Imprint Of Primordial Gravitational Waves On Redshift Space HI Power Spectrum

By

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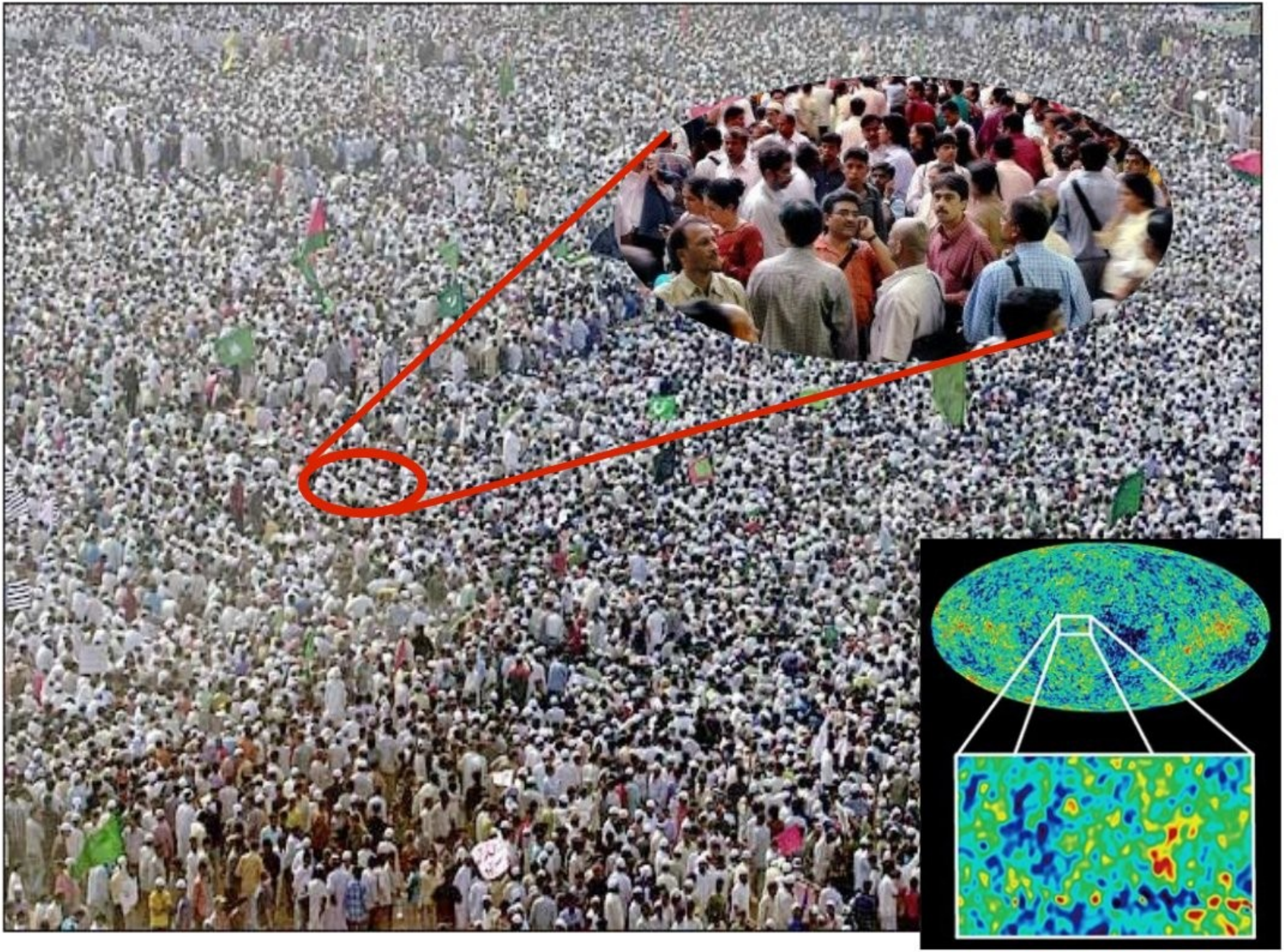

Hubble's Law is the only possible expansion law consistent with the large scale homogeneity and isotropy of the universe

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But there are deviations from the cosmological principle /Hubble's law at small scales

Redshift Space *Distortion*

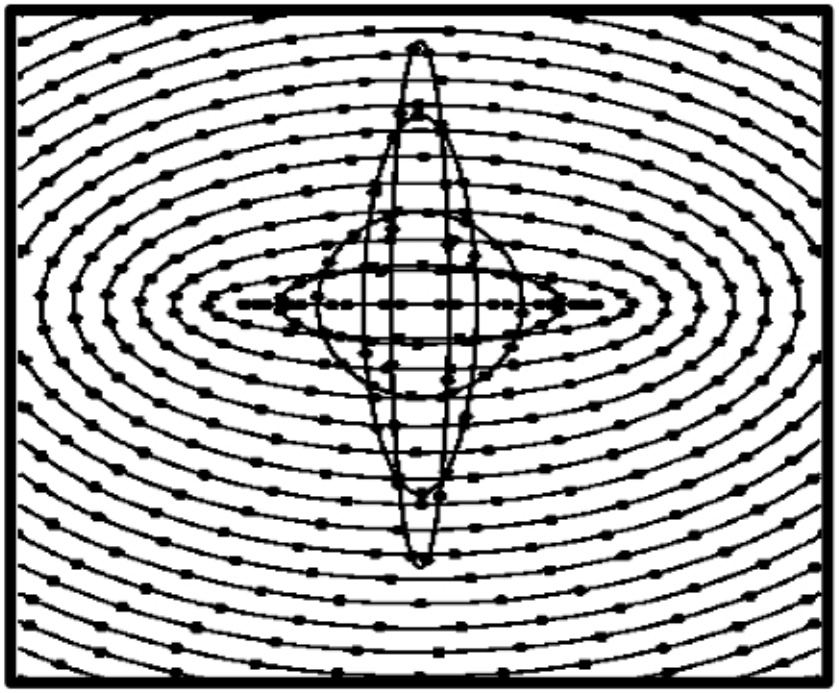
In trying to measure distances of faraway objects astronomers rely on Hubble's Law & spectroscopically measured redshifts.

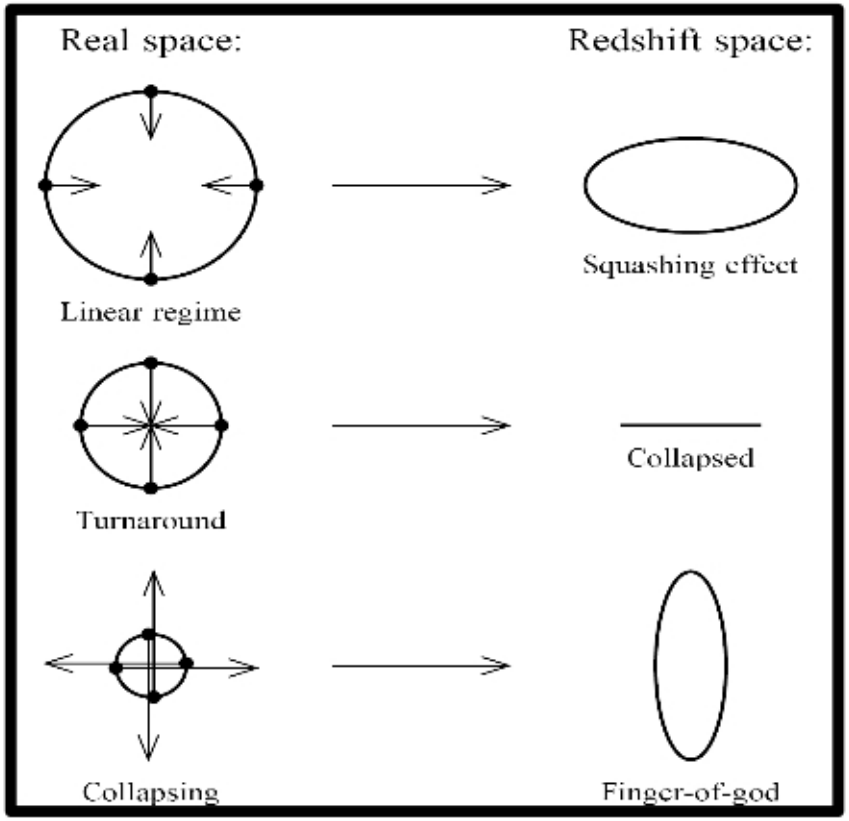
However distance calculated this way 's'

would in general be different from the actual comoving distance of the source 'r' due to the presence of some anomalous redshift apart from the one due to Hubble flow.

A homogeneous mass distribution in real space (r) appears to be inhomogeneous in redshift space (s) due to anomalous redshift (radial in fall peculiar velocities in this case) Hamilton 1997

An anomalous redshift thus manifests as density perturbation in Redshift Space.



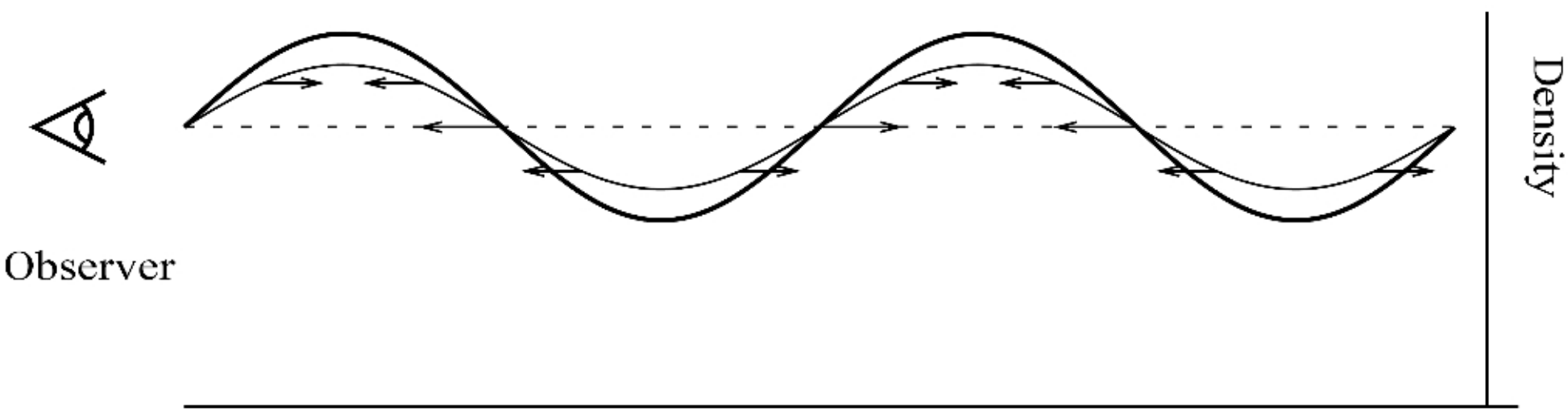


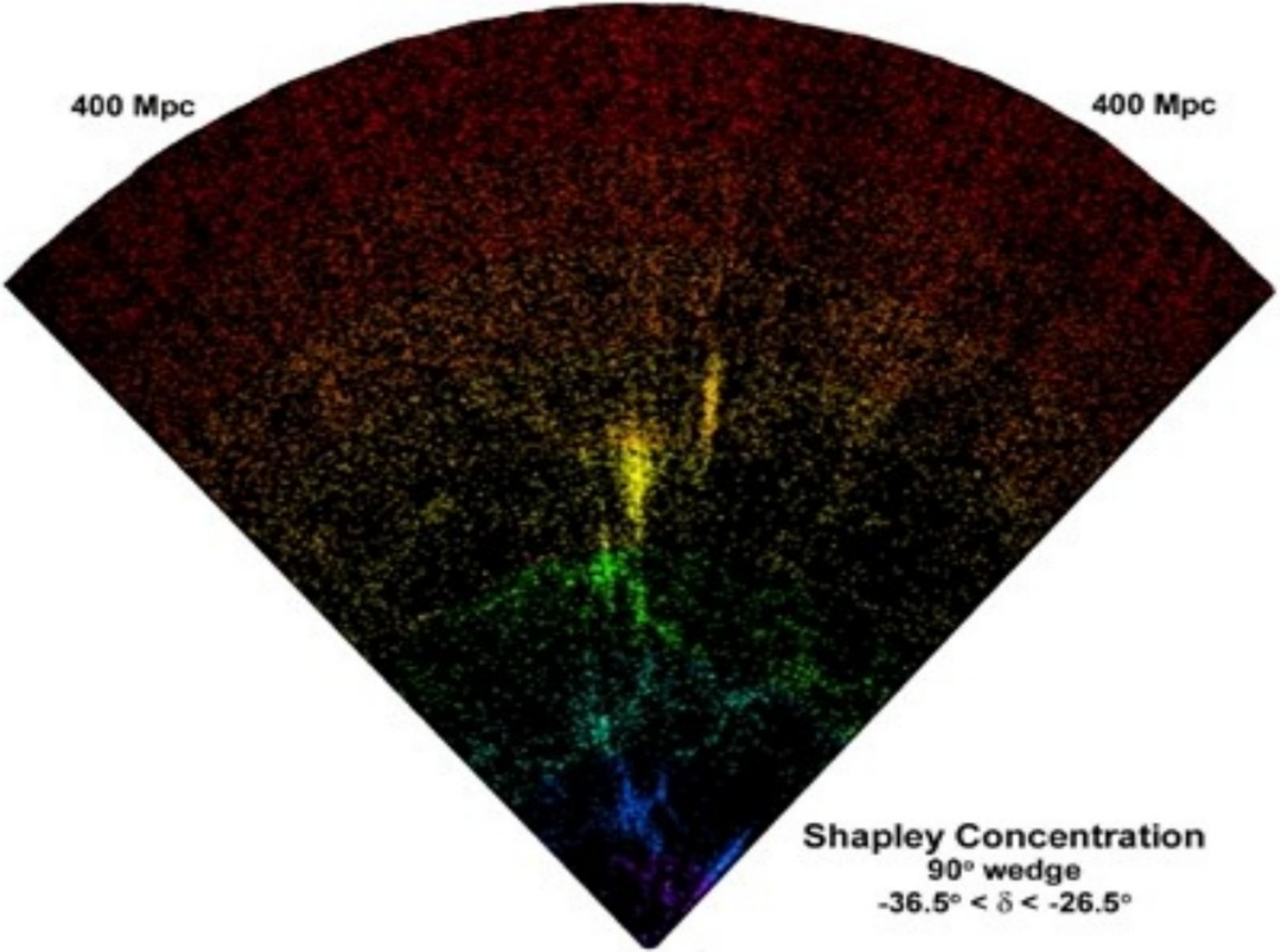
With $$\delta(\boldsymbol{r}) \equiv \frac{\rho(\boldsymbol{r}) - \bar{\rho}}{\bar{\rho}}$$

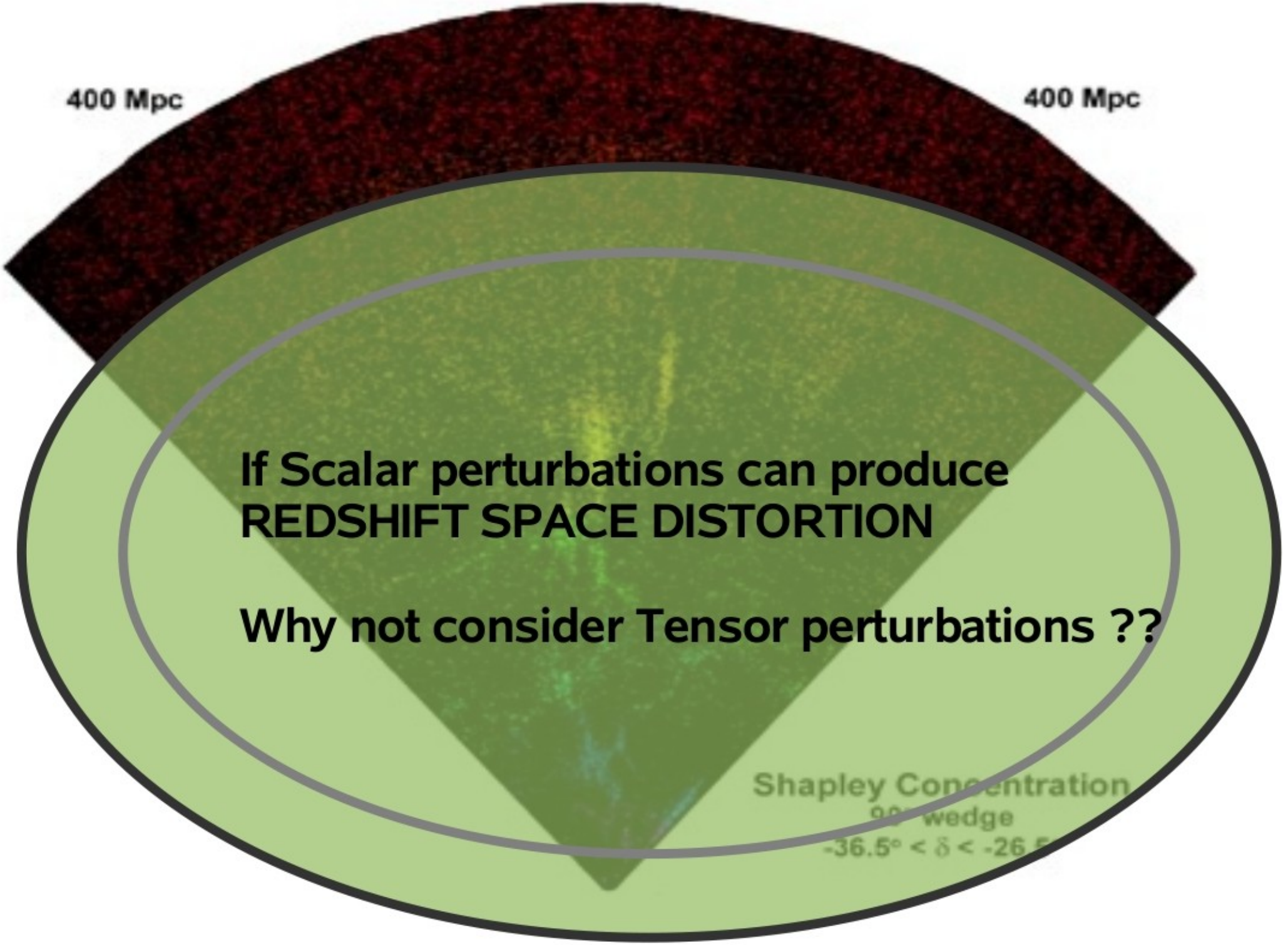
We have $$\delta^s = \delta^r - \frac{c}{aH(a)} \frac{\partial z_v}{\partial x}$$

In Fourier Space with z arising due to peculiar velocities

$$\Delta^s(\mathbf{k}) = (1 + f\mu^2)\Delta^r(\mathbf{k})$$




400 Mpc
400 Mpc
Shapley Concentration
90° wedge
-36.5° < δ < -26.5°



If Scalar perturbations can produce REDSHIFT SPACE DISTORTION

Why not consider Tensor perturbations ??

Motivation

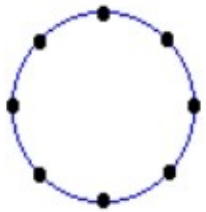
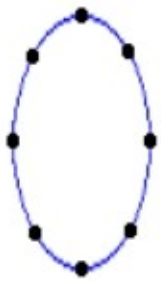
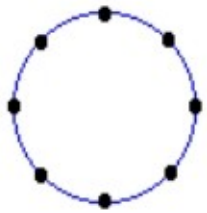
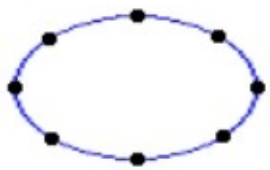
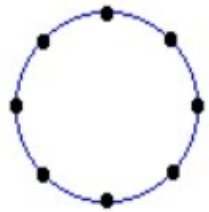
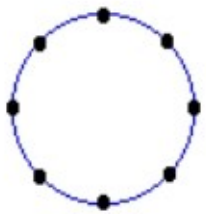
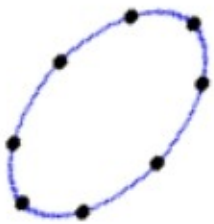
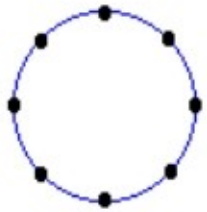
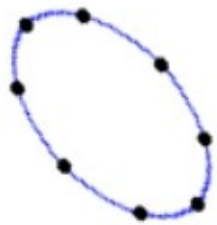
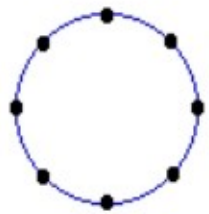
Inflation scenarios predict a stochastic gravitational wave background. Though observations of CMBR anisotropy puts an upper bound on these, there has been no direct detection of the primordial gravitational waves - making it one of the prime challenges of modern cosmology. Observation of these gravitational waves or their indirect effects has the potential to probe the physics of very early universe.

Gravitational Waves

Einstein's equations linearized for weak fields around the Flat space-time leads to wave solutions.

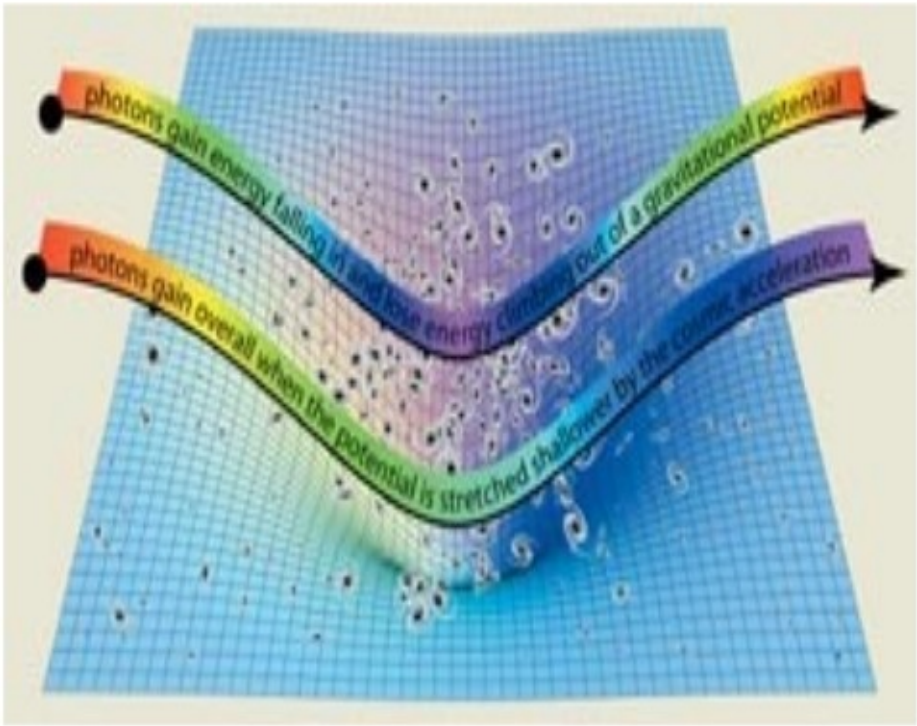
Looking at cosmological Tensor Perturbations to the FRW space-time, gravitational waves are represented by the traceless transverse component of metric perturbation, describable by two independent functions (the polarization states).

Propagation Of Gravitational Waves

h_+					
h_x					
phase	0	$\frac{\pi}{2}$	π	$\frac{3\pi}{2}$	2π

Anomalous redshift induced by Gravitational wave_

A gravitational wave traversing the line of sight to a distant source will contribute to its redshift in addition to that caused by Hubble expansion and peculiar velocities.



$$z_h = -\frac{1}{2} n^a n^b \int_{\eta_e}^{\eta_0} h'_{ab}(\vec{x}, \eta)\, d\eta$$

Anomalous redshift induced by a gravitational wave will manifest as a density fluctuation in Redshift space.

For primordial stochastic gravitational wave in Fourier space represented by

$$\tilde{h}_{ab}(\mathbf{k},\eta) = h(k,\eta)\left[e^{+}_{ab}a^{+}(\mathbf{k}) + e^{\times}_{ab}a^{\times}(\mathbf{k})\right]\frac{\sqrt{(2\pi)^3 P_h(k)}}{2}$$

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Temporal Dependence

Two Polarization states

Primordial Spectrum

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With $$\langle \tilde{h}^{*}_{ab}(\mathbf{k},\eta)\tilde{h}^{ab}(\mathbf{k}',\eta)\rangle = (2\pi)^3\delta^3(\mathbf{k}-\mathbf{k}')h^2(k,\eta)P_h(k)$$

$$\boxed{\Delta^s(\mathbf{k},\eta) = \frac{h'}{4aH}\sin\theta\left[\cos 2\phi\, a^{+}(\mathbf{k}) + \sin 2\phi\, a^{\times}(\mathbf{k})\right]\sqrt{(2\pi)^3 P_h(k)}}$$

Total POWER SPECTRUM in Redshift Space

$$P^s(\mathbf{k}) = (1 + f\mu^2)^2 P^r(k) + (1 - \mu^2)^2 P_h^r(k)$$

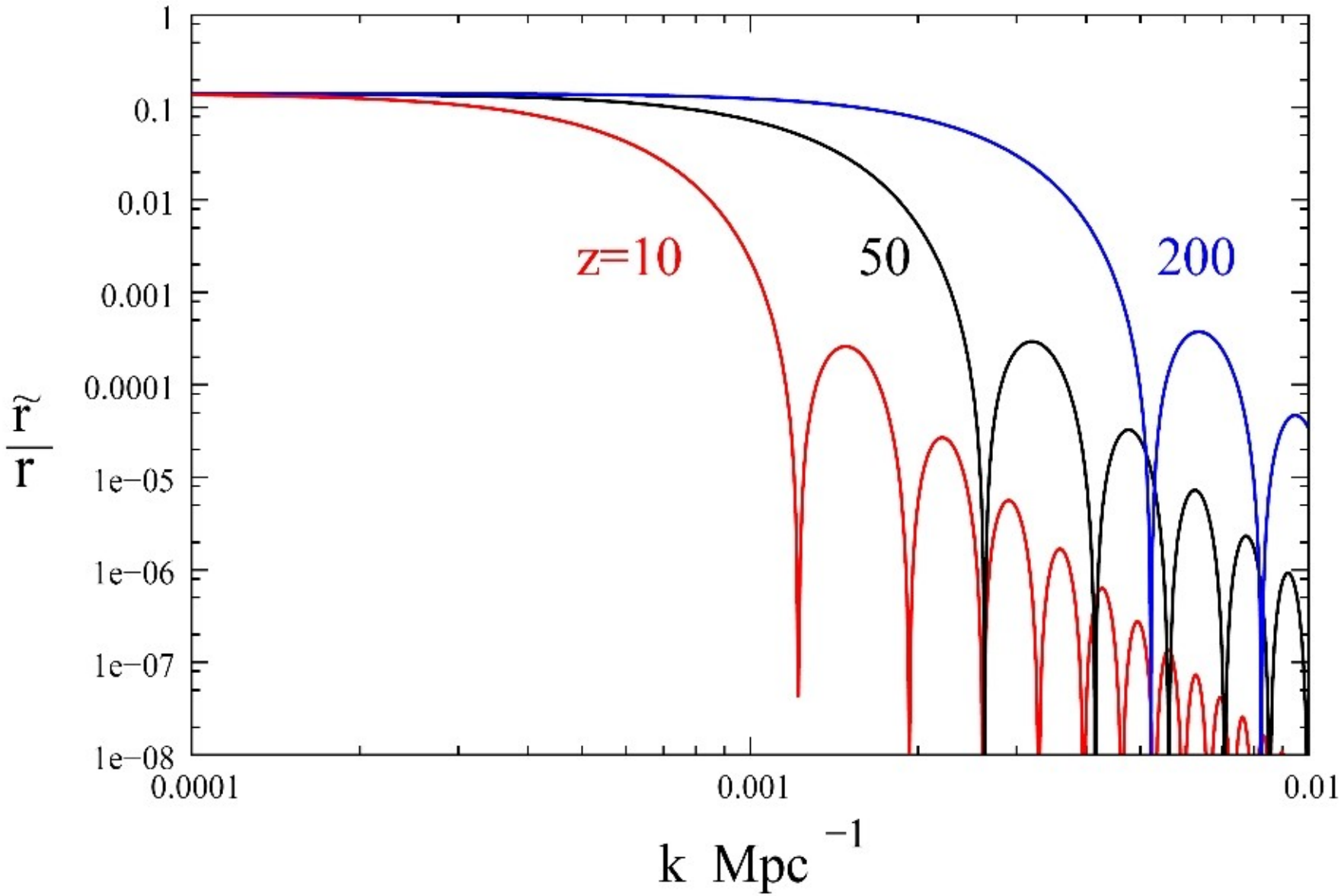
[Bharadwaj, Guha Sarkar (2009)]

Total POWER SPECTRUM in Redshift Space

$$P^s(\mathbf{k}) = (1 + f\mu^2)^2 P^r(k) + (1 - \mu^2)^2 P_h^r(k)$$

Where $P_h^r(k)$ Is given by $\left\{ \left[\frac{h'}{4aH} \right]^2 \quad P_h(k) \right\}$

The contribution from matter and gravitational Waves can be separated because of the difference in the dependence on cos (**k.n**)



[Bharadwaj, Guha Sarkar (2009)]

- The gravitational wave contribution peaks where the matter contribution is minimum
- The ratio is severely suppressed on sub-horizon scales and are oscillatory
- The prospect of detecting the gravitational wave signal is most favorable on super-horizon scales. On these scales the gravitational wave will make a 16 r % contribution to the power spectrum.
- The k- range amenable for such observations increases with redshift !

HI as a Cosmological Probe

Galaxy /quasar redshift surveys can't probe the universe at very high redshifts.

CMB photons free streaming from the LSS Undergoes a dip in its brightness temperature on passing through a HI cloud depending on its optical depth and spin temperature (Barkana & Loeb 2001, Bharadwaj & Ali 2004).

The spatial fluctuations of this "dip" depends directly and indirectly on the fluctuations of the HI which in turn follows the underlying dark matter

A Schematic Outline of the Cosmic History

S.G. Djorgovski et al. & Digital Media Center, Caltech

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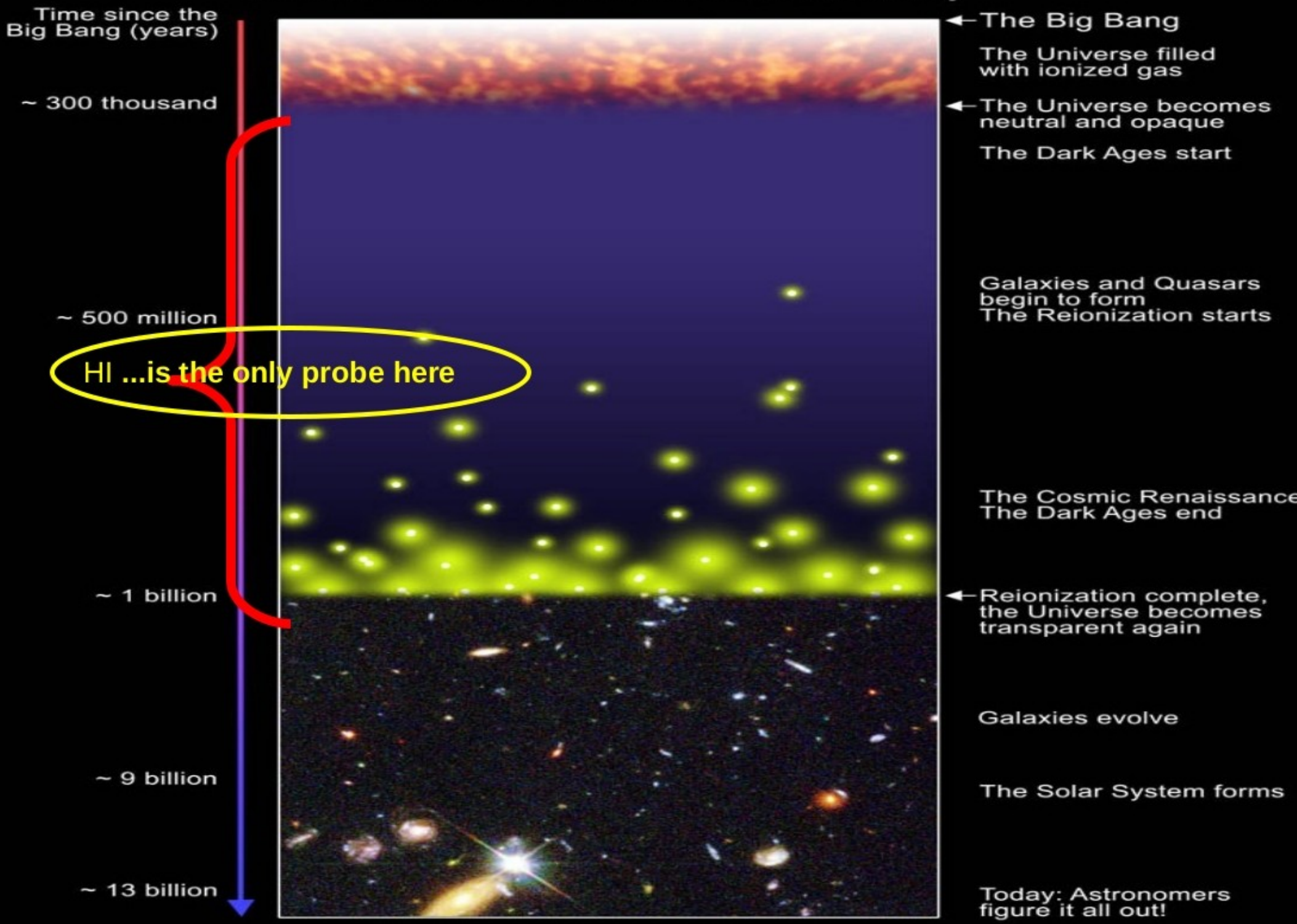

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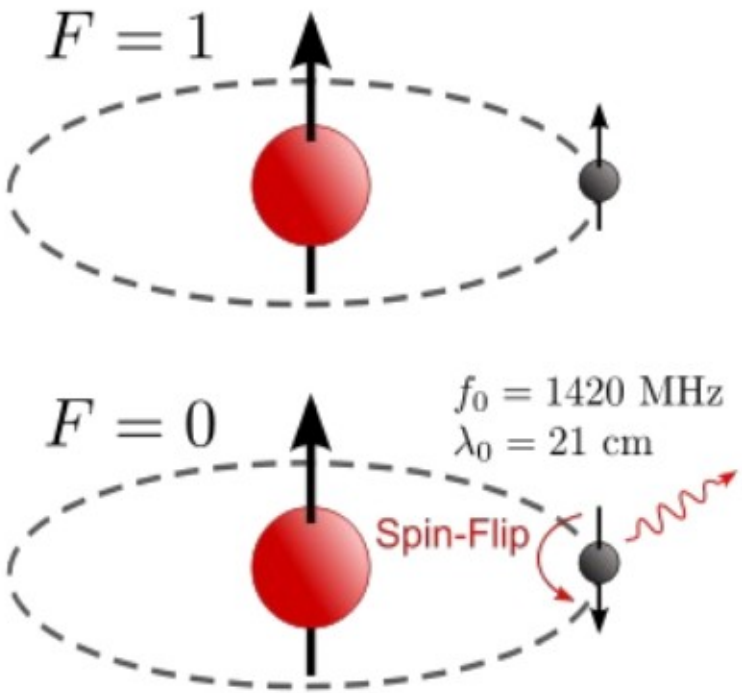
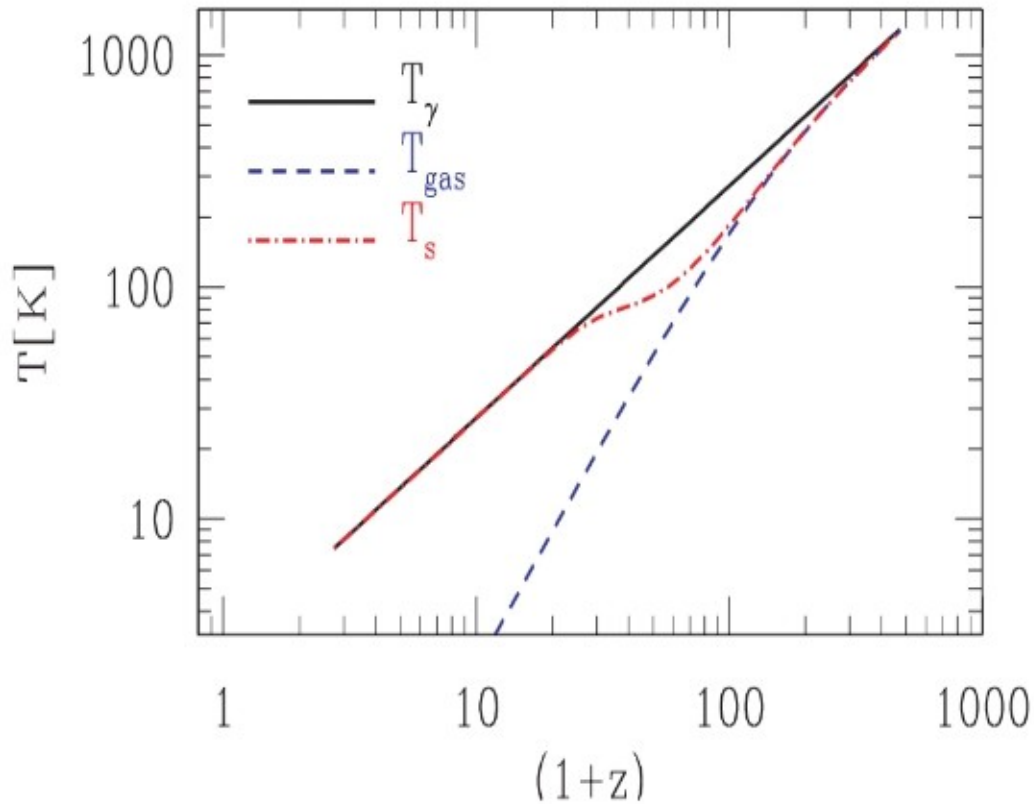




$$\frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-T_\star/Ts}$$

$$T_b(\mathbf{n}, \nu) = (T_s - T_\gamma)\,\tau/(1+z)$$

$$T_b \;\propto\; (1 - T_\gamma/T_s)\, n_{\rm H}$$

$$\delta T_b(\mathbf{n},\nu) = \bar{T}\left[\left(1-\frac{T_\gamma}{T_s}\right)\left(\Delta_{\mathrm{H}} - \frac{1}{H\,a}\frac{\partial v}{\partial r}\right) + \frac{T_\gamma}{T_s} s\Delta_{\mathrm{H}}\right]$$

$$\bar{T}(z) = 4.0\,\mathrm{mK}(1+\mathrm{z})^2\left(\frac{\Omega_{\mathrm{b}}\mathrm{h}^2}{0.02}\right)\left(\frac{0.7}{\mathrm{h}}\right)\frac{\mathrm{H}_0}{\mathrm{H(z)}}$$

[Bharadwaj Ali 2005]

As a tracer of the underlying LSS the HI brightness temperature is a probe of matter distribution and can be used to measure the matter power spectrum

Detectability

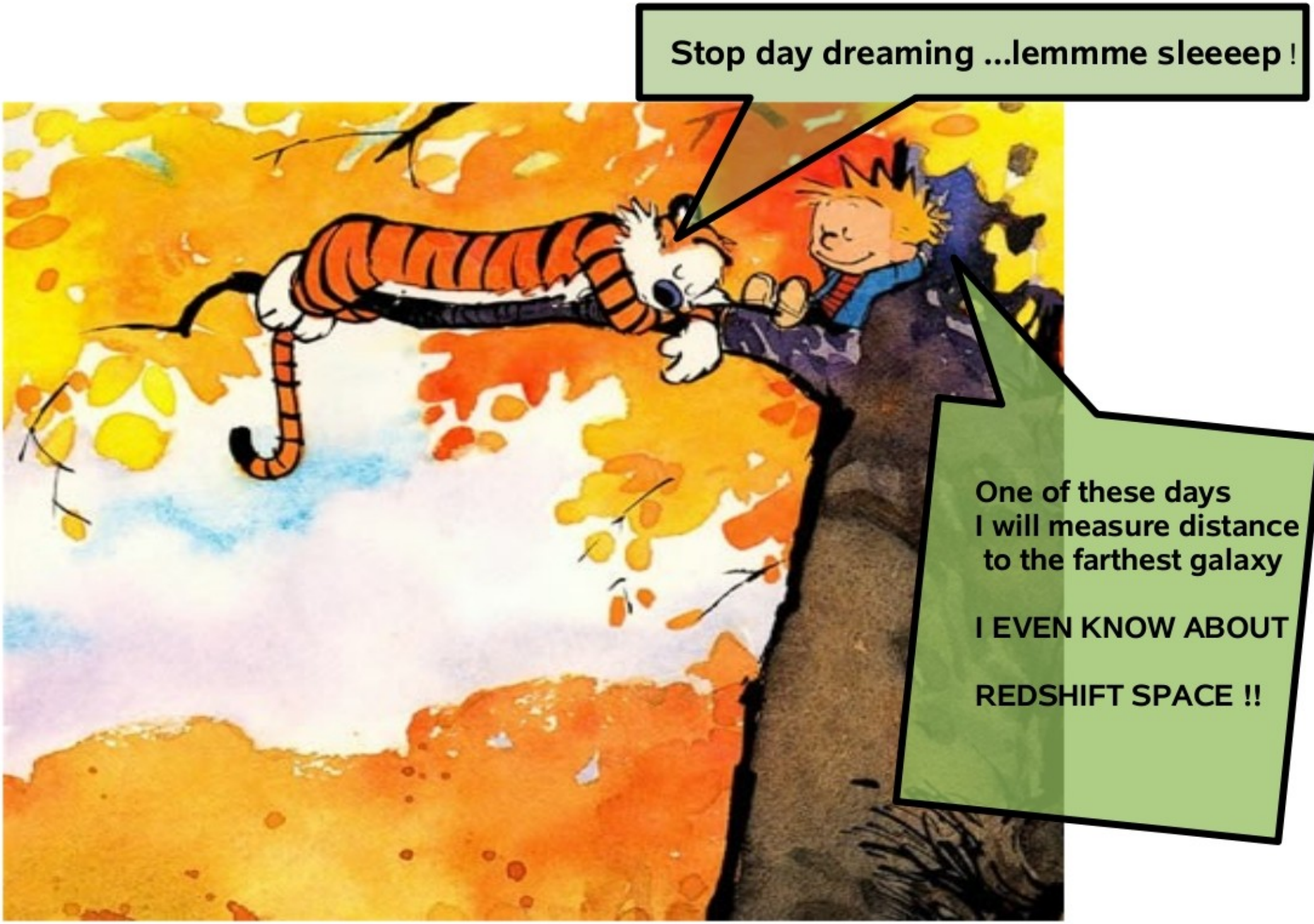
For a cosmic variance dominated experiment we have

$$\delta P(k)/P(k) \sim 1/\sqrt{N(k)}$$

Thus the number of modes required for detection is

$$N(k) > \tilde{r}^{-2} \sim 10^4$$

However if we consider only super horizon modes and extend the survey volume to z = 200
we still have only N ~ 100 !!!!
SO THE SIGNAL IS COSMIC VARIANCE LIMITED


Stop day dreaming ...lemmme sleeeep !
One of these days
I will measure distance
to the farthest galaxy
I EVEN KNOW ABOUT
REDSHIFT SPACE !!