Seeing Cosmic Strings In The Dark And With A Little Light From The Very First Stars

i.e.

The Wouthuysen-Field absorption trough is the best place to look for cosmic strings

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Cosmic Gas 21 cm Global δT_b

- 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

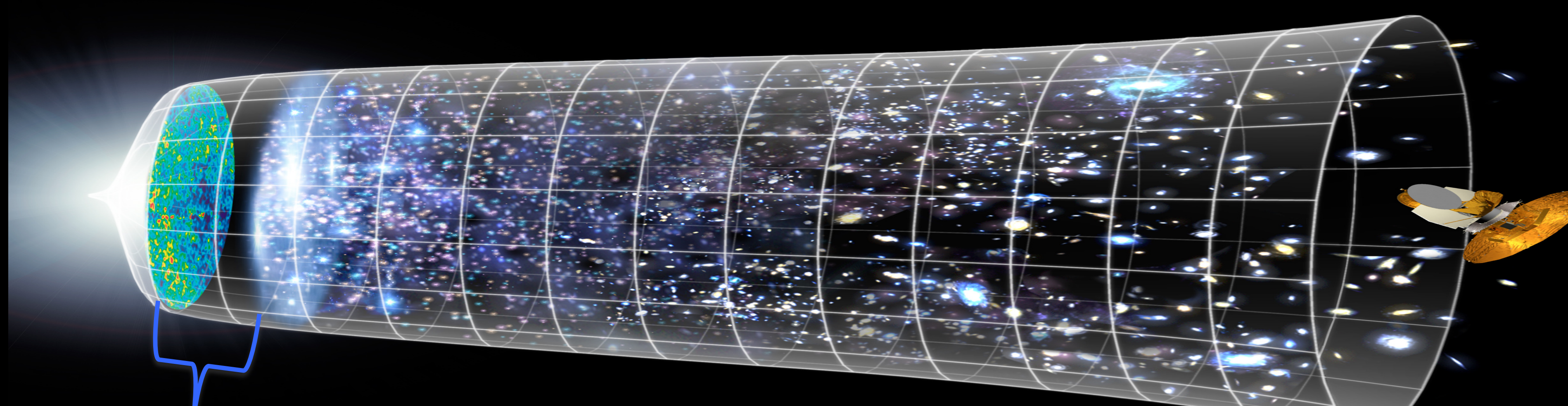

image from the WMAP http://map.gsfc.nasa.gov/media/060915/index.html

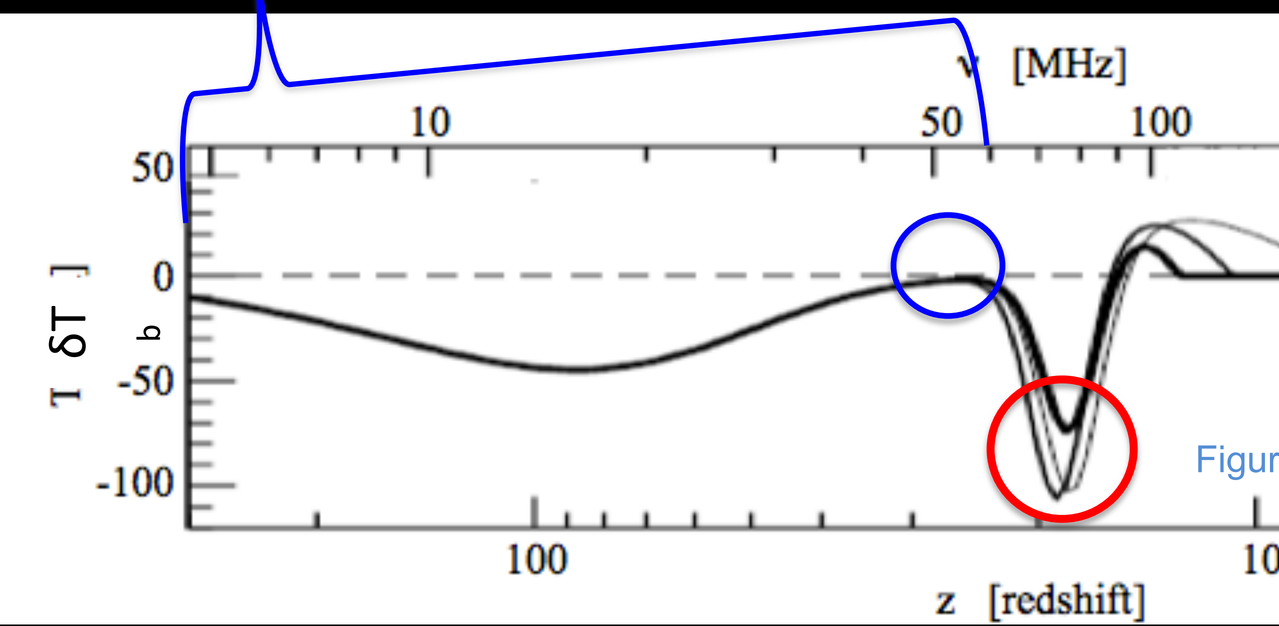

Figure from Pritchard & Loeb 2008

WF absorption trough

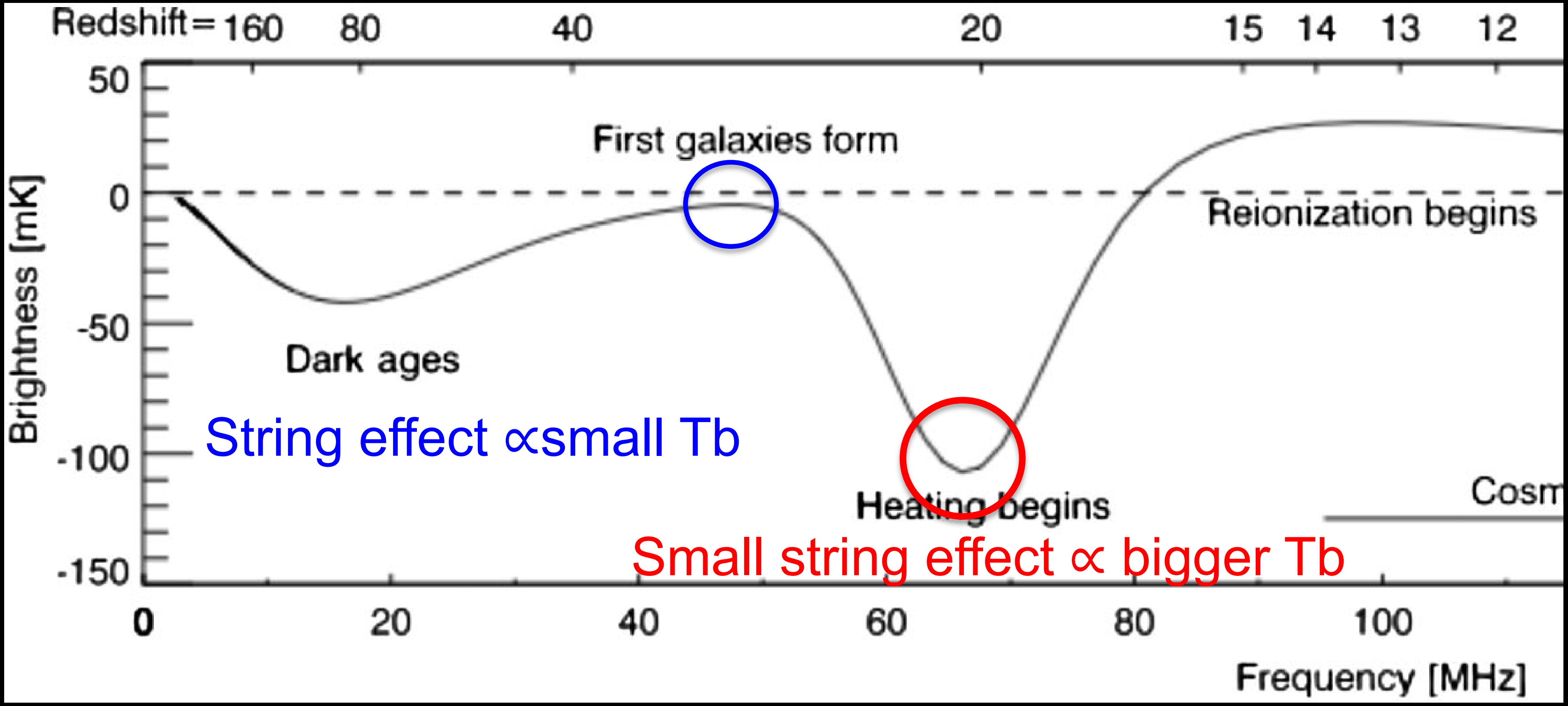

Figure from Liu, Pritchard, Tegmark & Loeb 2013

Best place to look for strings

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Wouthuysen-Field absorption trough in cosmic string wakes

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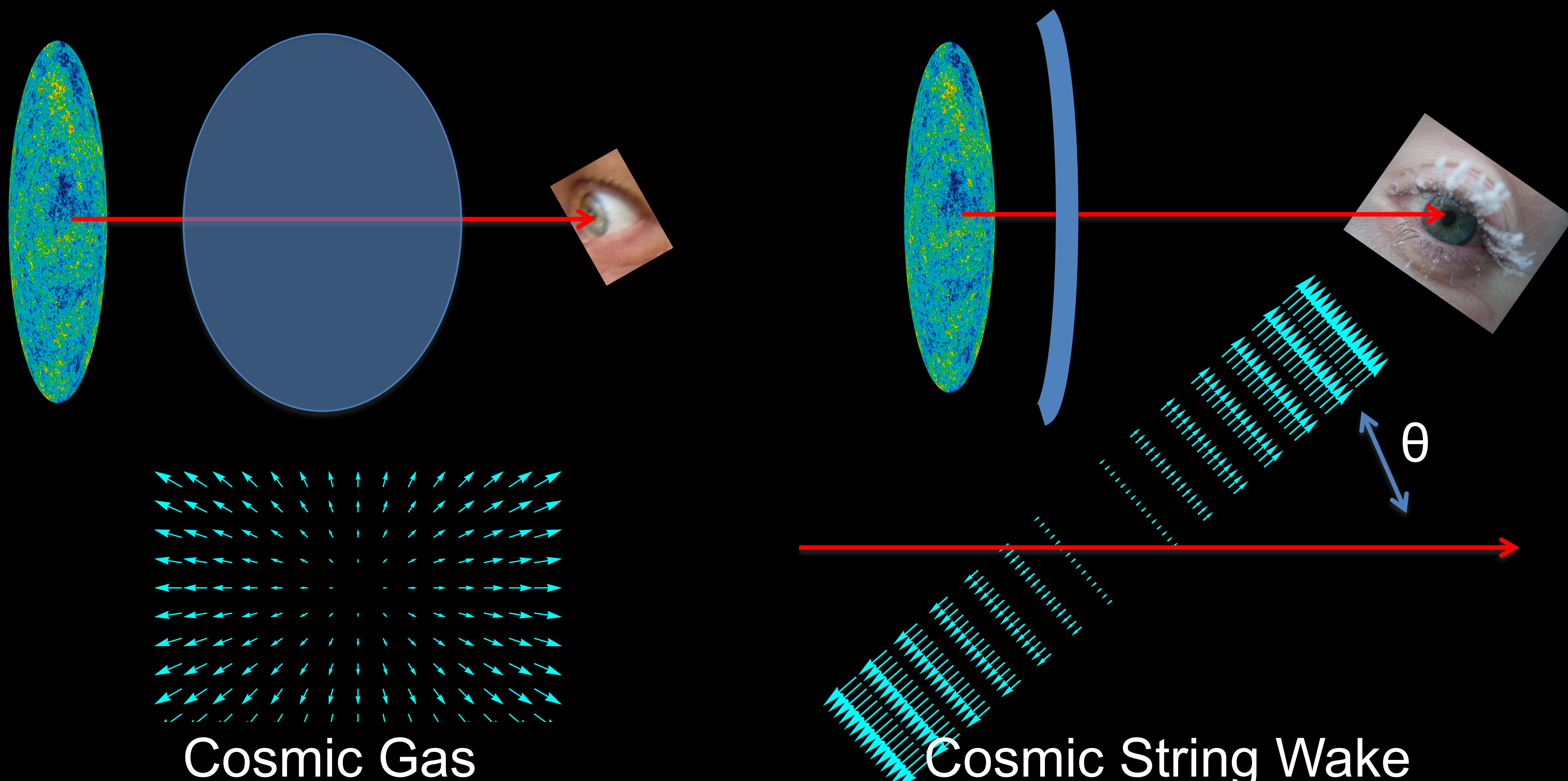
The baryon density enhancement in cosmic string wakes leads to a stronger coupling of the spin temperature to the gas kinetic temperate inside these string wakes than in the intergalactic medium (IGM). The Wouthuysen-Field (WF) effect has the potential to enhance this coupling to such an extent that it may result in the strongest and cleanest cosmic string signature in the currently planned radio telescope projects. Here we consider this enhancement under the assumption that x-ray heating is not significant. We show that the size of this effect in a cosmic string wake leads to a brightness temperature at least two times more negative than in the surrounding IGM. If the SCI-HI [T. C. Voytek *et al.*, Astrophys. J. 782, L9 (2014), J. B. Peterson *et al.*, arXiv:1409.2774] or EDGES [J. D. Bowman and A. E. E. Rogers Nature (London) 468, 796 (2010), J. D. Bowman *et al.*, Astrophys. J. 676, 1 (2008)] experiments confirm a WF absorption trough in the cosmic gas, then cosmic string wakes should appear clearly in 21 cm redshift surveys of $z = 10$ to 30.

21 cm cosmology

Use the CMB as a backlight for the Cosmic Hydrogen Gas or Cosmic String Wake



Cosmic String Wake

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

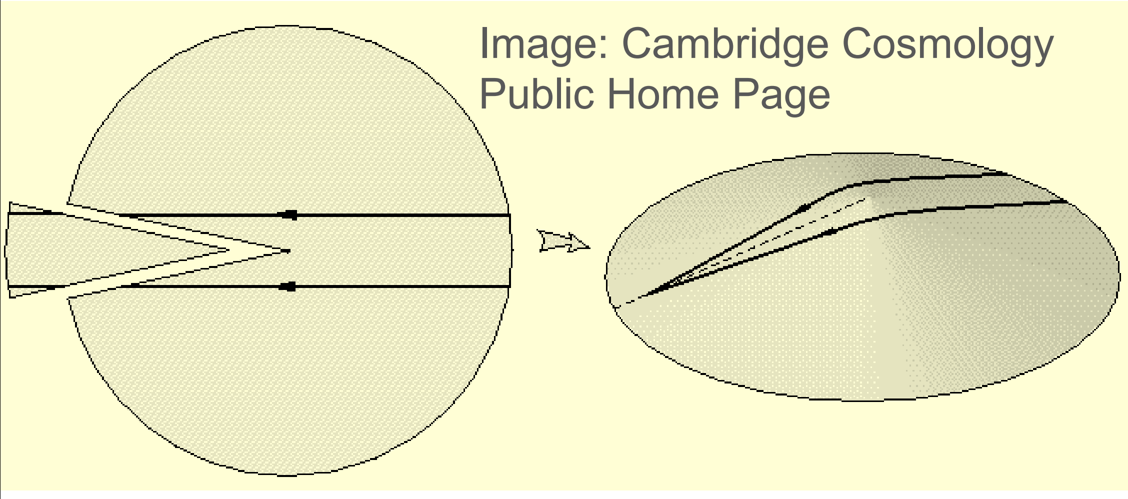


Image: Cambridge Cosmology Public Home Page

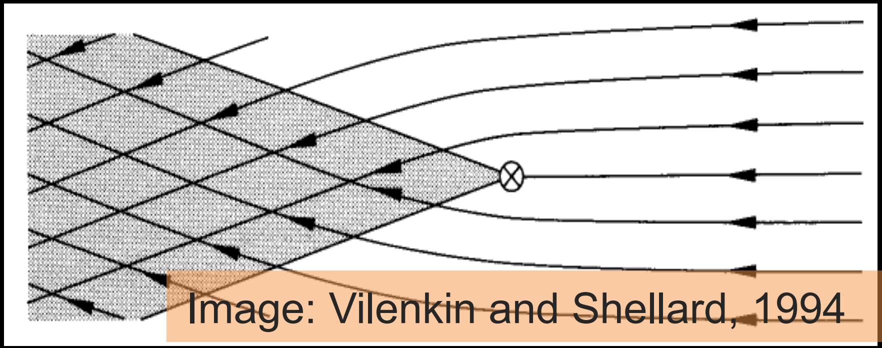


Image: Vilenkin and Shellard, 1994

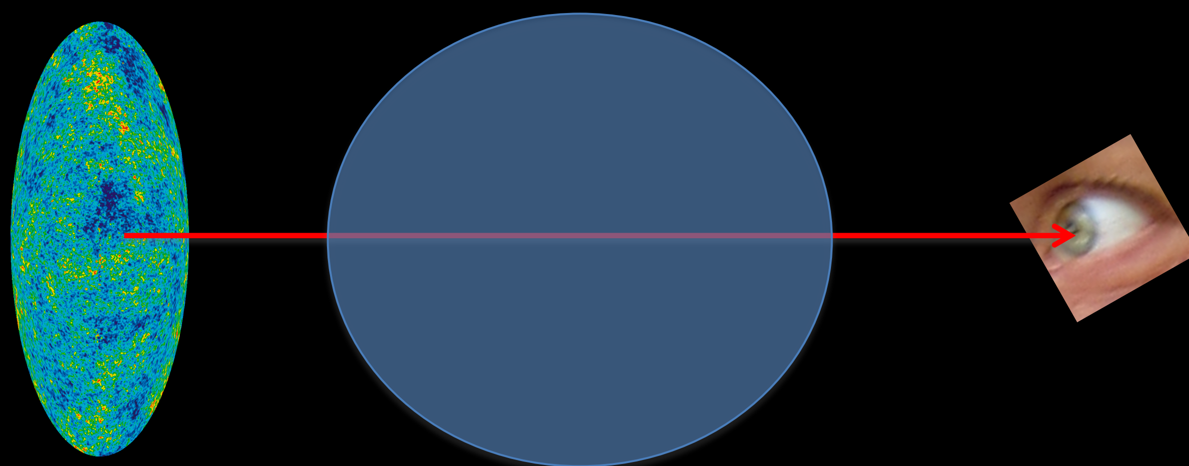
- Dark matter streams through and oscillates about the central plane.
- Baryons collide in the centre and can form shocks and heat the gas.

Radiative transfer

A light ray with frequency º is travelling through the hydrogen cloud in direction $\hat{\mathbf{k}}$. It has a position dependent intensity $\mathbf{I}(\vec{\mathbf{x}}, \nu, \hat{\mathbf{k}}) = T_\gamma \; (2k_B\nu^2/c^2)$

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

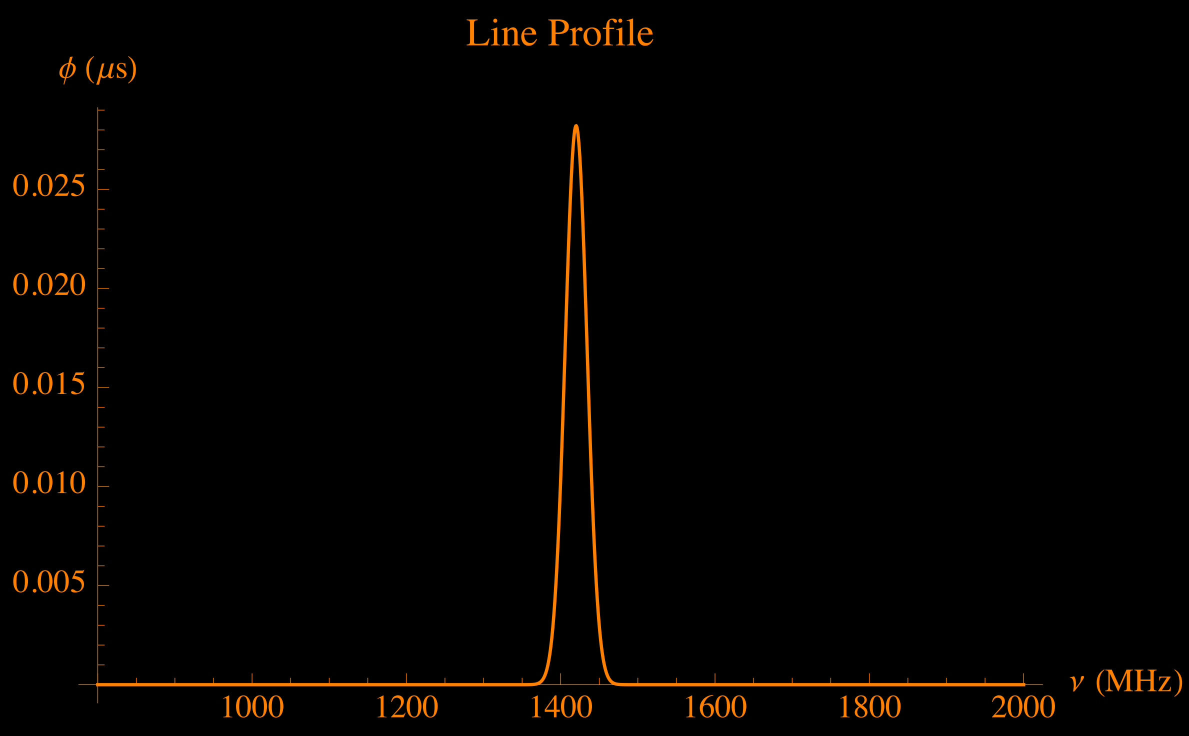
1. Absorption — (Einstein B_{01} coeff) × (density) × (length) × (line profile)
2. Stimulated Emission — (Einstein B_{10} coeff) × (density) × (length) × (line profile)
3. Spontaneous Emission — (Einstein A_{10} coeff) × (density) × (length) × (line profile)



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

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

- The line profiles ≠ ± (º − 1420 MHz) because of the Hubble flow or the Hubble expansion of the wake's lengths. The width is not in Hubble flow.



Brightness Temperature difference δT_b

- Imagine observing the 21 cm ray after it has passed through a slab of hydrogen gas (thin enough so that T_S is constant) at a particular distance, specified by the redshift of the 21 cm photon.

absorption-stimulated emission spontaneous emission

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

- Now compare the 21 cm ray to what it would have been had we had a clear view of the CMB.

$$\delta \mathbf{T_b} \equiv \mathbf{T}_\gamma(\tau_\nu) - \mathbf{T}_\gamma(\mathbf{0}) \approx (\mathbf{T_S} - \mathbf{T}_\gamma(\mathbf{0}))\tau_\nu$$

- 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

$$\tau_\nu(\mathbf{s}) = \frac{1}{\mathbf{T_S}}(\mathbf{x_{HI} n_H \Delta s}\,\phi(\mathbf{s},\nu))\left(\frac{\mathbf{3hc^2 A_{10}}}{\mathbf{32}\pi\nu\mathbf{k_B}}\right)$$

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

Up to this point the hydrogen cloud could be anything:

•the cosmic gas (CG)

•a cosmic string wake.

It is T_S and $x_{HI} n_H \Delta s\ \phi$ that are different for each of the two cases.

Brightness temp. from a Δs Slab of Hydrogen

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

The main distinguishing feature between the cosmic gas and a cosmic string wake is the line profile ϕ, especially for $G\mu < 10^{-8}$.

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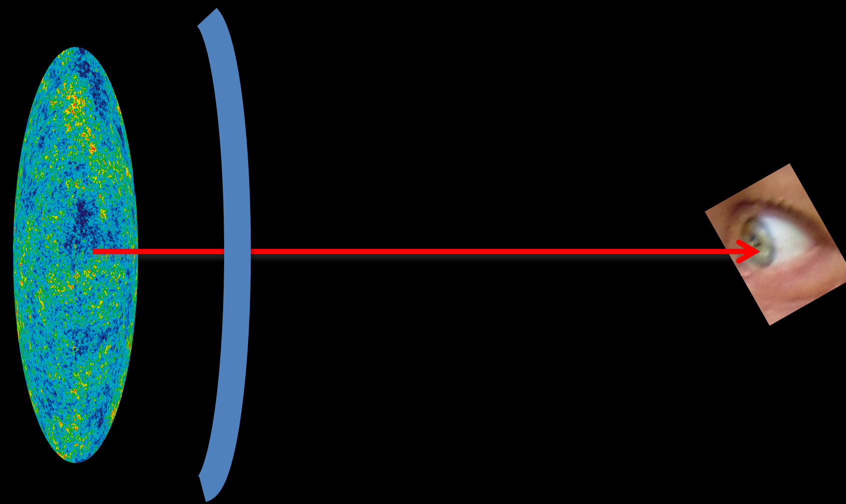
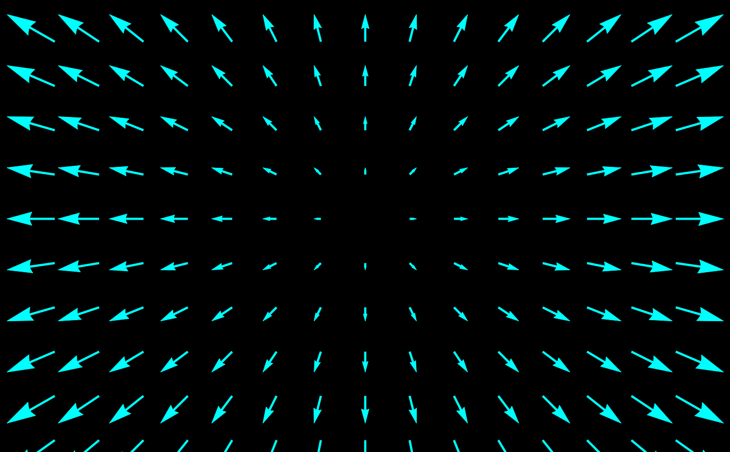
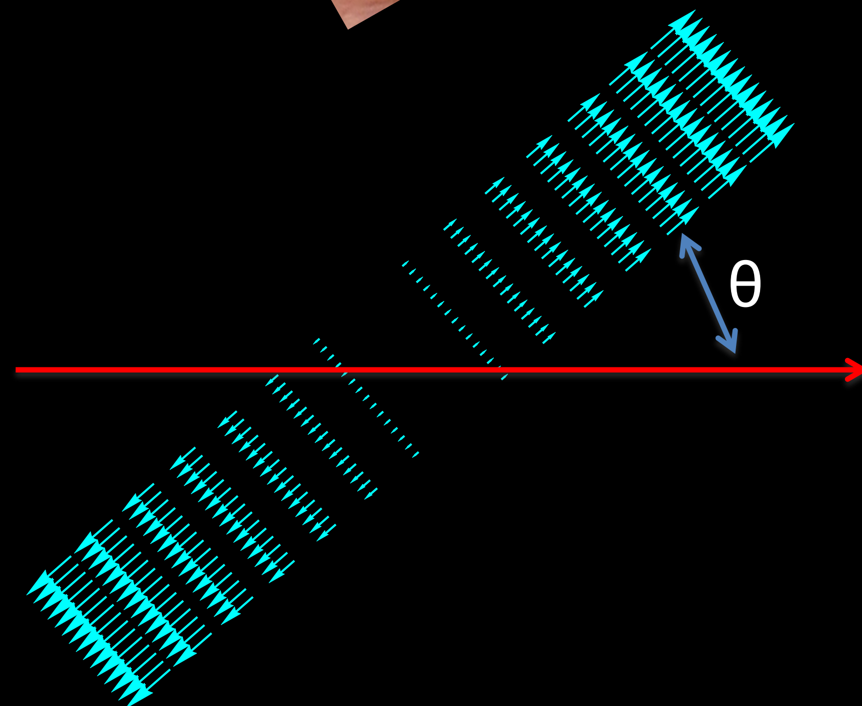
The line profile φ depends on the velocity gradient of the bulk motion along the line of sight.

Line Profile $\varphi(v)$





Cosmic Gas



Cosmic String Wake

$$[\Delta s\ \phi(s,v)]_{wake} = [\Delta s\ \phi(s,v)]_{CG} / \sin^2\theta$$

Brightness tempurature

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

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
- Scattering with UV photons (WF effect)

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

determines spin temperature in equilibrium.

$$x_c \equiv C_{10} T_* / (A_{10} T_\gamma),$$

$$x_\alpha \equiv P_{10} T_* / (A_{10} T_\gamma)$$

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

C_{10}, P_{10} depend on densities and T_K

$$\delta T_b(z) \approx [9\ \mathrm{mK}](1+z)^{1/2}\ \frac{x_c + x_\alpha}{1 + x_c + x_\alpha}\left(1 - \frac{136}{1+z}\right)$$

To calculate absorption trough due to the WF effect we need a model for the production of UV photons to calculate the Lyman scattering coefficient x_α

$$x_\alpha \equiv P_{10} T_* / (A_{10} T_\gamma)$$

$$\approx 1.4e11\ \mathrm{cm}^2\ (J_\alpha)\ /\ (1+z)$$

(average Lyα flux in units $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{Hz}^{-1}\ \mathrm{sr}^{-}$)

Calculate the average Lyα flux J_α

- J_α is the sum of background photons that have redshifted into the Lyn resonances and cascade down to Lyα.

- For a given frequency **ν** and redshift *z*, the number of these photons emitted ϵ is proportional to the star formation efficiency f*.

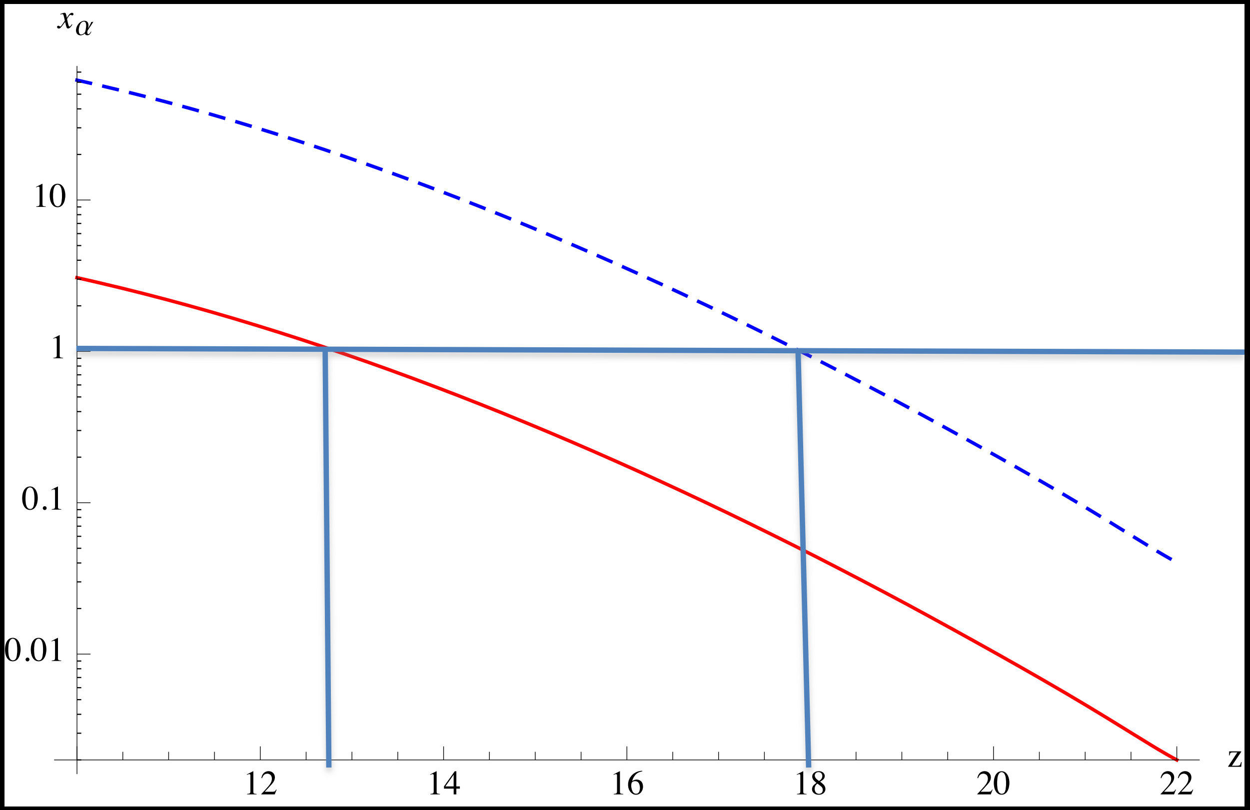
- The star formation efficiency f* is the largest source of uncertainty in our calculation.

- We model our calculation after those in
  - Furlanetto MNRAS 371, 867 (2006)
  - Barkana and Loeb, APJ 626, 1 (2005).
  - Chen and Miralda-Escude, APJ. 684, 18 (2008).

The Lyman scattering coefficients x_α vs z

for UV photons produced by Pop II (dotted blue) and Pop III (solid red) stars, where we take the star formation efficiency f⋆ = 0.1 and 0.01, respectively.

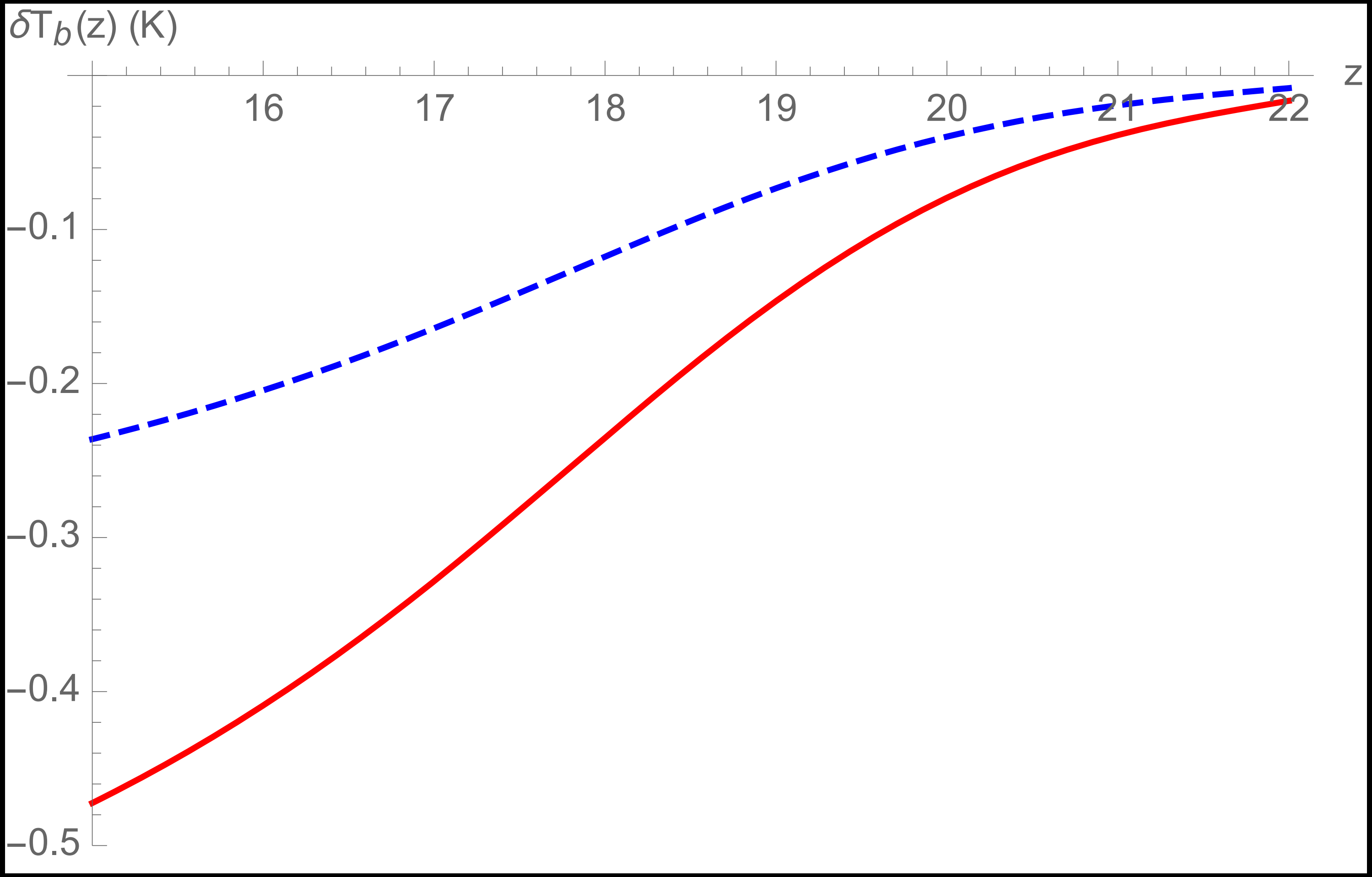
WF effect saturated, $T_S=T_K$, when $x_\alpha>>1$



Brightness temperatures (K) vs. redshift z (horizontal axis) with UV photons produced by Pop II stars.

The surrounding cosmic gas is in dotted blue.

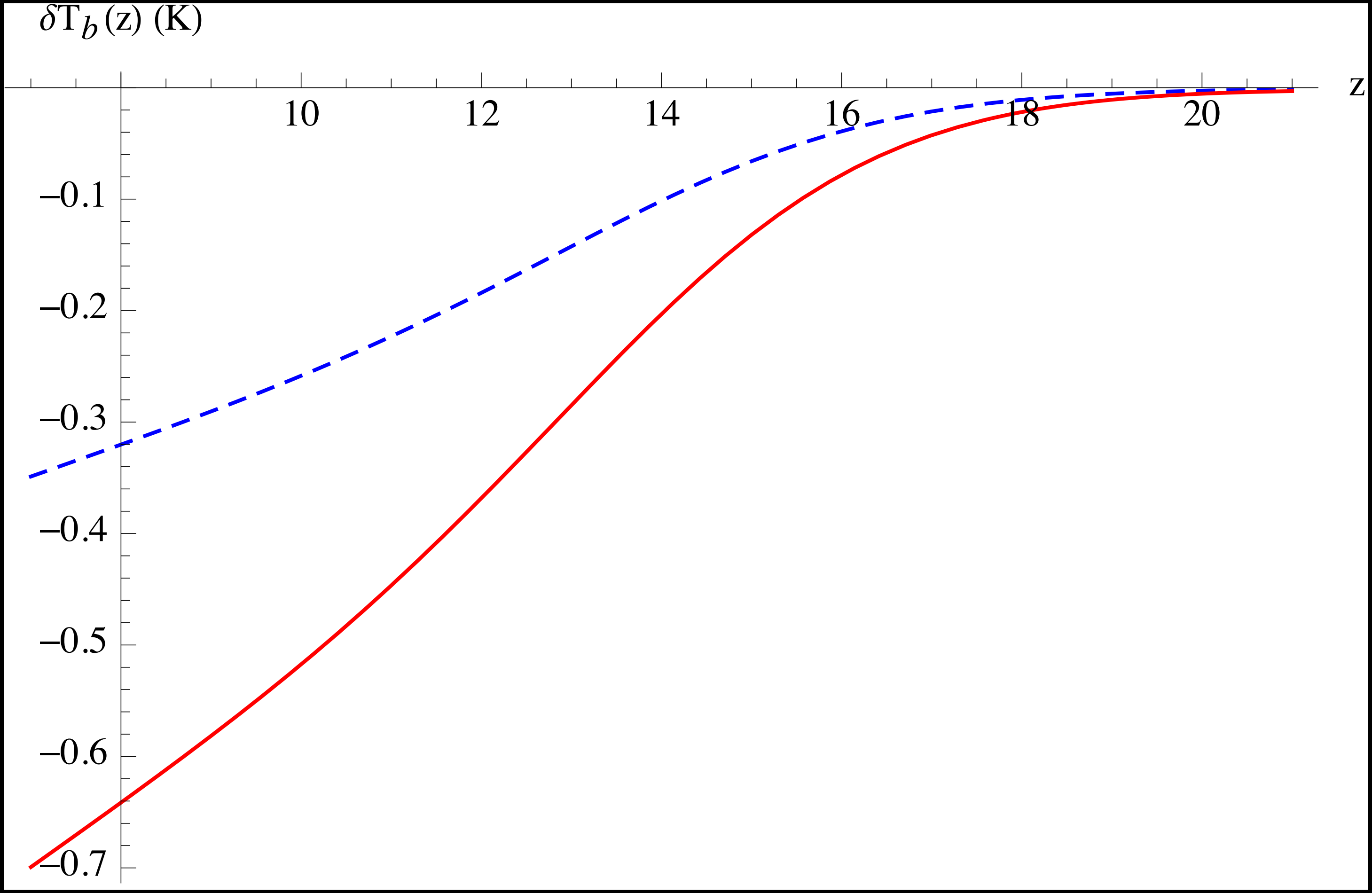
A cosmic string wake with $G\mu = 10^{-10}$ is in solid red.



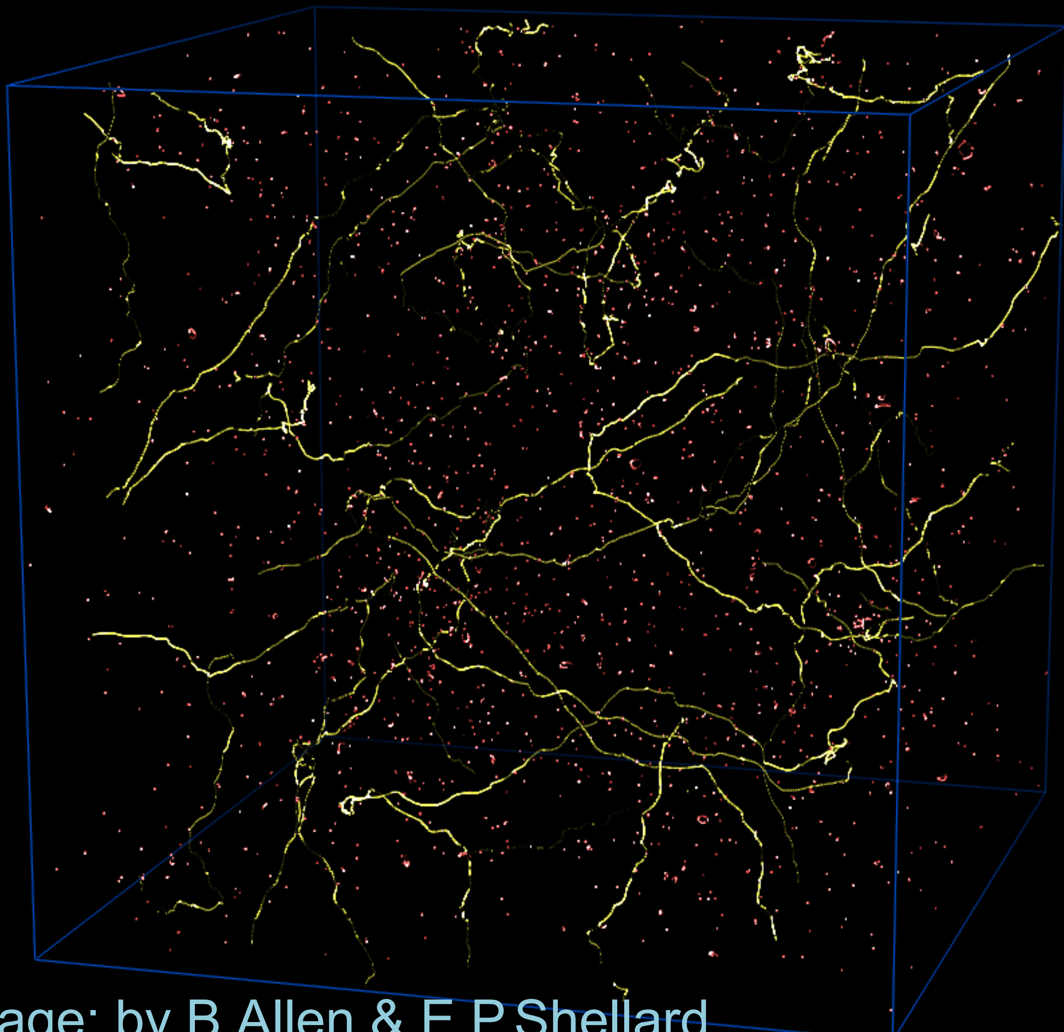
Brightness temperatures (K) vs. redshift z (horizontal axis) with UV photons produced by Pop III stars.

The surrounding cosmic gas is in dotted blue.

A cosmic string wake with $G\mu = 10^{-10}$ is in solid red.



A network of strings (the scaling solution) creates a network of wakes:



- Average number of long strings ranges from 1 to 10 per Hubble volume.
- Wake's initial physical size $\sim L_H\,(1 \times 1 \times 4\pi G\mu)$
- 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

Conclusion

I. 21 cm brightness temperature a powerful tool to search for new physics such as cosmic strings.
II. Wouthysen-Field absorption trough (if confirmed) would give the brightest 21 cm signature of cosmic string wakes.

- 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 21 cm Signature of Shock Heated and Diffuse Cosmic String Wakes, O.H., R. Brandenberger, JCAP 1207 (2012) 032, arXiv:1203.2307.
- Wouthuysen–Field Absorpton Trough in Cosmic Strings Wakes, O.H., Phys.Rev. D90 (2014) 12, 123504.
- Work in progress, O.H, C. Ringeval (2019)