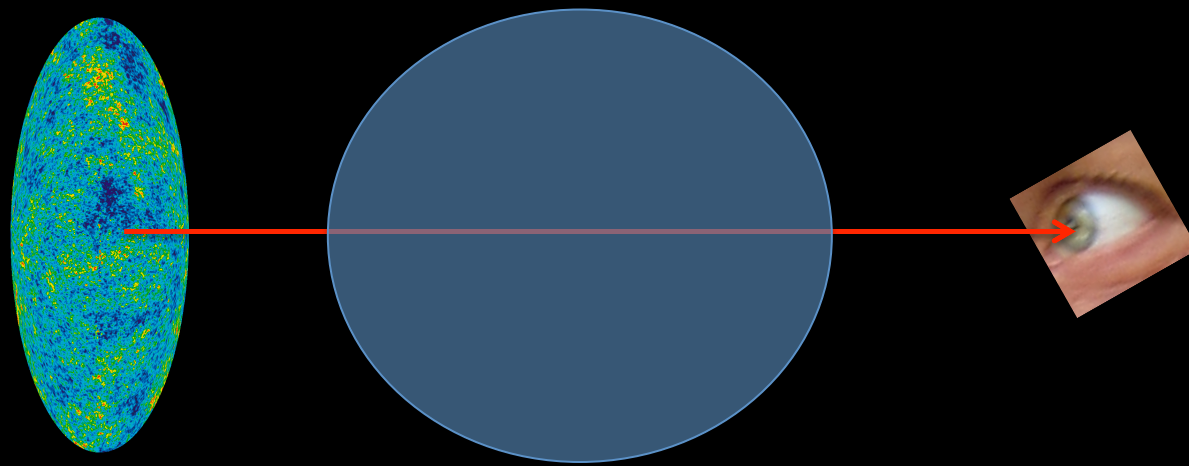


Radiative transfer

A light ray with frequency ν is travelling through the hydrogen cloud in direction $\hat{\mathbf{k}}$. It has a position dependent intensity $\mathbf{I}(\vec{\mathbf{x}}, \nu, \hat{\mathbf{k}})$.

The change in its intensity, dI, at the point $\vec{\mathbf{x}}$ is due to:

1. Absorption
2. Stimulated Emission
3. Spontaneous Emission



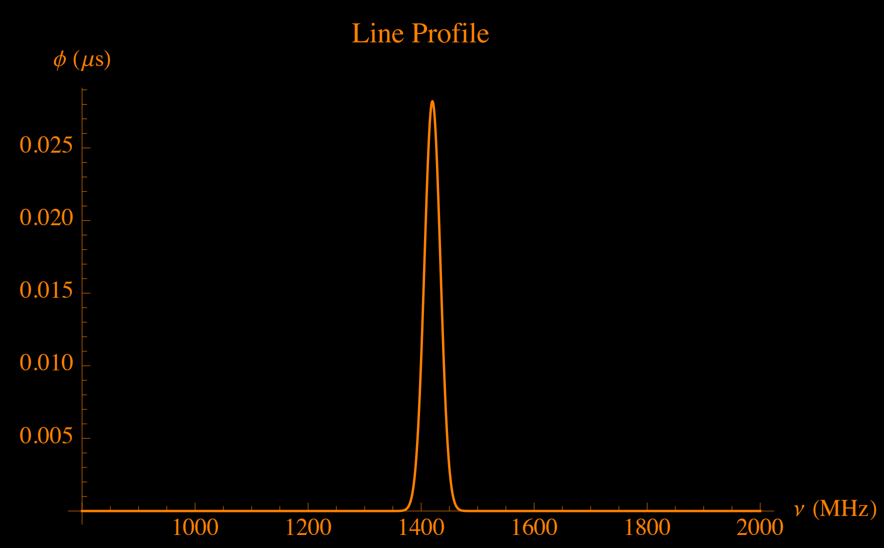
Absorption & Stimulated Emission	Spontaneous Emission
Proportional to: • Intensity = I • distance travelled = *ds* • H particle density = n_0 , n_1 • cross sections σ_{01} , $\sigma_{10} \propto$ (Einstein coeff) ×(line profile)	Proportional to: • distance travelled = *ds* • H particle density = n_1 • emission coefficient $\epsilon_\nu \propto$ (Einstein coeff) ×(line profile)
$\mathrm{dI} = -\mathrm{I}\,(n_0\,\sigma_{01} - \sigma_{10}\,n_1)\,\mathrm{ds}$	$\mathrm{dI} = \epsilon_\nu\, n_1 \mathrm{ds}$

Absorption & Stimulated Emission	Spontaneous Emission
Cross sections σ_{01}, σ_{10} $\propto$ (Einstein coefficients) ×(line profile) σ_{01}=hν/(4π) $B_{01}\,\phi_A(\nu)$ σ_{10}=hν/(4π) $B_{10}\,\phi_A(\nu)$	Atomic emission coefficient $\epsilon_\nu \propto$: (Einstein coefficients) ×(line profile) ϵ_ν = hν/(4π) $A_{10}\,\phi_E(\nu)$

- The Einstein coefficients A_{10} , B_{10} , B_{01} characterize an atomic property. Of the three only one is independent:

$$B_{01}/B_{10} = 3 , \qquad A_{10}/B_{10} = 2\, h\, \nu^3/c^2 \qquad A_{10} = 2.85 \times 10^{-15}\ s^{-1}$$

- The line profiles $\phi_A = \phi_E$ $\neq \delta\,(\,\nu - 1420\ \mathrm{MHz})$ because of the Hubble flow.



$$dI = \left(- I\,\alpha_\nu + j_\nu\right) ds$$

$$= (h\nu/(4\pi))\left[\, I\,(-n_0 B_{01} + n_1 B_{10})\,\phi_A + n_1 A_{10}\,\phi_E \,\right] ds$$

$$= \frac{\mathbf{3n_0 A_{10} c^2 \phi_E}}{\mathbf{8\pi\nu^2}} \left[(-I + I\,\frac{\mathbf{n_1}}{\mathbf{3n_0}}) + \frac{\mathbf{n_1}}{\mathbf{3n_0}}\,\frac{\mathbf{2h\nu^3}}{\mathbf{c^2}}\right] ds$$

absorption

stimulate emission

spontaneous emission

Ugly formula

- Quantify $I(\nu)$ through brightness temperature T_γ

$$I = T_\gamma \, 2k_B\nu^2/c^2$$

- Define the spin temperature T_S through the ratio of triplet to singlet particle densities as $n_1/n_0 = 3\,\mathrm{Exp}(-h\nu_{21}/(k_B T_S))$.

$$T_S >> T^*$$

- Define the optical depth $d\tau_\nu$ which depends on Einstein coeff, line profile, distance travelled

Ugly formula becomes beautiful

$$\mathbf{dT}_\gamma = \left[-\mathbf{T}_\gamma + \mathbf{T_S}\right] \mathbf{d}\tau_\nu$$

$$\mathbf{dT}_\gamma = \left[-\mathbf{T}_\gamma + \mathbf{T_S}\right] \mathbf{d}\tau_\nu$$

- Multiply both sides by the integrating factor e$^{\tau_\nu}$
- Imagine observing the 21 cm ray after it has passed through a slab of hydrogen gas at particular distance, specified by the redshift of the 21 cm photon. The slab is thin enough that T_S is constant.

absorption-stimulated emission

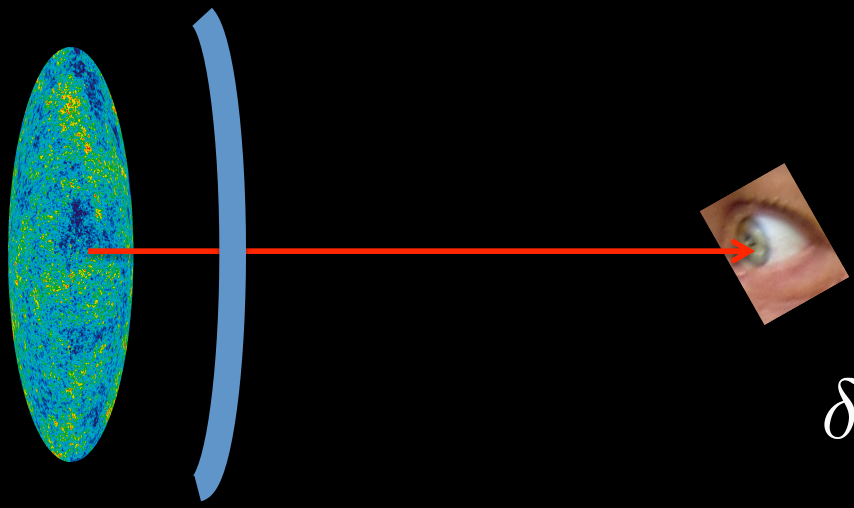
spontaneous emission

$$\mathbf{T}_\gamma(\tau_\nu) = \mathbf{T}_\gamma(\mathbf{0})\mathbf{e}^{-\tau_\nu} + \mathbf{T_S}(\mathbf{1} - \mathbf{e}^{-\tau_\nu})$$

Brightness Temperature difference δT_b

Compare the 21 cm ray after passing through a high redshift hydrogen cloud to what it would have been had we had a clear view of the CMB.

$$
\begin{aligned}
\delta \mathbf{T_b} &\equiv \mathbf{T}_\gamma(\tau_\nu) - \mathbf{T}_\gamma(\mathbf{0}) \\
&= (\mathbf{T_S} - \mathbf{T}_\gamma(\mathbf{0}))(\mathbf{1} - \mathbf{e}^{-\tau_\nu}) \\
&\approx (\mathbf{T_S} - \mathbf{T}_\gamma(\mathbf{0}))\tau_\nu
\end{aligned}
$$



When we finally observe these photons they are redshifted:

$$
\delta \mathbf{T_b} \approx \frac{(\mathbf{T_S} - \mathbf{T}_\gamma(\mathbf{0}))}{\mathbf{1} + \mathbf{z}} \tau_\nu
$$

Optical Depth τ_ν of a Δs Slab of Hydrogen

$$\tau_\nu(\mathbf{s}) = \frac{\mathbf{3hc^2 A_{10} x_{HI} n_H}}{\mathbf{32\pi\nu k_B T_S}} \, \mathbf{\Delta s}\, \phi(\mathbf{s},\nu)$$

$$\approx \frac{\mathbf{2.6{\times}10^{-12}\ n_H \Delta s}\, \phi(\mathbf{s},\nu)\ \mathbf{mKcm^2s^{-1}}}{\mathbf{T_s}}$$

Brightness temp. from a Δs Slab of Hydrogen

$$\delta \mathbf{T_b} \approx \left(\mathbf{1} - \frac{\mathbf{T_\gamma(0)}}{\mathbf{T_S}}\right) (\mathbf{2.6 \times 10^{-12}\ mK\, cm^2 s^{-1}})\ \mathbf{n_H} \frac{\mathbf{\Delta s}\, \phi(\mathbf{s},\nu)}{\mathbf{1+z}}$$

Observing 21 cm radiation depends crucially on T_S :

- T_S above T_γ emission.
- T_S below T_γ absorption.

What mechanisms drive T_S above or below T_γ ?

- Interaction with CMB photons
- Spontaneous emission
- Collisions with hydrogen, electrons, protons
- Near the end of the Dark Ages, scattering with UV photons. Ignore this for now.

$$n_1 (B_{10} I + A_{10} + C_{10}) = n_0 (B_{01} I + C_{01})$$

determines spin temperature in equilibrium.

$$\left(1 - \frac{T_\gamma}{T_S}\right) = \frac{x_c}{1 + x_c}\left(1 - \frac{T_\gamma}{T_K}\right) \quad x_c \equiv C_{10} T_* / (A_{10} T_\gamma),$$

C_{10} depends on densities and T_K

Collision coefficients x_C drive T_S towards T_γ or T_K

- If x_c is small T_s is driven towards T_γ
- If x_c is large T_s is driven towards T_K

$$\left(1 - \frac{T_\gamma}{T_S}\right) = \frac{x_c}{1 + x_c}\left(1 - \frac{T_\gamma}{T_K}\right)$$

Optical Depth τ_ν of a Δs Slab of Hydrogen

$$\tau_\nu(\mathbf{s}) = \frac{\mathbf{3hc^2 A_{10} x_{HI} n_H}}{\mathbf{32}\pi\nu\mathbf{k_B T_S}}\,\boldsymbol{\Delta}\mathbf{s}\,\phi(\mathbf{s},\nu)$$

$$\approx \frac{\mathbf{2.6\times 10^{-12}}\ \mathbf{n_H}\boldsymbol{\Delta}\mathbf{s}\,\phi(\mathbf{s},\nu)\ \mathbf{mKcm^2 s^{-1}}}{\mathbf{T_s}}$$

Up to this point the hydrogen cloud could be anything:

- the cosmic gas (CG)
- a cosmic string wake.

The combination $\mathbf{n_H}\boldsymbol{\Delta}\mathbf{s}\,\phi(\mathbf{s},\nu)/\mathbf{T_s}$ is different for each of the two cases.

Cosmic String Wake

From the point of view of an observer behind the string and moving with it, matter flowing past the string acquires a velocity kick $4\pi G\mu \, v_{string} \, \gamma_{Vstring}$ towards the central plane

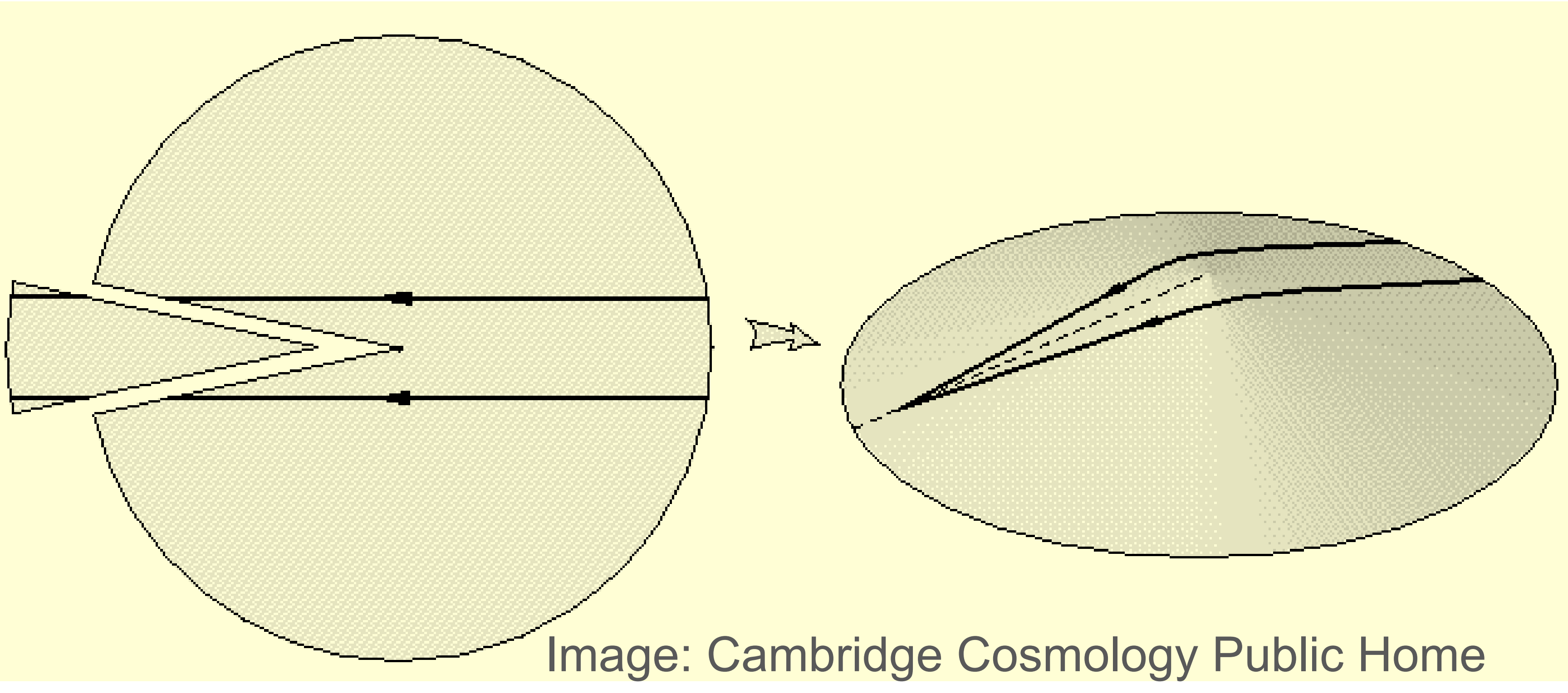
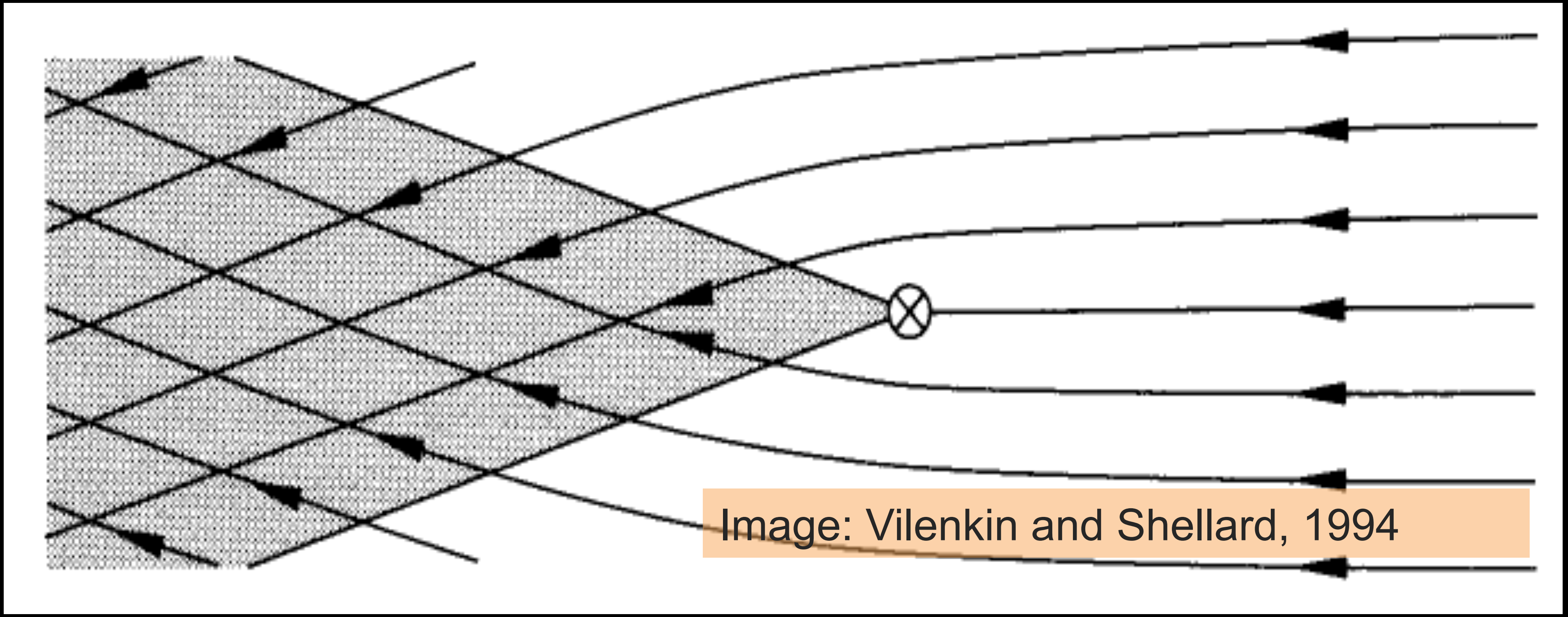


Image: Cambridge Cosmology Public Home Page

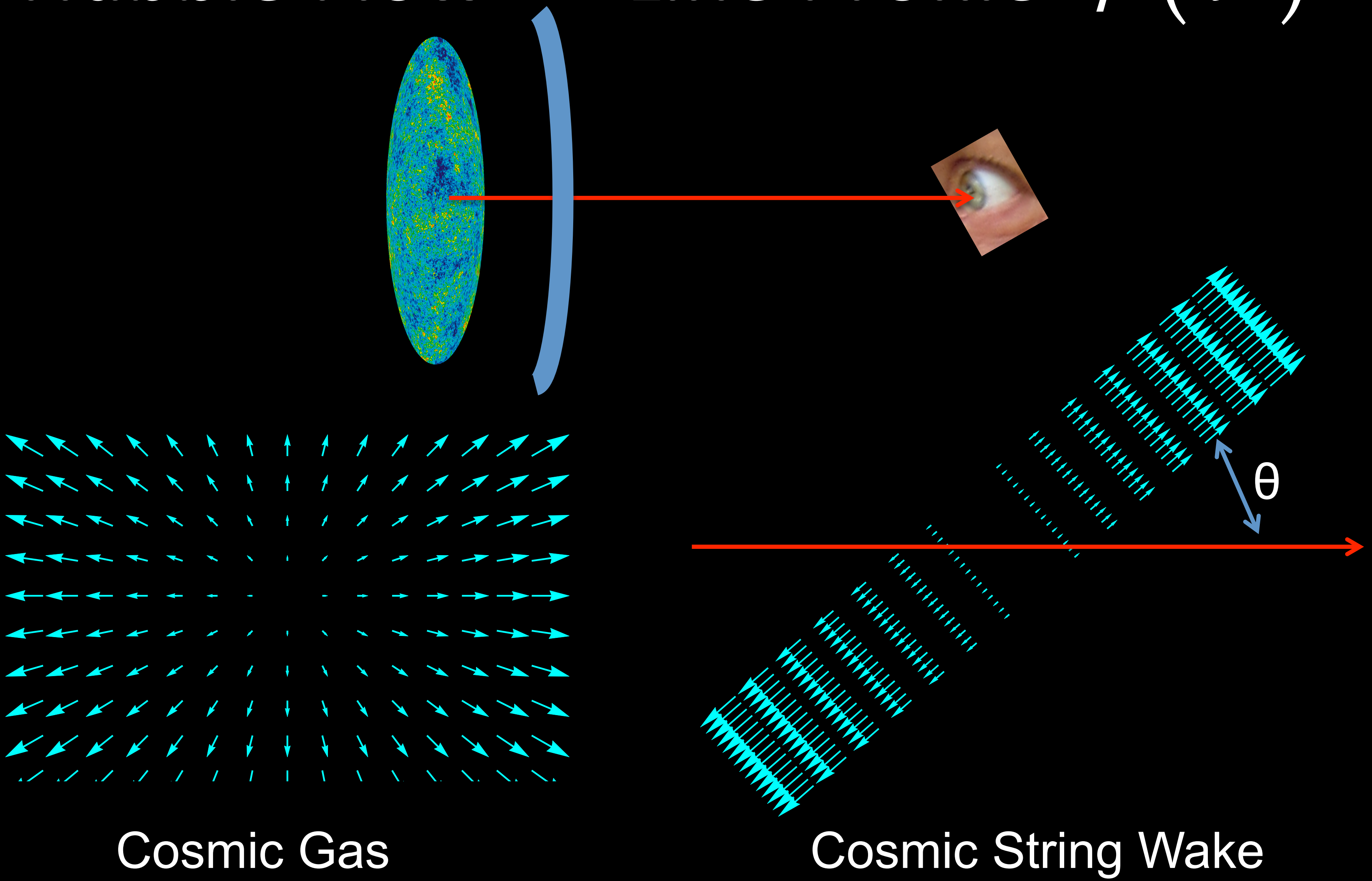


- Dark matter streams through and oscillates about the central plane,
- Baryons collide in the centre form shocks and heat the gas. Shocks can lead to a factor of 4 in the overdensity of the baryons.

The combination $\mathbf{n_H \Delta s}\, \phi(\mathbf{s}, \nu)/\mathbf{T_s}$ is different for each of the two cases.

- For shock heated string wakes $(n_H)_{wake} \approx 4(n_H)_{CG}$
- T_S depends on
  - gas temperature T_K (estimated in Zel'dovich approximation for wakes),
  - collision coefficients x_C, (that also depend on T_K and densities)
- Line profile ϕ depends on the velocity gradient of the bulk motion along the line of sight.

Hubble Flow ⇒ Line Profile $\phi(\nu)$



Optical Depth

$$\tau_\nu(\mathbf{s}) \approx \frac{2.6\times10^{-12}\ \mathbf{n_H \Delta s}\,\phi(\mathbf{s},\nu)\ \mathbf{mKcm^2s^{-1}}}{\mathbf{T_s}}$$

- Cosmic Gas: $\approx \mathbf{8.6\,mK}\,\frac{\mathbf{1}}{\mathbf{T_S}}(\mathbf{1+z})^{\mathbf{3/2}}(\mathbf{1}+\delta_{\mathbf{b}})$

- String Wake: $\approx \frac{\mathbf{17\,mK}}{\mathbf{2}\sin^{\mathbf{2}}\theta}\frac{(\overline{\mathbf{n_H}})_{\mathbf{wake}}}{(\overline{\mathbf{n_H}})_{\mathbf{CG}}}\frac{\mathbf{1}}{\mathbf{T_S}}(\mathbf{1+z})^{\mathbf{3/2}}(\mathbf{1}+\delta_{\mathbf{b}})$

$$\approx \mathbf{70\,mK}\frac{\mathbf{1}}{\mathbf{T_S}}(\mathbf{1+z})^{\mathbf{3/2}}(\mathbf{1}+\delta_{\mathbf{b}})$$

For wakes we see a 8x enhancement (70 ≈ 8 x 8.6):

- $\theta \sim \pi/4$
- $(n_H)_{wake}/(n_H)_{CG} \sim 4$

But there's more ...

Collision coefficients, x_c , enhancement

$$\delta T_b \approx \frac{(T_S - T_\gamma(0))}{1+z}\,\tau_\nu$$

$$= \frac{17\,\mathrm{mK}}{2\sin^2\theta}\,\frac{(\overline{n_H})_{\mathrm{wake}}}{(\overline{n_H})_{\mathrm{CG}}}(1+z)^{1/2}(1+\delta_b)\left(1-\frac{T_\gamma}{T_S}\right)$$

$$\frac{x_c}{1+x_c}\left(1-\frac{T_\gamma}{T_K}\right)$$

The collision coefficient factor can be a factor of 10 larger for wakes vs. CG.

All together this makes for a factor of 80 enhancement for string wakes versus the cosmic gas.

Cosmic Gas 21 cm Global δT_b

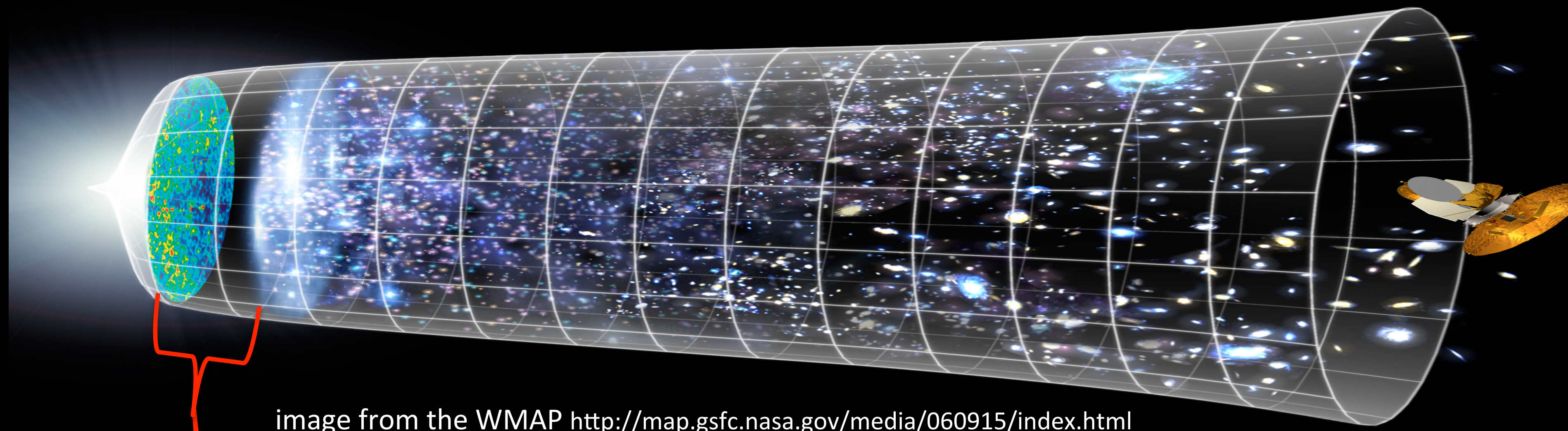


image from the WMAP http://map.gsfc.nasa.gov/media/060915/index.html

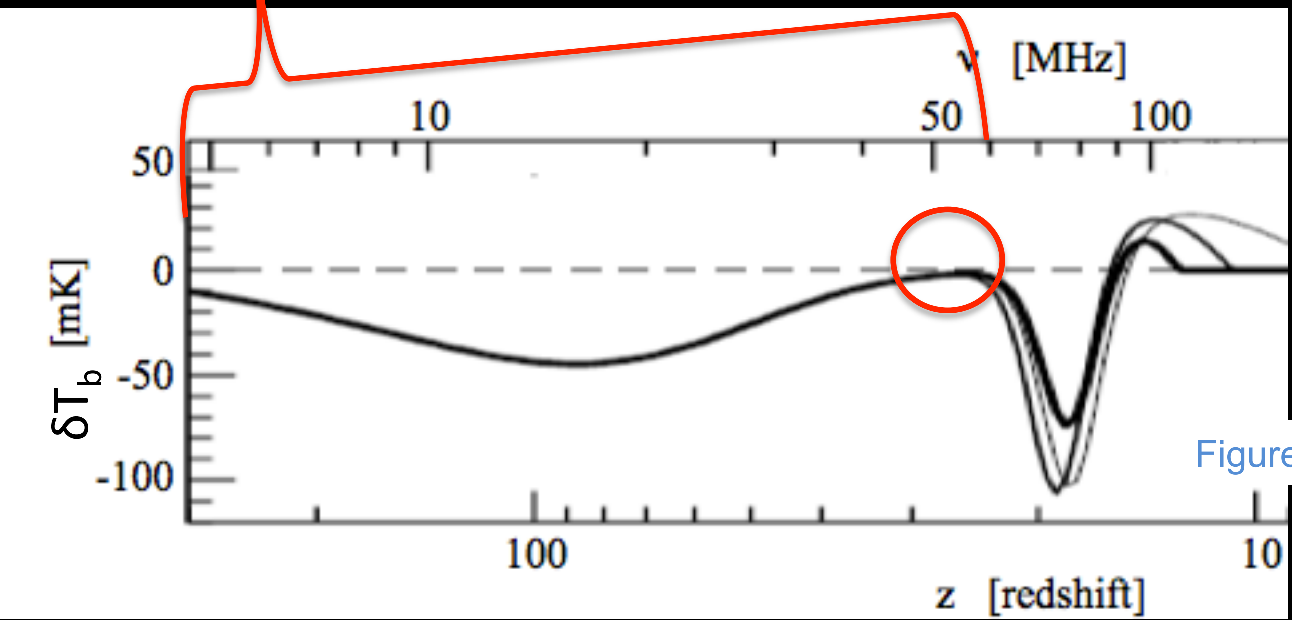


Figure from Pritchard & Loeb 2008

Cosmic Wake Temperature

$$\mathbf{T_K \simeq [20\ K](G\mu\, 10^6)^2 (v_s \gamma_s)^2 \frac{z_i + 1}{z + 1}}$$

Determined by considering thermalization of shock heated baryons. (Zel'dovich approximation and hydrocode of Sornborger et al.)

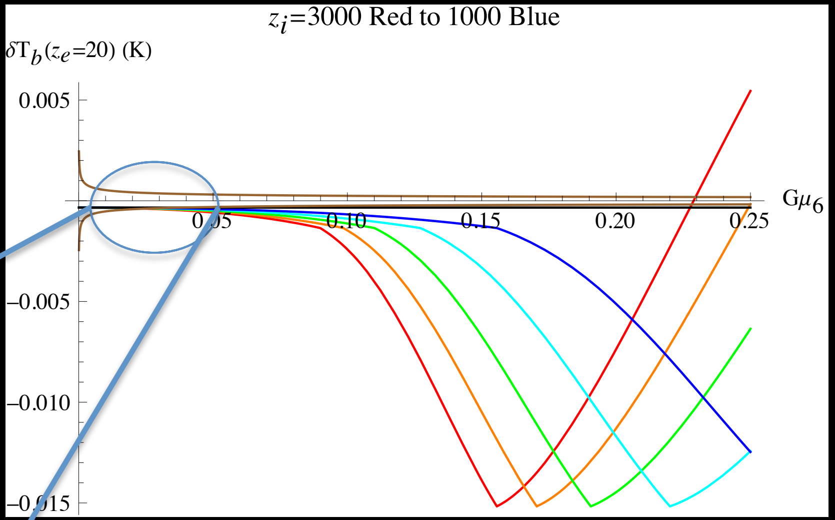
Current limits on the cosmic string tension $G\mu$

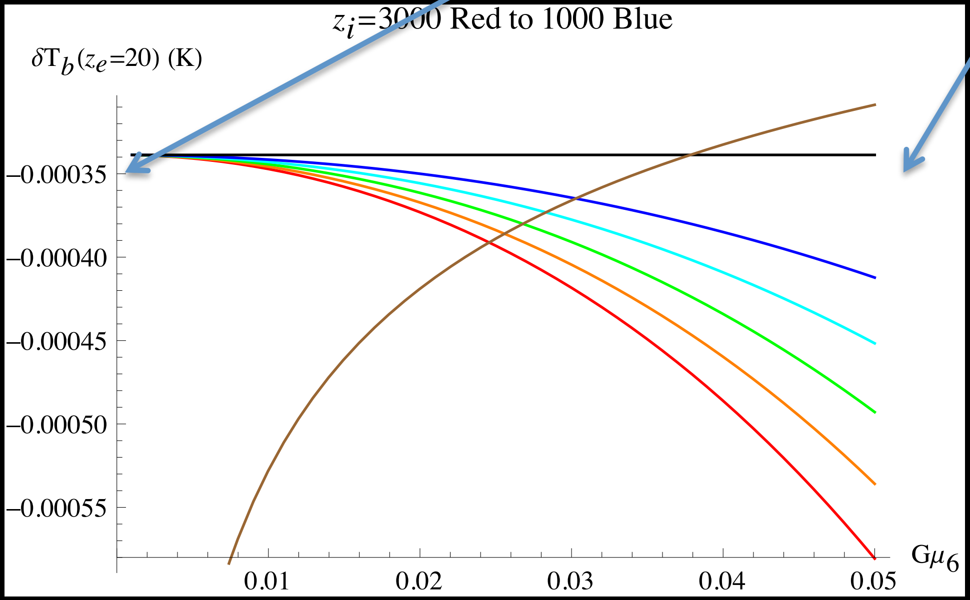
using the combined data from

WMAP and SPT

$G\mu \lesssim 10^{-7}$

Global 21 cm δT_b vs. string tension Gμ





- z_i , redshift when wake began
- z_e , redshift when wake is observed
- $(G\mu)_6$, string tension in units of 10^{-6}.

Figures from O.H., R. Brandenberger, 2012

What about the Noise?

- Between z=20 and 35 the average δT_b of the cosmic gas varies between -0.34 mK to -8.6 mK.
- Thermal noise per redshift cell:
  - T_{sys} is approximately the sky temperature,
  - B is the bandwidth,
  - τ is the total observing time,
  - $\theta_{desired}$ is the resolution desired (e.g. 1 arcminute)
  - $\theta_{diffraction}$ is the diffraction limited resolution 21cm (1+z) /A_e
  - A_e is the effective antenna area.

$$\mathbf{T_n} = \frac{\sqrt{\mathbf{2}}\,\mathbf{T_{sys}}}{\sqrt{\mathbf{B}\,\tau}} \frac{\theta_{\rm diffraction}}{\theta_{\rm desired}}$$

$$\mathbf{T_{sys}} = \mathbf{1.26}\ \mathrm{K} \left((\mathbf{1} + \mathbf{z}) \frac{\mathrm{1GHz}}{\nu_{\mathbf{21}}} \right)^{\mathbf{2.6}}$$

ARCADE 2, 2009

Angular resolution needed to see a string wake:

- $\theta_L(z)$ resolution needed for the wake's length.
- $\theta_W(z)$ resolution needed for the wake's width.
- $\theta_{desired}(z) \sim \theta_W(z)^{1/3}\theta_L(z)^{2/3}$, estimate of the resolution in radians needed to calculate the noise per pixel.

$$\sim \frac{1}{3}\frac{1}{(\sqrt{z+1}-1)}\sqrt{\frac{(z+1)}{(z_i+1)}}\left(4\pi G\mu\frac{3}{10}\frac{(z_i+1)}{(z+1)}\right)^{1/3}$$

Put this together to arrive at ….

At SKA:

- $z=20$,
- $A_e=1km^2$,
- $\tau=10^4 hr$
- For $G\mu \gtrsim 3 \times 10^{-8}$ we would be able to pick out the wakes above the noise and measure their density.

But is there any hope of having a cosmic string signal before the SKA ?

The first Starlight

As the first galaxies form a possibly deeper absorption feature appears around z~20

From http://scienceblogs.com/startswithabang/2010/01/25/seeing-red-in-the-sky/

Wouthysen-Field effect

H atoms can change hyperfine states through the absorption and spontaneous re-emission of a Lyman alpha photons.

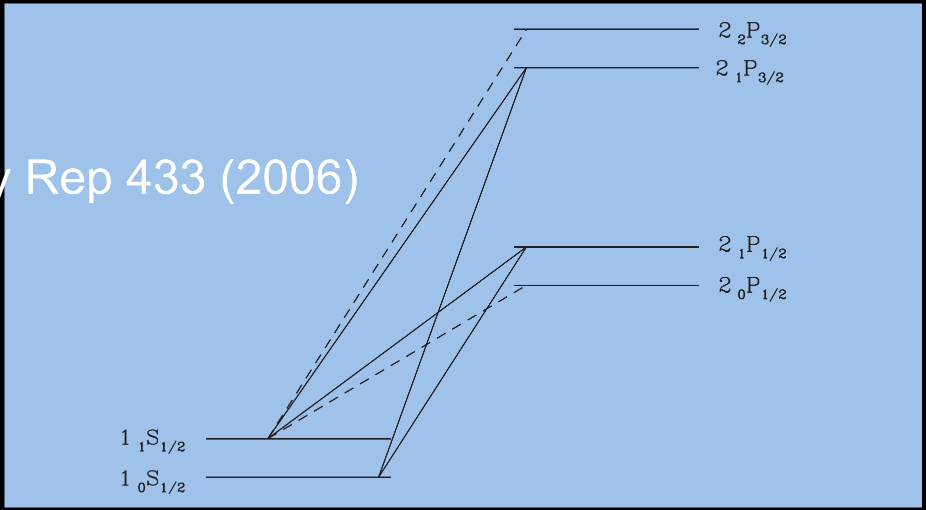


Figure from Furlanetto, Oh, Briggs, Phy Rep 433 (2006)

Lyman alpha photons are produced in stars and these resonantly scatter off H coupling T_S to the cooler T_K

WF absorption trough

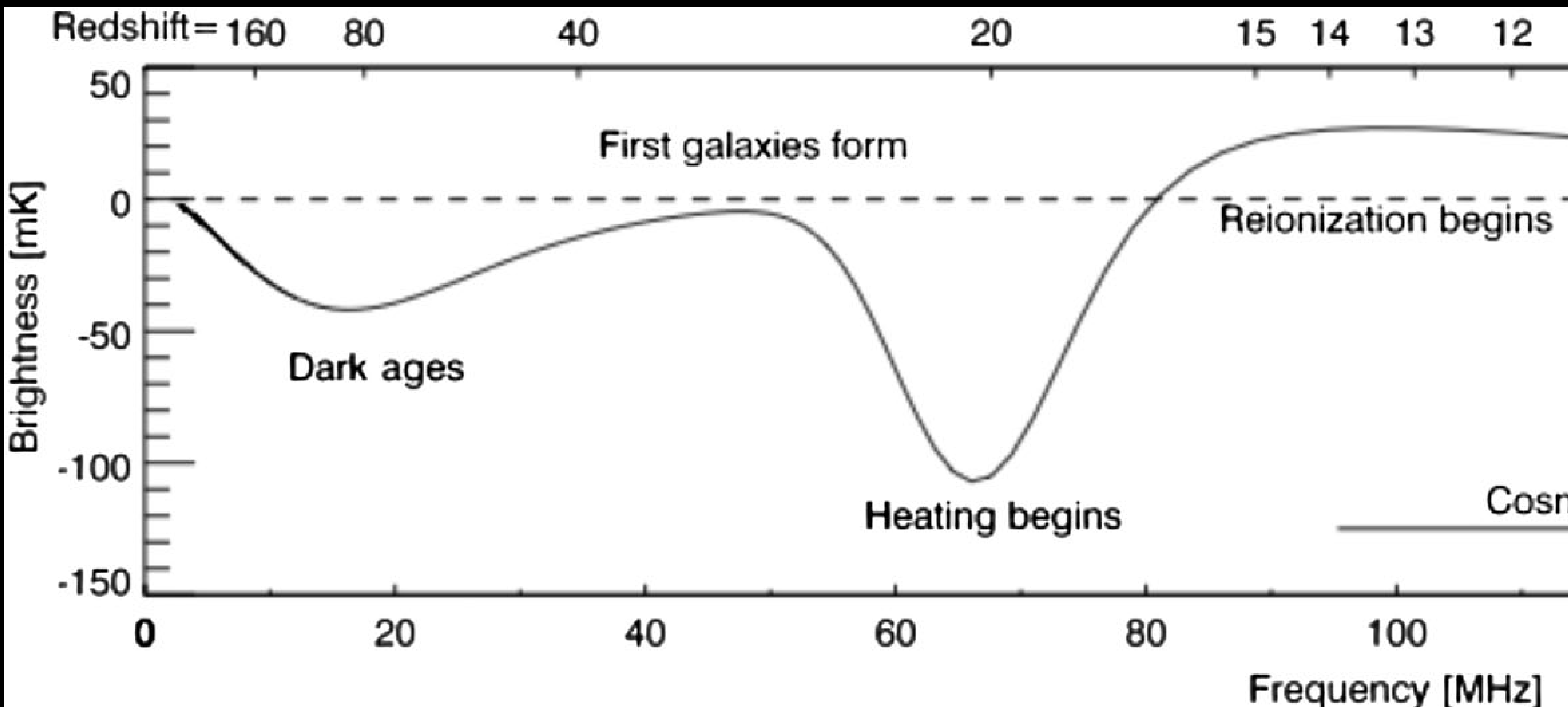


Figure from Liu, Pritchard, Tegmark & Loeb 2013

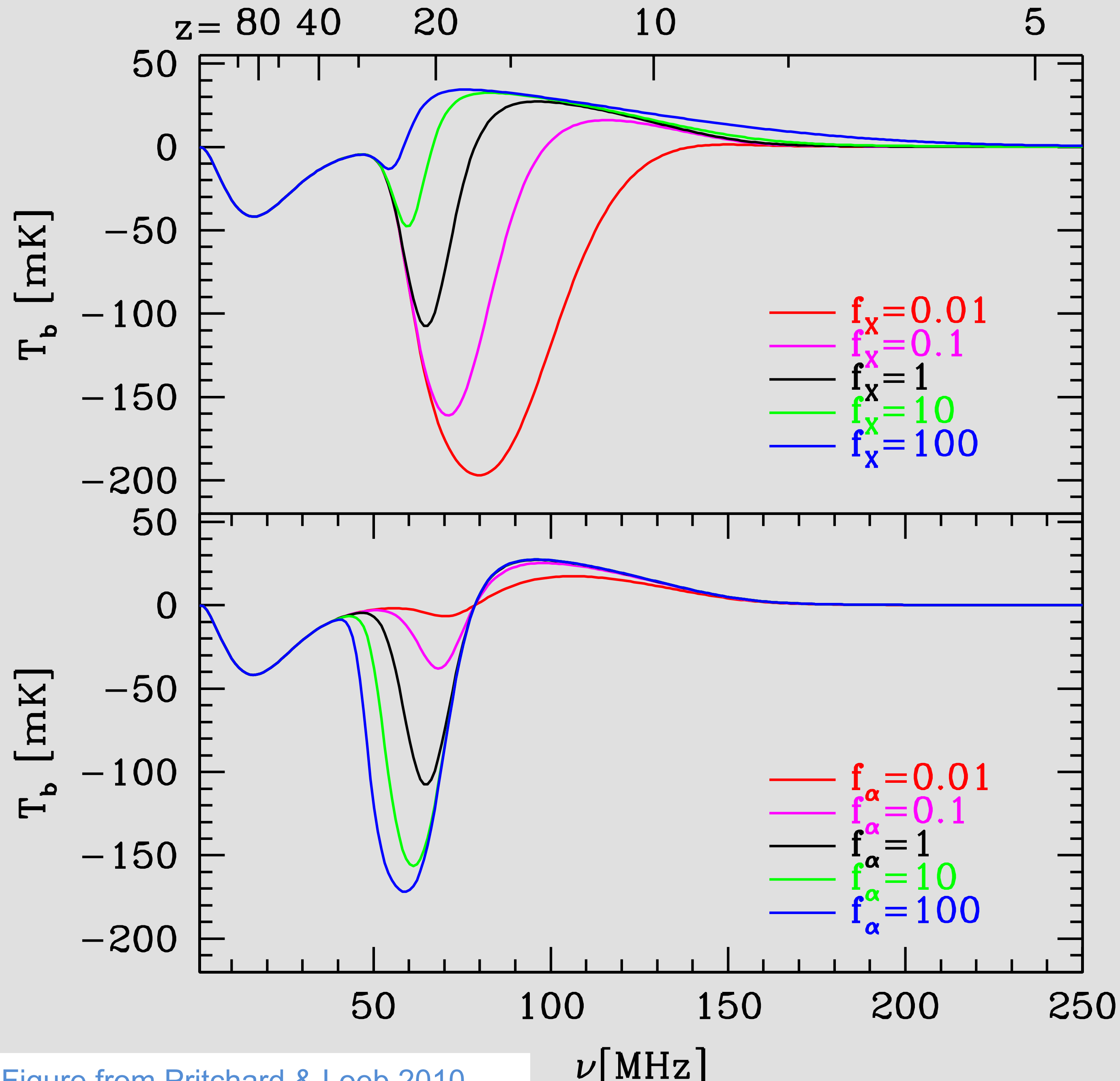


Figure from Pritchard & Loeb 2010

Stars formation generates Lyman alpha, but also X rays which heat the cosmic gas.

No absorption trough if the cosmic gas is heated to CMB temperatures or beyond before enough Lyman alphas are produced to couple the T_S to the T_K there will be no Wouthysen-Field effect absorption trough.

We may soon find out if it exist!

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PROBING THE DARK AGES AT $z \sim 20$: THE SCI-HI 21 cm ALL-SKY SPECTRUM EXPERIMENT

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ABSTRACT

We present first results from the SCI-HI experiment, which we used to measure the all-sky-averaged 21 cm brightness temperature in the redshift range $14.8 < z < 22.7$. The instrument consists of a single broadband sub-wavelength size antenna and a sampling system for real-time data processing and recording. Preliminary observations were completed in 2013 June at Isla Guadalupe, a Mexican biosphere reserve located in the Pacific Ocean. The data was cleaned to excise channels contaminated by radio frequency interference, and the system response was calibrated by comparing the measured brightness temperature to the Global Sky Model of the Galaxy and by independent measurement of Johnson noise from a calibration terminator. We present our results, discuss the cosmological implications, and describe plans for future work.

Astrophys.J. 782 (2014) L9, arXiv:1311.0014

Conclusion

I. 21 cm brightness temperature a powerful tool to search for cosmic strings or other new physics.
II. Noise is the problem.
III. Wouthysen-Field effect (if it exists) would give a brighter above noise signature of cosmic strings

$$\mathbf{dI} = \frac{\mathbf{3n_0 A_{10} c^2} \phi}{\mathbf{8}\pi\nu^{\mathbf{2}}} \left[-\mathbf{I}\left(\mathbf{1} - \frac{\mathbf{n_1}}{\mathbf{3n_0}}\right) + \frac{\mathbf{n_1}}{\mathbf{3n_0}} \frac{\mathbf{2h}\nu^{\mathbf{3}}}{\mathbf{c^2}} \right] \mathbf{ds}$$

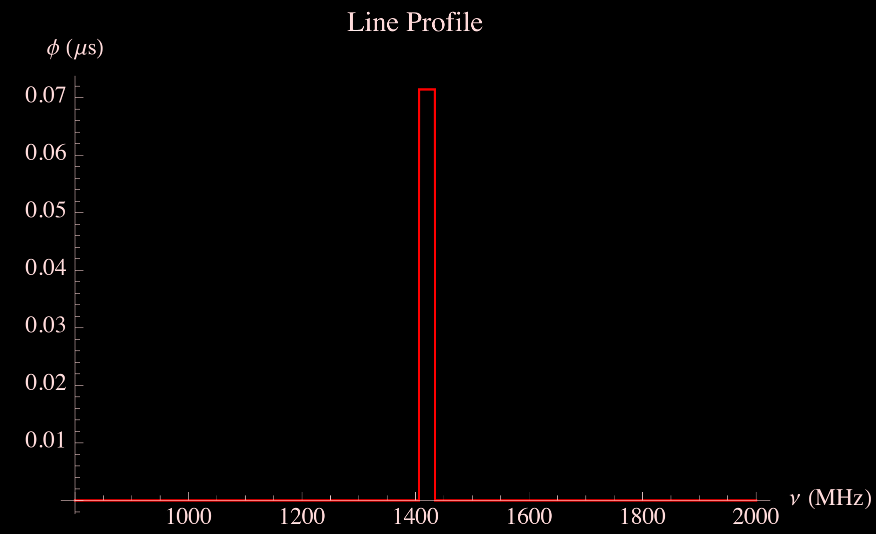
$$\equiv -\mathbf{I}\,\mathbf{d}\tau_\nu + \frac{\mathbf{n_1}}{\mathbf{3n_0}} \frac{\mathbf{2h}\nu^{\mathbf{3}}}{\mathbf{c^2}} \mathbf{ds}$$

Define the optical depth τ_ν through $d\tau_\nu$ as shown.

$$\mathbf{dT}_\gamma = \left[-\mathbf{T}_\gamma + \mathbf{T_S} \right] \mathbf{d}\tau_\nu$$

Radial Velocity Gradient $\partial_r V_r$ $\Rightarrow$ Line Profile $\phi(\nu)$

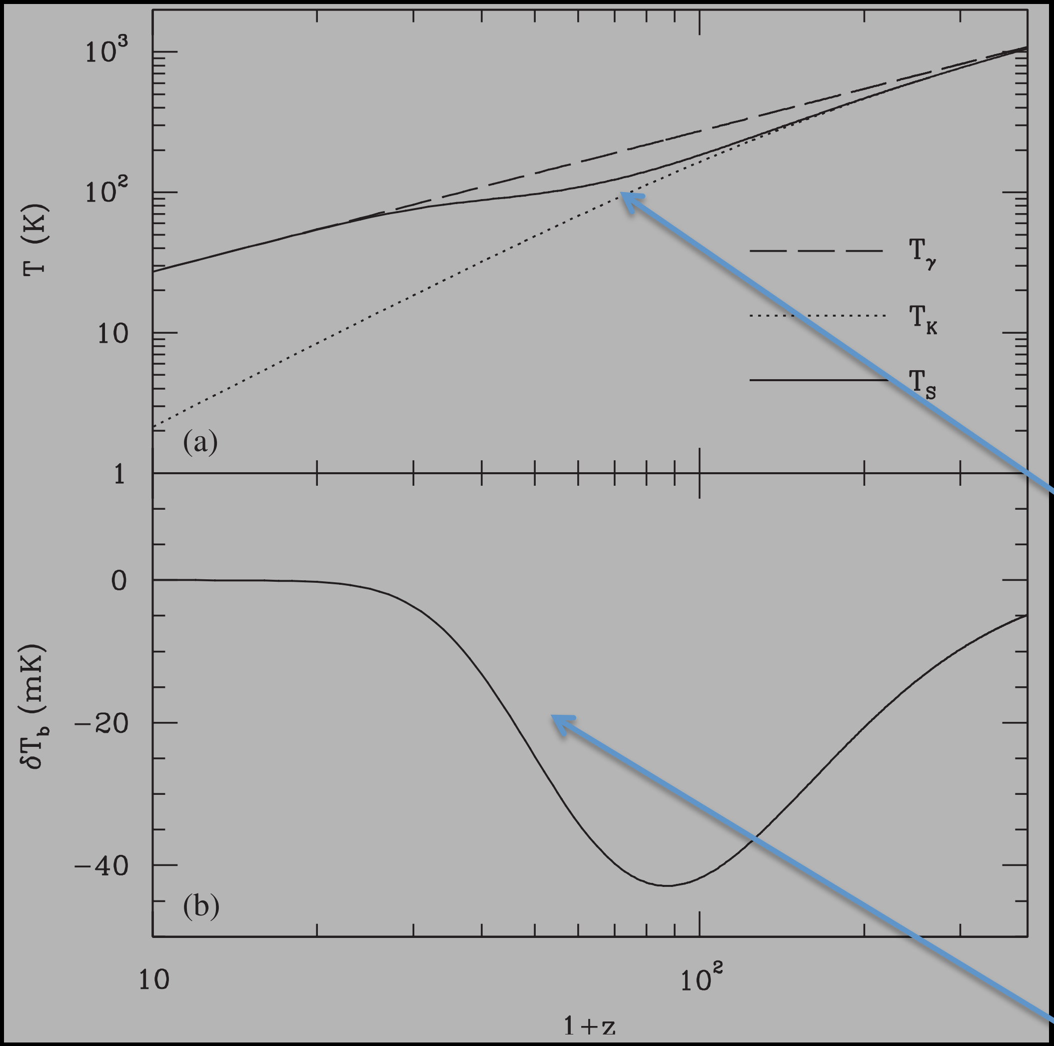
- Gradient of velocity along line of sight gives a spread in frequency. As ray travels through column length Δs ≡ Δr each frequency is equally likely ⇒ $\phi(\nu)=(\Delta\nu)^{-1}$



- Cosmic Gas:
$$\nu(\mathbf{r}) = \nu(\mathbf{r_o})[\mathbf{1} - \mathbf{\Delta r}(\mathbf{aH}(\mathbf{a}) + \partial_\mathbf{r}\mathbf{v_r^{pec}})/\mathbf{c}]$$

- String Wake:
$$\nu(\mathbf{r}) = \nu(\mathbf{r_o})[\mathbf{1} - \mathbf{\Delta r}(\mathbf{aH}(\mathbf{a})\sin^\mathbf{2}\theta + \partial_\mathbf{r}\mathbf{v_r^{pec}})/\mathbf{c}]$$

Cosmic Gas Temperature Evolution



- Heats via γ+e^- scattering
- Cools via Hubble expansion

z > 300 : residual e^- couple hydrogen gas to CMB.

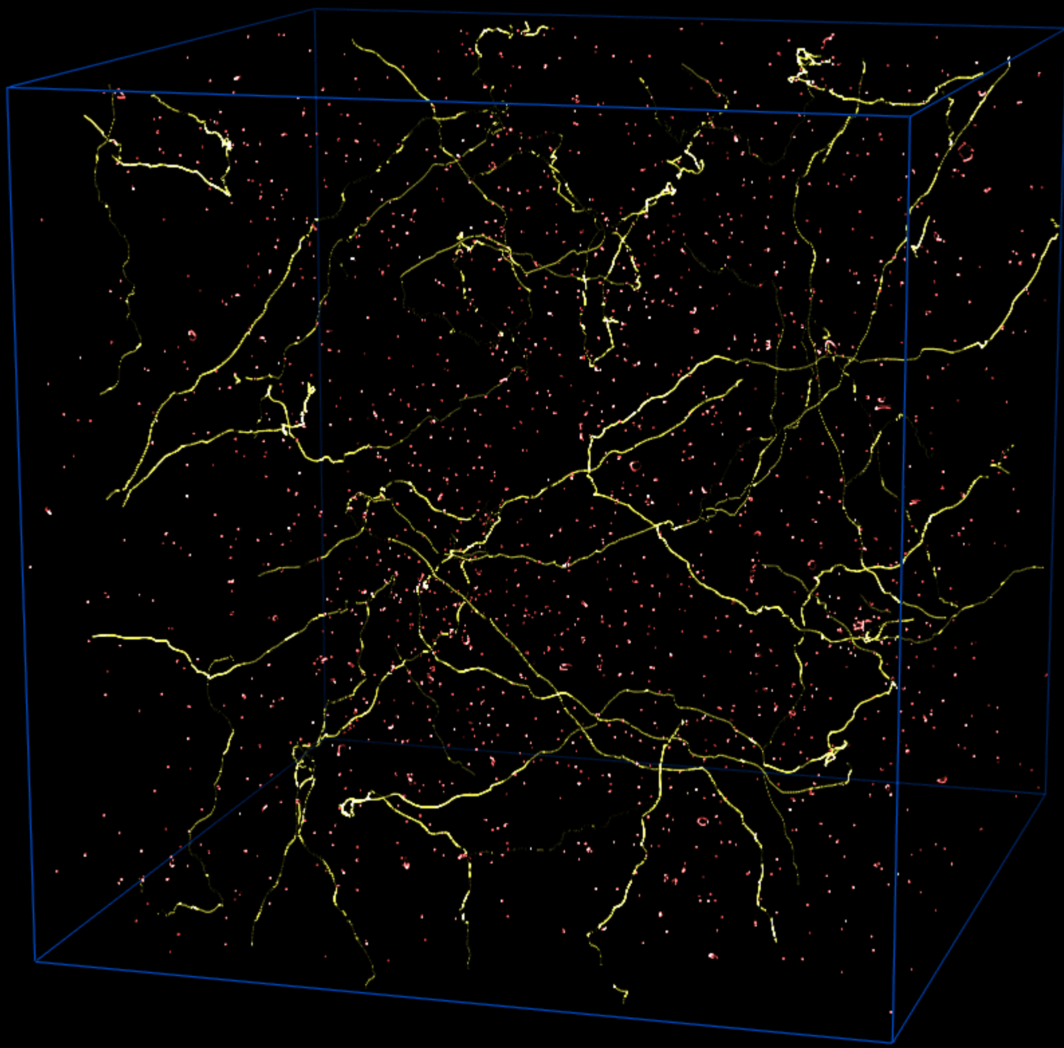
300 > z > 150: Compton heating becomes inefficient at z ~ 300 and decouples by z ~ 150.

z<150: hydrogen gas is adiabatically expanding

Up until z~80 T_S is collisionally coupled to T_K. After that atomic collisions become rare and $T_S \rightarrow T_\gamma$ through absorption.

δT_b < 0 until reionization.

Cosmic Strings Scaling Solution



- Average number of long strings ranges from 1 to 10 per Hubble volume.
- Wake's initial physical size

  ~ $L_H\,(1 \times 1 \times 4\pi G\mu)$
- Wake lengths Hubble expand.
- Wake width grows by gravitational accretion.

Image: by B.Allen & E.P.Shellard,
from Cambridge Cosmology Cosmic Strings et al. public web site

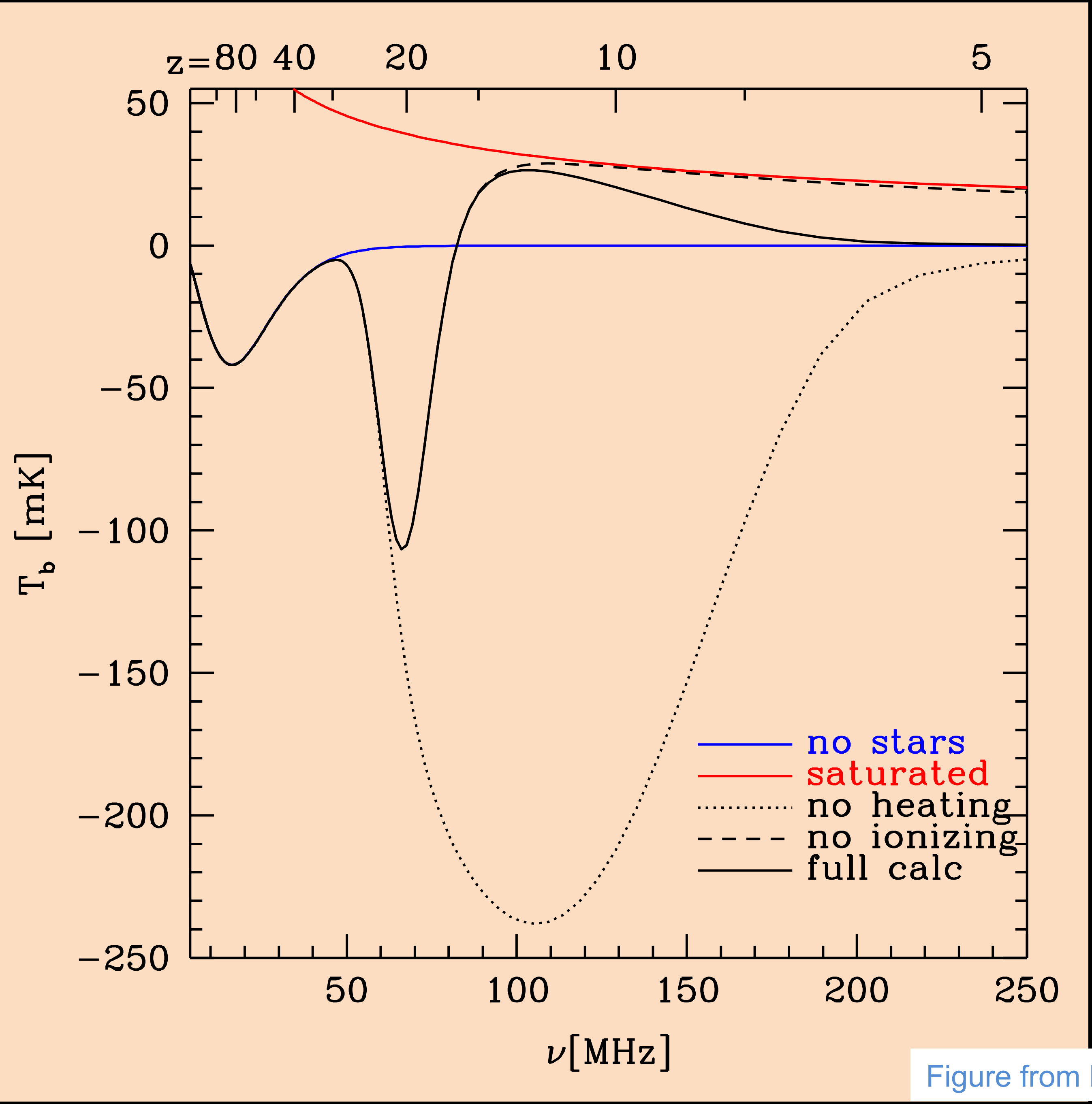


Figure from Pritchard & Loeb 2010

Stars formation generates Lyman alpha, but also X rays which heat the cosmic gas.