Testing General Relativity with 21cm Intensity Mapping

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KICC and DAMTP, Cambridge

University of Heidelberg, November 2012

The universe accelerated expansion

Current challenge: understand what drives the **accelerated expansion** of the universe.

Three ideas:

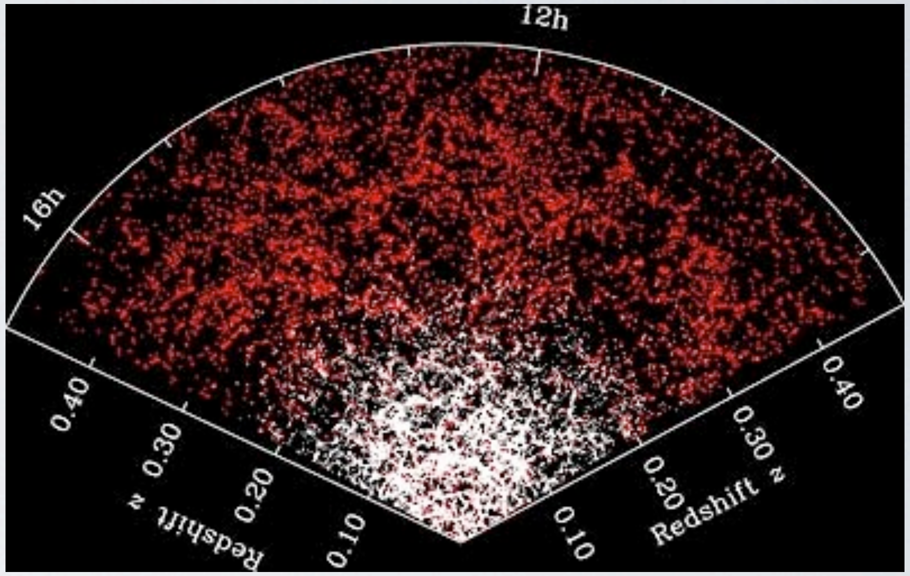
- Dark energy
- Modified Gravity
- Back-reaction, breakdown of Copernican principle

At the level of the **background** most dark energy and modified gravity models are indistinguishable.

We can look at the **evolution** of large-scale **structure**: dark energy and modified gravity models predict different growth rate.

Large-scale structure observable

credit: M. Blanton SDSS



Galaxy number counts: sensitive to the distribution of **matter** and to peculiar **velocities** and to relativistic effects at large scales.

Weak lensing: distortion in the observed shape and size of galaxy by intervening matter. It probes $\Phi + \Psi$

CMB: gravitational lensing and Integrated Sachs-Wolfe due to the change in energy experienced by photons while going through a time-varying potential. It is sensitive to $\dot{\Phi} + \dot{\Psi}$

21cm intensity mapping

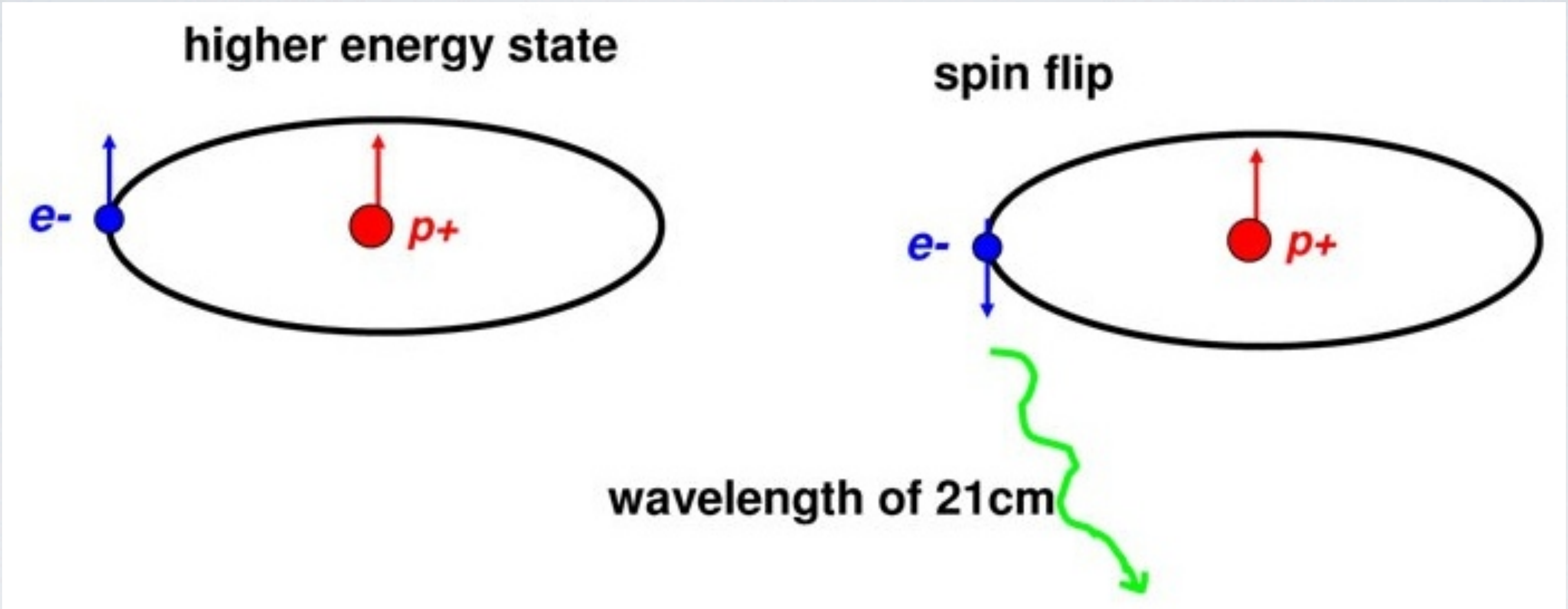
Outline

- What is 21cm **intensity mapping**?

- **Fluctuations** in the 21cm brightness temperature. They can be related to the perturbed variables: $\Phi,\, \Psi,\, D,\, V$

- How can 21cm intensity mapping constrain **modified** theories of **gravity**?

21cm line

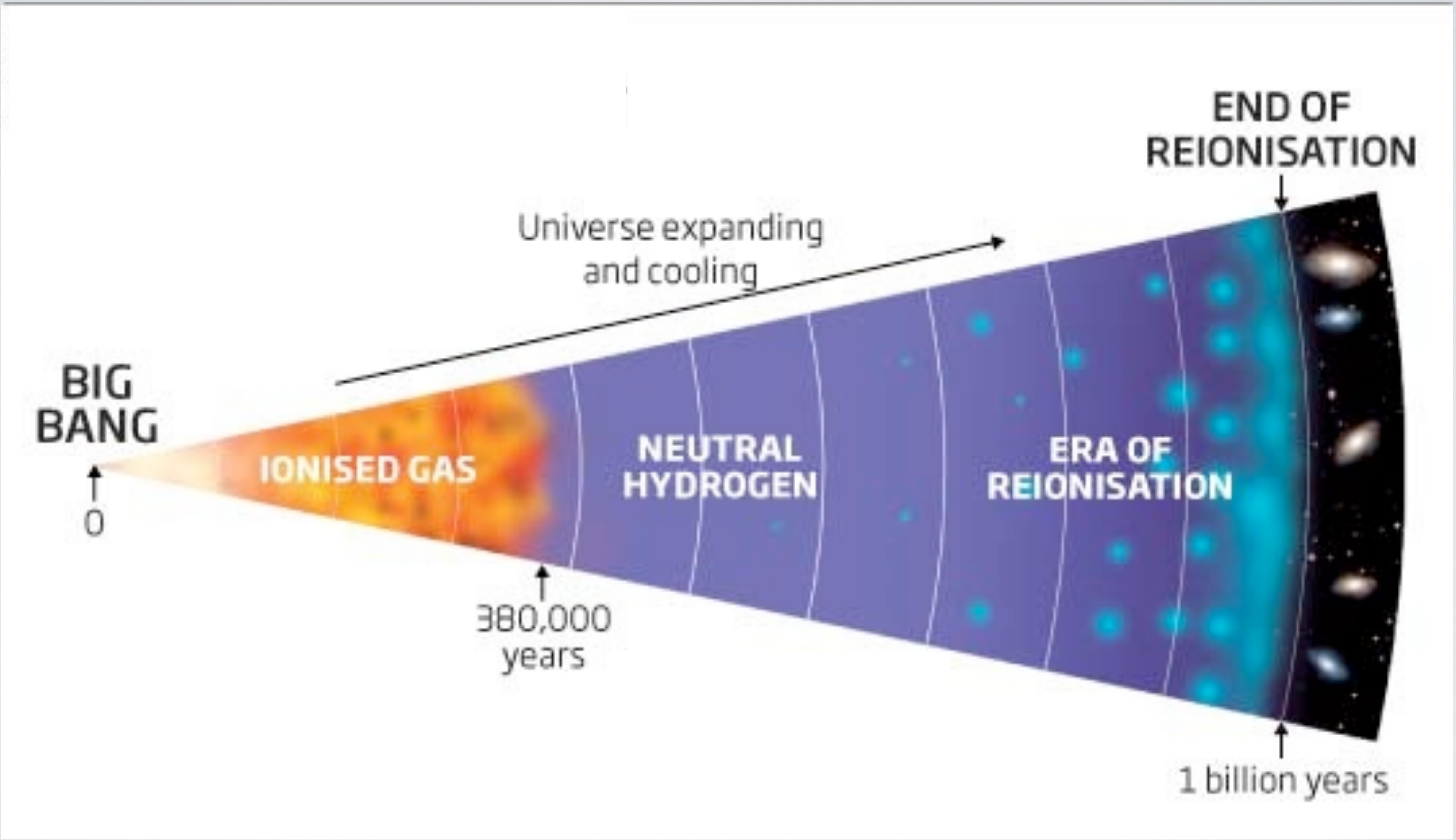


The transition from the higher to the lower state emits a photon at **21cm**, i.e. at 1.4 GHz.

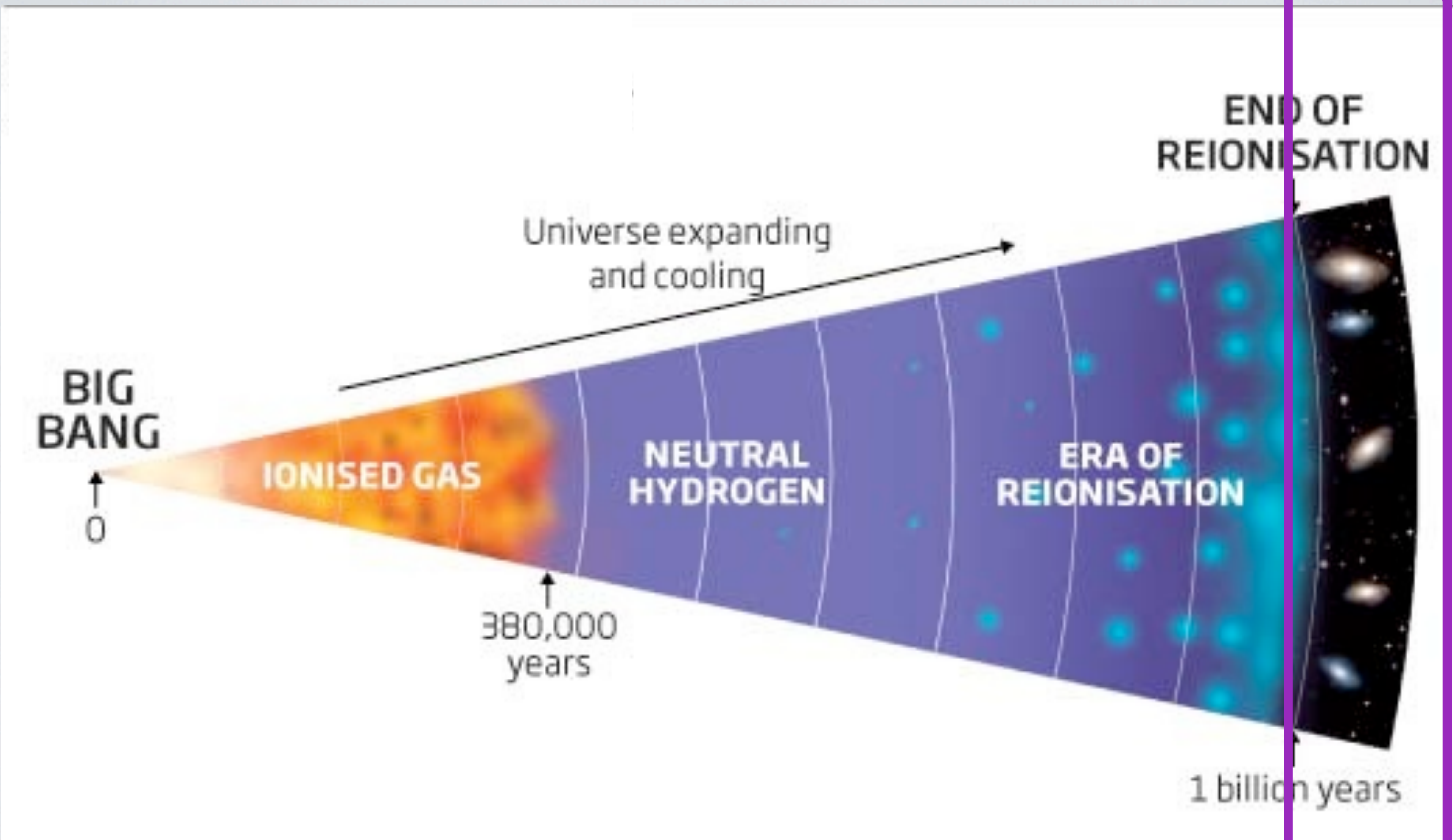
If we detect this line with radio surveys we can map the **distribution** of neutral **hydrogen** in the universe.

Intensity → quantity of hydrogen
Frequency → redshift
→ 3D map of hydrogen

Evolution of neutral hydrogen



post-reionisation



Post-reionisation 21cm emission

Neutral hydrogen is concentrated in dense **pockets** inside galaxies, called damped Lyman-alpha systems.

We measure the **21cm intensity**

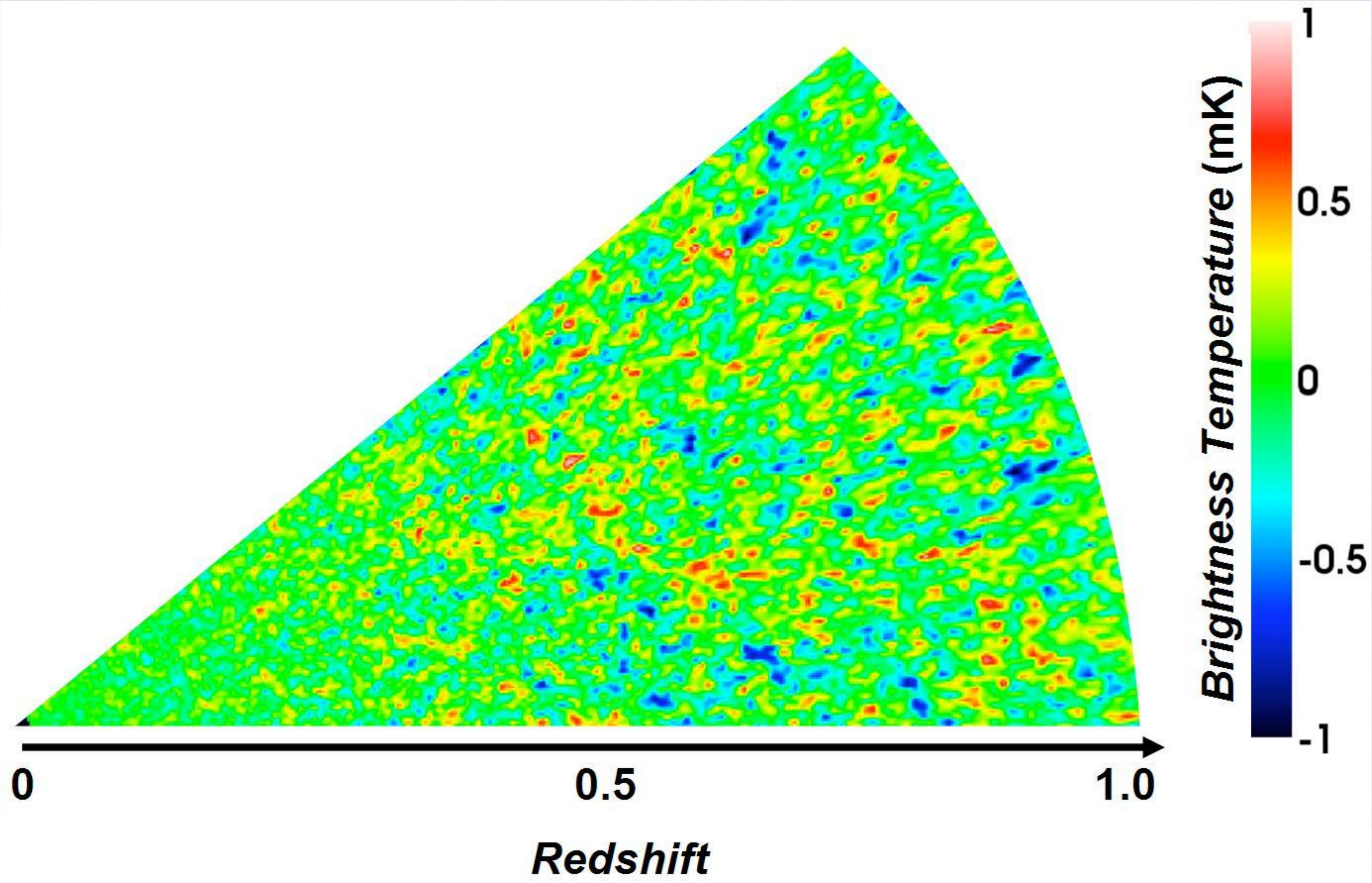
- → we trace the distribution of neutral hydrogen.
- → we trace the distribution of galaxies.
- → we trace the distribution of dark matter.

It is not necessary to resolve for each galaxy: we look at the **collective signal** from many sources.

Instead of counting the number of galaxies, we measure the **intensity** received from small patches of the sky.

CHIME will observe 10'000 square degrees up to z=2.5

21cm intensity mapping



Simulation from Peterson et al. (2011)

Colours code for the intensity or temperature of the 21cm emission. Similar to CMB maps.

Brightness temperature

The brightness temperature is measured as a function of direction and redshift.

$$T_b(\mathbf{n}, z) = \alpha\, \frac{n_g(\mathbf{n}, z)}{d_L^2(\mathbf{n}, z)}$$

galaxies number density

luminosity distance

We calculate the **fluctuations** in the temperature

$$n_g(\mathbf{n}, z) = \bar{n}_g\Big(1 + \Delta(\mathbf{n}, z)\Big) \qquad d_L(\mathbf{n}, z) = \bar{d}_L\left(1 + \frac{\delta d_L(\mathbf{n}, z)}{\bar{d}_L}\right)$$

$$\boxed{\Delta_{21}(\mathbf{n}, z) = \frac{T_b(\mathbf{n}, z) - \langle T_b\rangle}{\langle T_b\rangle} = \Delta(\mathbf{n}, z) - 2\frac{\delta d_L(\mathbf{n}, z)}{\bar{d}_L(z)}}$$

Fluctuations in galaxy number count

CB and R. Durrer (2011)

Three sources of fluctuations

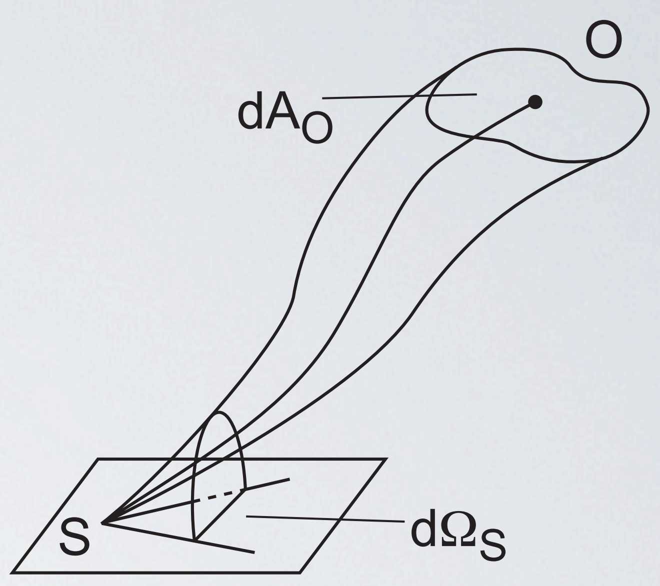
- Intrinsic fluctuations in the matter distribution.
- Fluctuations in the volume of observation, which is distorted with respect to the physical volume at the source position.
- Fluctuations in the redshift.

$$\Delta(\mathbf{n}, z) = b \cdot \delta(\mathbf{n}, z) - 3\frac{\delta z}{1+\bar{z}} + \frac{\delta V(\mathbf{n}, z)}{V(z)}$$

Perturbations in the luminosity distance

CB and R. Durrer (2006)

$$d_L(\mathbf{n}, z) = \sqrt{\frac{L}{4\pi F}} = (1+z)\sqrt{\frac{dA_O}{d\Omega_S}}$$



d_L is sensitive to: the **distance**, the **expansion** and the **perturbations**.

To calculate Δ_{21} we need the perturbations in: the redshift, the matter density, the volume element, the surface mapping.

$$ds^2 = -a^2(1+2\Psi)d\eta^2 + a^2(1-2\Phi)\delta_{ij}dx^i dx^i$$

We solve the **null geodesic** equation and **Sachs** equation.

Brightness temperature perturbations

A. Hall, CB, A. Challinor, in preparation

density

redshift space distortion

$$\Delta_{21}(\mathbf{n}, z_S) = b \cdot D - \frac{1}{\mathcal{H}}\partial_r(\mathbf{V}\cdot\mathbf{n})$$

$$-\left(2+\frac{\dot{\mathcal{H}}}{\mathcal{H}^2}\right)\mathbf{V}\cdot\mathbf{n}$$ → Doppler

$$+\left(2+\frac{\dot{\mathcal{H}}}{\mathcal{H}^2}\right)\int_0^{r_S} dr\,(\dot{\Phi}+\dot{\Psi})$$ → ISW

$$+\left(3+\frac{\dot{\mathcal{H}}}{\mathcal{H}^2}\right)\Psi+\frac{\dot{\Phi}}{\mathcal{H}}-3\frac{\mathcal{H}}{k}V$$ → gravitational potential

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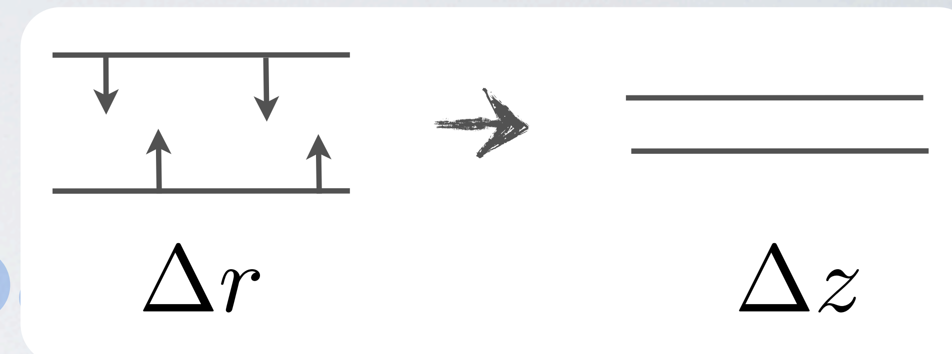

$$- \left(2 + \frac{\dot{\mathcal{H}}}{\mathcal{H}^2}\right)\mathbf{V}\cdot\mathbf{n}$$

D

$$+ \left(2 + \frac{\dot{\mathcal{H}}}{\mathcal{H}^2}\right)\int_0^{r_S} dr\,(\dot{\Phi} + \dot{\Psi})$$

ISW

$$+ \left(3 + \frac{\dot{\mathcal{H}}}{\mathcal{H}^2}\right)\Psi + \frac{\dot{\Phi}}{\mathcal{H}} - 3\frac{\mathcal{H}}{k}V$$

gravitational potential

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gravitational potential

No lensing: $\int_0^{r_S} dr\,\frac{r_S - r}{r r_S}\Delta_\Omega(\Phi+\Psi)$

Brightness temperature perturbations

A. Hall, CB, A. Challinor, in preparation

$$\Delta_{21}(\mathbf{n}, z_S) = b\cdot D - \frac{1}{\mathcal{H}}\partial_r(\mathbf{V}\cdot\mathbf{n}) \qquad \sim \left(\frac{k}{\mathcal{H}}\right)^2\Psi$$

$$-\left(2+\frac{\dot{\mathcal{H}}}{\mathcal{H}^2}\right)\mathbf{V}\cdot\mathbf{n} \qquad \sim \left(\frac{k}{\mathcal{H}}\right)\Psi$$

$$\left.\begin{aligned}&+\left(2+\frac{\dot{\mathcal{H}}}{\mathcal{H}^2}\right)\int_0^{r_S} dr\,(\dot\Phi+\dot\Psi)\\ &+\left(3+\frac{\dot{\mathcal{H}}}{\mathcal{H}^2}\right)\Psi+\frac{\dot\Phi}{\mathcal{H}}-3\frac{\mathcal{H}}{k}V\end{aligned}\right] \sim \Psi$$

The Doppler term and potential terms become relevant **near** the **horizon**.

Brightness temperature perturbations

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redshift space distortion

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Valid in **metric theory** of gravity with standard Euler equation.
Modified gravity modifies the growth of Φ, Ψ, D, V

Brightness temperature in General Relativity

We compute the 2-points correlations in redshift bins.

Bin average: $$\bar{\Delta}_{21}(\mathbf{n}, z) = \int dz'\, W_\sigma(z', z)\Delta_{21}(\mathbf{n}, z')$$

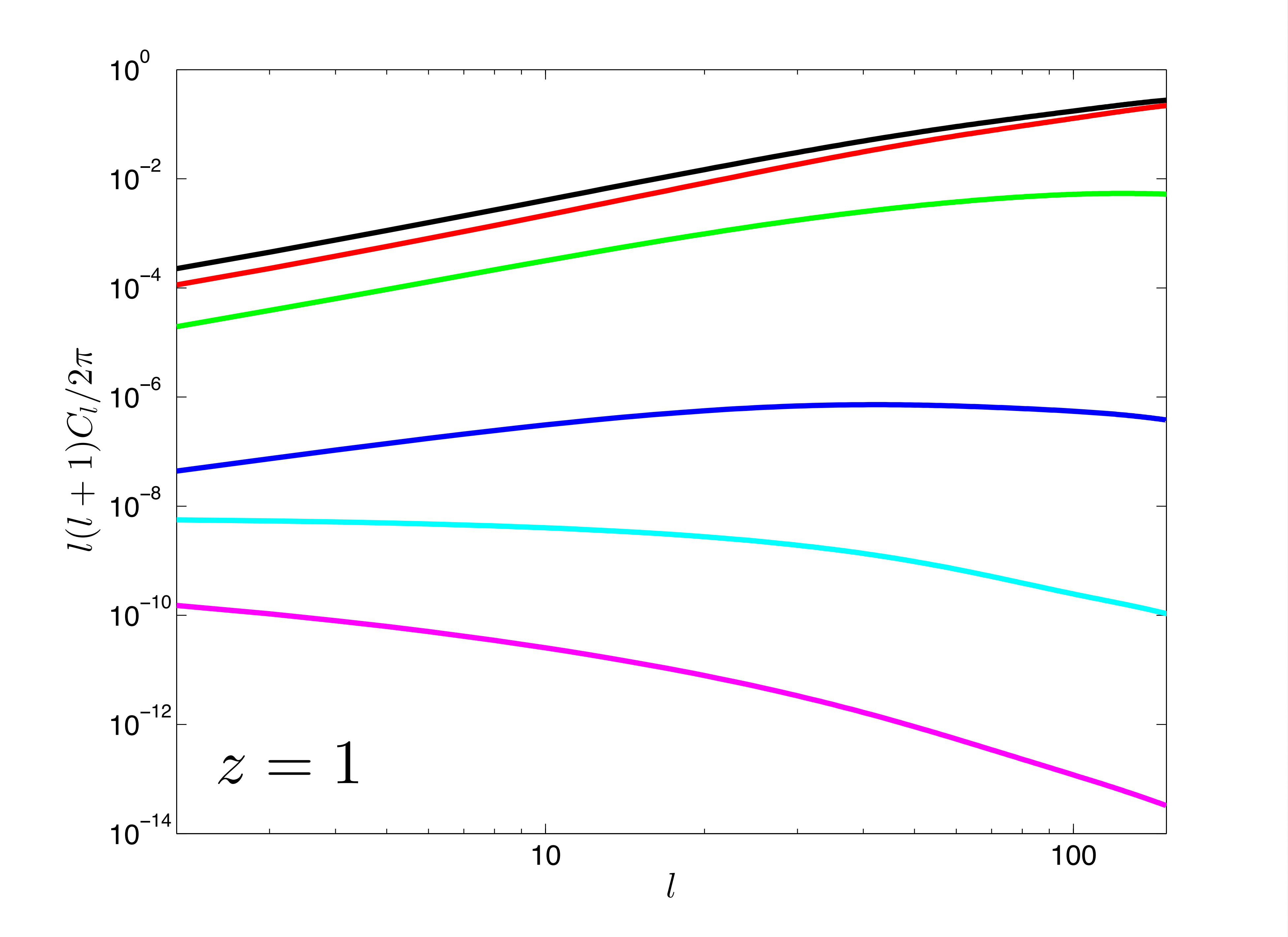
$$\bar{\Delta}_{21}(\mathbf{n}, z) = \sum_{\ell m} a_{\ell m}(z) Y_{\ell m}(\mathbf{n})$$

Angular power spectrum

$$\langle \bar{\Delta}_{21}(\mathbf{n}, z)\bar{\Delta}_{21}(\mathbf{n}', z')\rangle = \sum_{\ell} \frac{2\ell+1}{4\pi} C_\ell(z, z') P_\ell(\mathbf{n}\cdot\mathbf{n}')$$

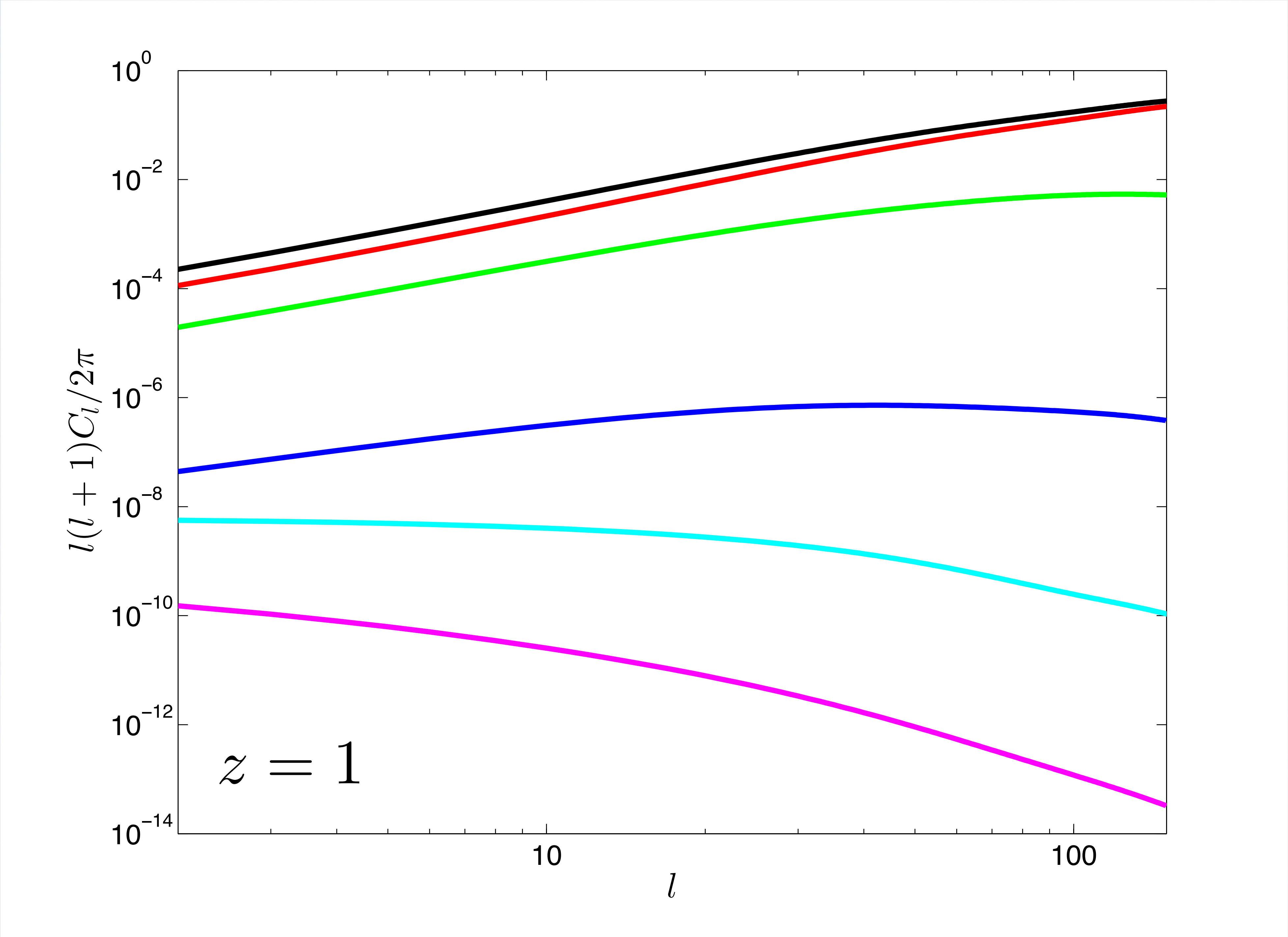
We compute C_ℓ in a $\Lambda\mathrm{CDM}$ universe with gaussian initial conditions.

♦ density ♦ Doppler ♦ ISW
♦ z-distortion ♦ potential ♦ total



Redshift-space distortion is large due to the narrow redshift bin: $2\,\mathrm{MHz} \rightarrow \delta z = 0.006$

♦ density ♦ Doppler ♦ ISW
♦ z-distortion ♦ potential ♦ total



We can increase the relevance of the relativistic terms by using cross-correlation at different redshift or larger window.

Modified Gravity

Which kind of **deviation** from General Relativity can we constrain with 21cm intensity mapping?

We use a **Principal Component Analysis** (PCA)

Modified gravity modifies the relationship between the variables: this can be encoded in two functions μ and γ

$$-k^2\Psi = 4\pi G a^2 \mu(k,z)\rho D$$

$$\Phi = \gamma(k,z)\Psi$$

In General Relativity: $\mu(k,z) = \gamma(k,z) = 1$ everywhere

How can we detect **deviations from 1** with 21cm?

Modified Gravity in 21cm

21cm is mainly sensitive to **density** D and **velocity** V

We combine modified Einstein equations + conservation

$$\ddot{D} + \mathcal{H}\dot{D} - \frac{3\mathcal{H}^2}{2}\mu\, D = 0$$

At sub-horizon scale

$$\ddot{V} + \left(\mathcal{H} - \frac{2\dot{\mathcal{H}}}{\mathcal{H}} - \frac{\dot{\mu}}{\mu}\right)\dot{V} - \left(\frac{3\mathcal{H}^2}{2}\mu + \dot{\mathcal{H}} + \mathcal{H}\frac{\dot{\mu}}{\mu}\right)V = 0$$

21cm constrains deviation in μ

Redshift-space distortion is specially sensitive to **time variations** in μ

We need another observable to constrain γ

Modified Gravity in CMB

We use CMB weak lensing and ISW to constrain γ

$$\Phi + \Psi = -\frac{3}{2}\left(\frac{\mathcal{H}}{k}\right)^2 (\gamma + 1)\mu\, D$$

CMB + 21cm can constrain both μ and γ

We introduce a new function $\Sigma = \dfrac{(\gamma + 1)\mu}{2}$

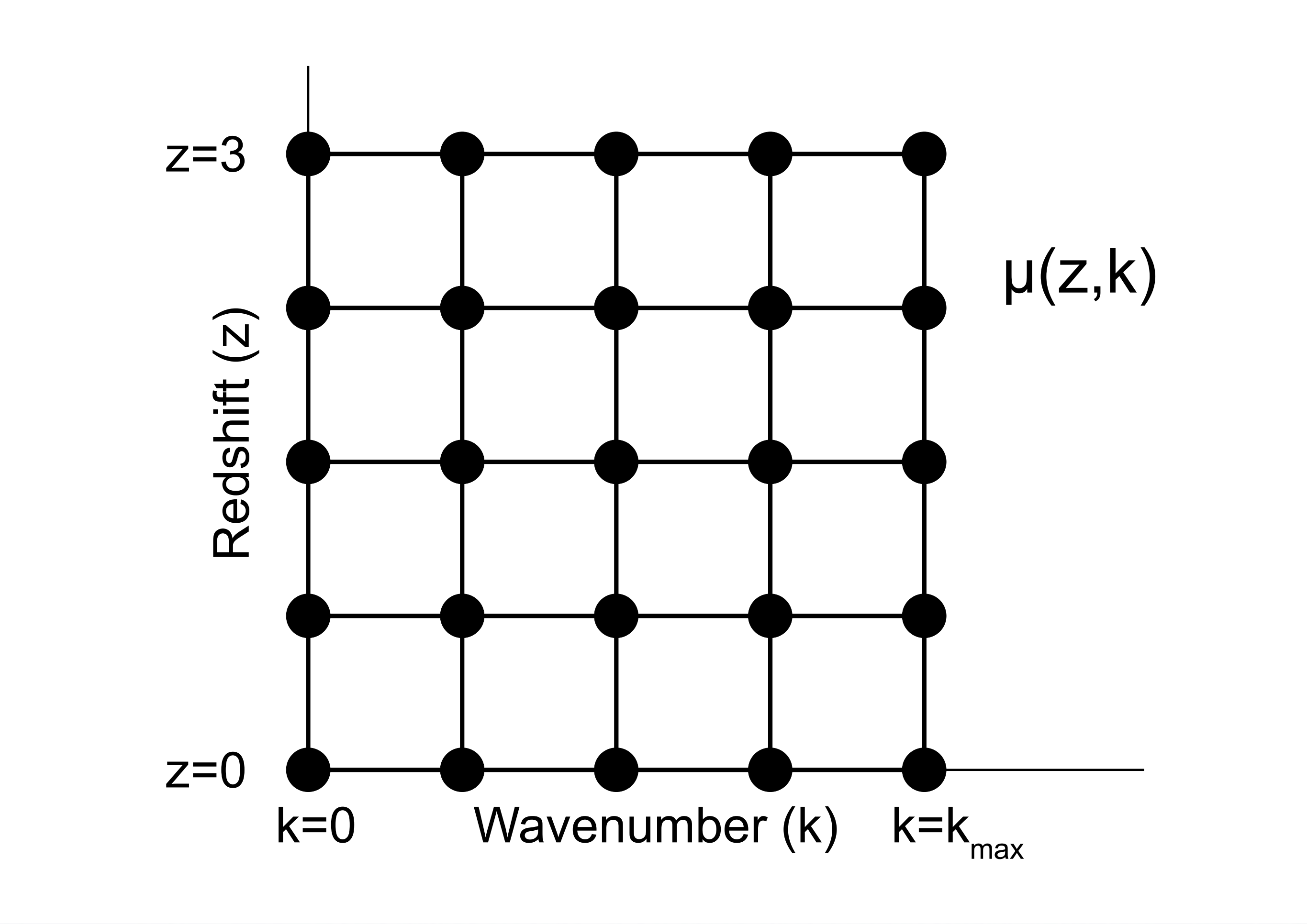
$$\Phi + \Psi = -3\left(\frac{\mathcal{H}}{k}\right)^2 \Sigma(k, z)\, D$$

μ modifies D and V → 21cm

Σ modifies the relation between $\Phi + \Psi$ and D → CMB

Principal component analysis

The function μ and Σ depends on k and z: we **sample** them on a **grid**.



We have 32 free **parameters** corresponding to the values of μ and Σ at the nodes: how well can we constrain them?

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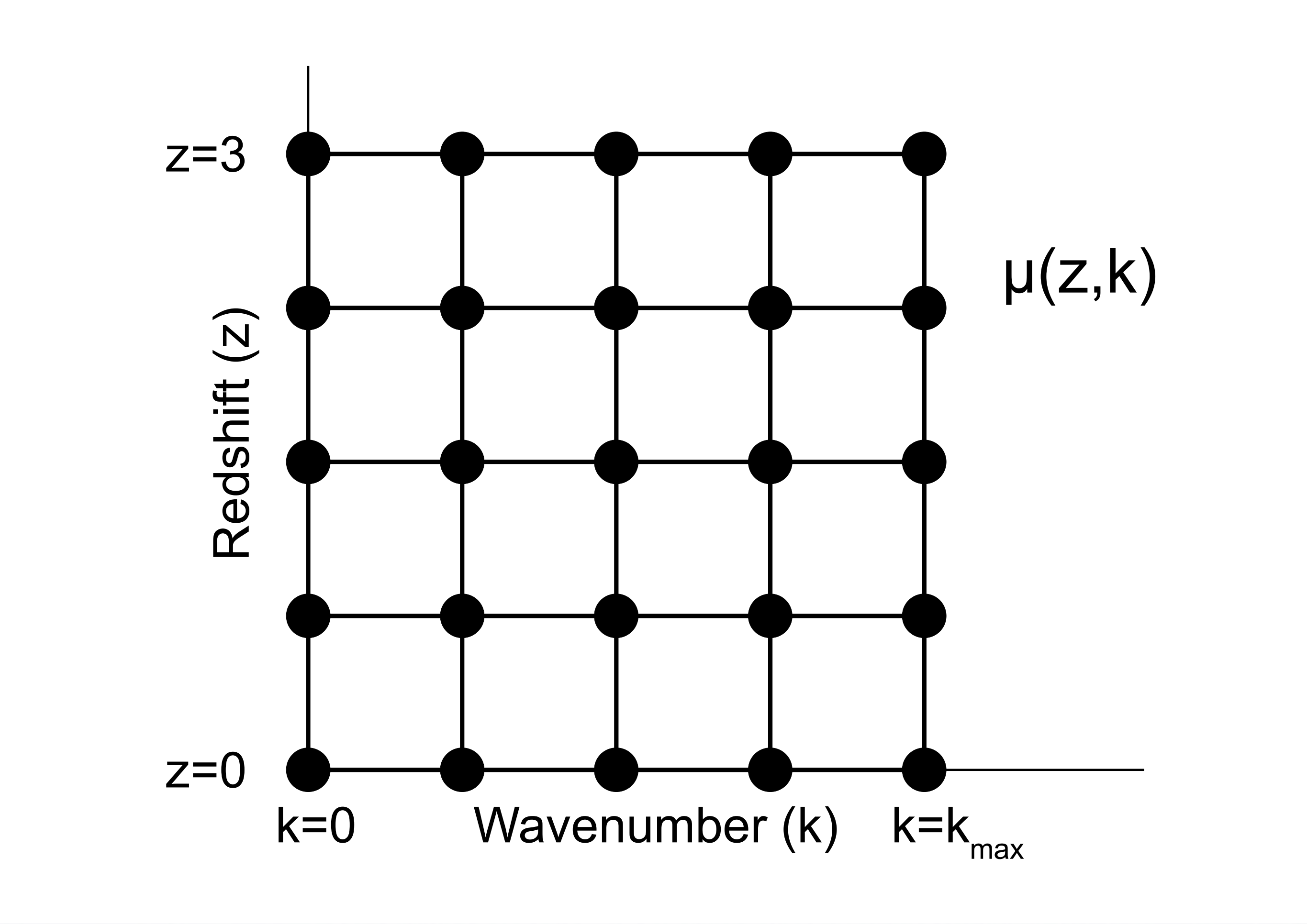


$k_{\mathrm{NL}} \sim 0.1\ \mathrm{Mpc}^{-1}$

$k_{\mathrm{NL}} \sim 0.05\ \mathrm{Mpc}^{-1}$

Jennings et al. (2012)

We have 32 free **parameters** corresponding to the values of μ and Σ at the nodes: how well can we constrain them?

Fisher matrix analysis

Parameters: 32 modified gravity parameters + 7 standard cosmological parameters. We assume a $\Lambda\mathrm{CDM}$ background.

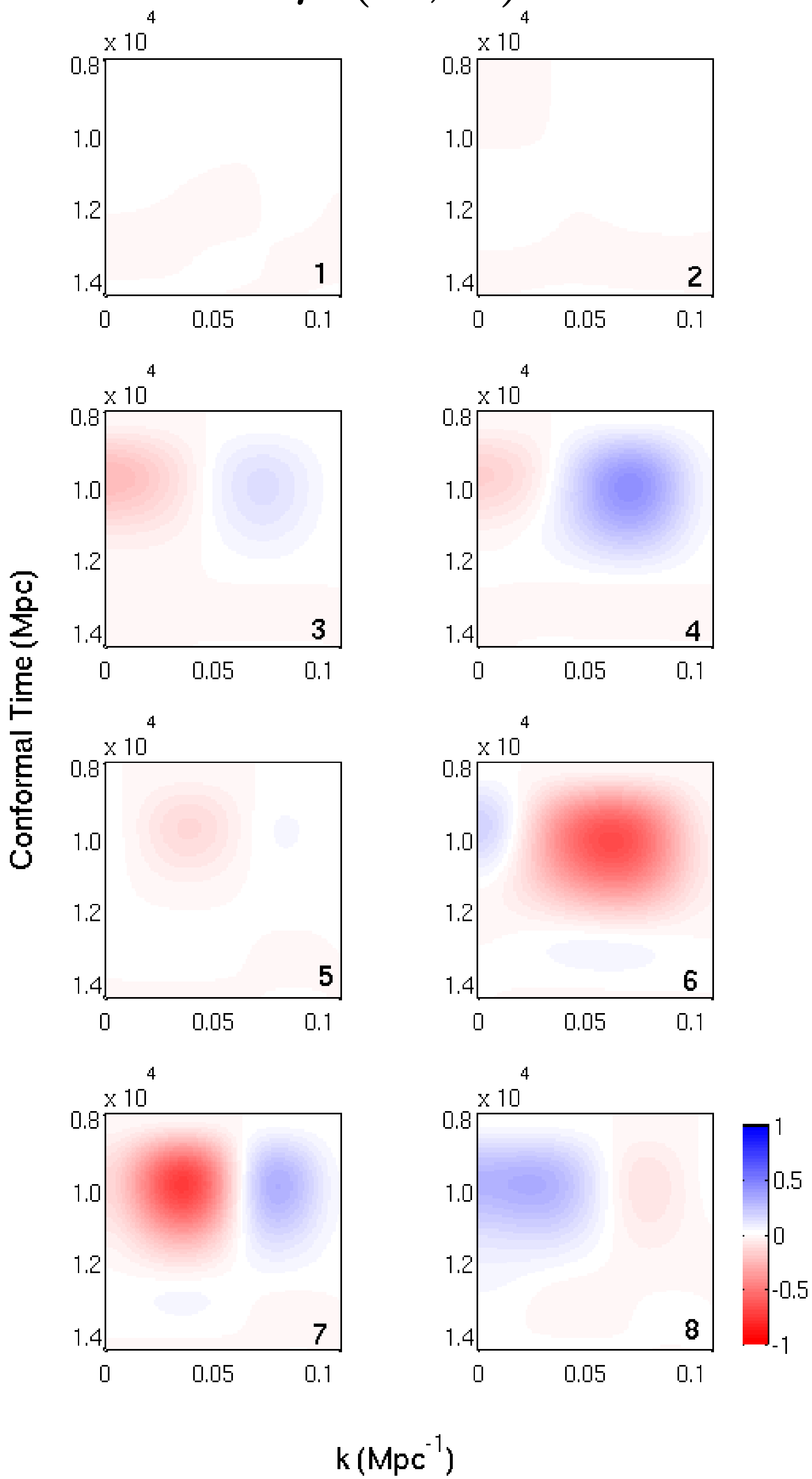
Data: 21cm angular power spectrum + CMB lensing and ISW.

$$F_{ij} = \frac{1}{2}\mathrm{Tr}\left[\mathbf{C}^{-1}\frac{\partial\mathbf{C}}{\partial\theta_\mathrm{i}}\mathbf{C}^{-1}\frac{\partial\mathbf{C}}{\partial\theta_\mathrm{j}}\right]$$

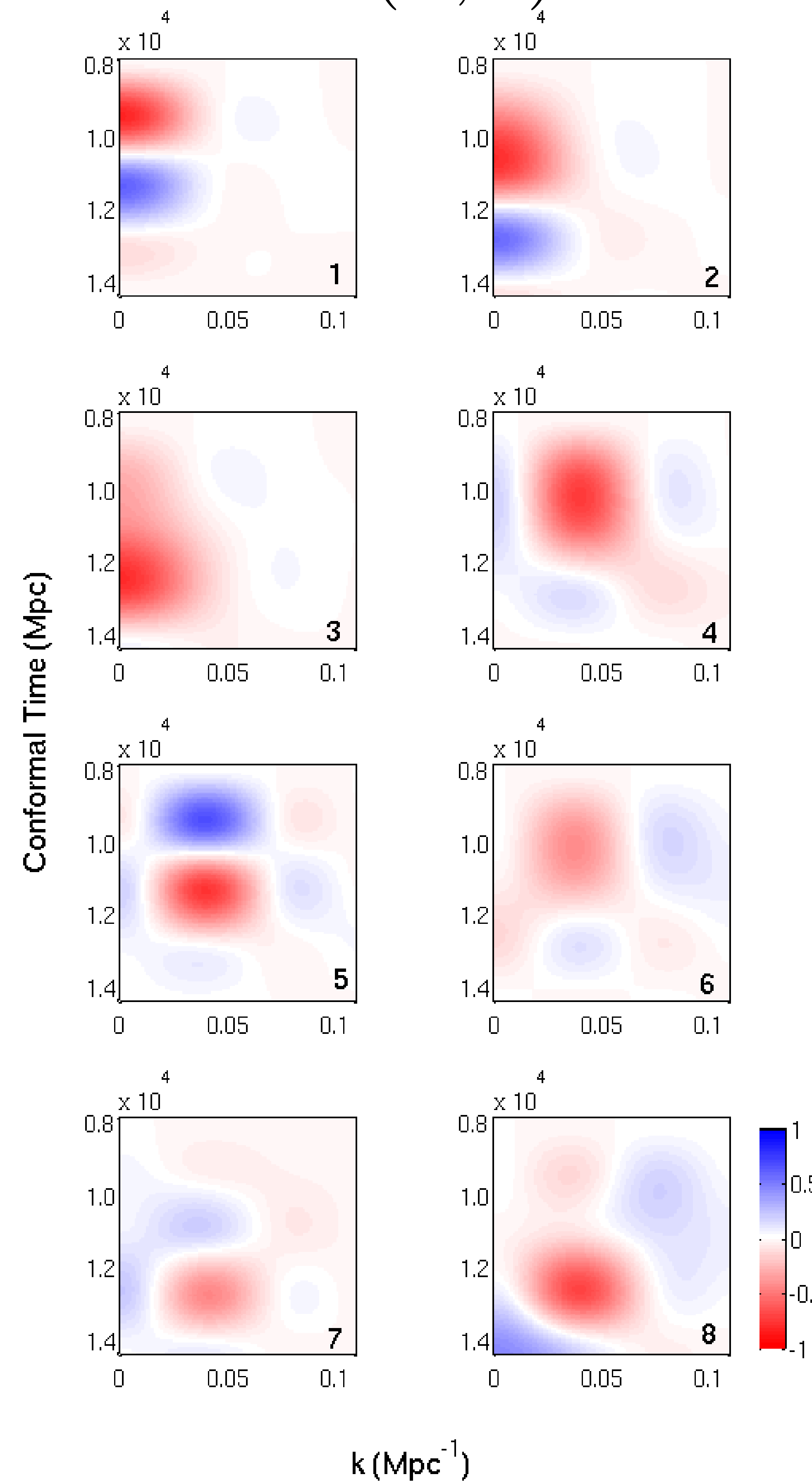
We diagonalise the matrix to find the **independent combinations** of parameters that can be constrained.

Eigenvector → independent mode
Eigenvalue → error on the mode

$\mu(\mathbf{n}, z)$

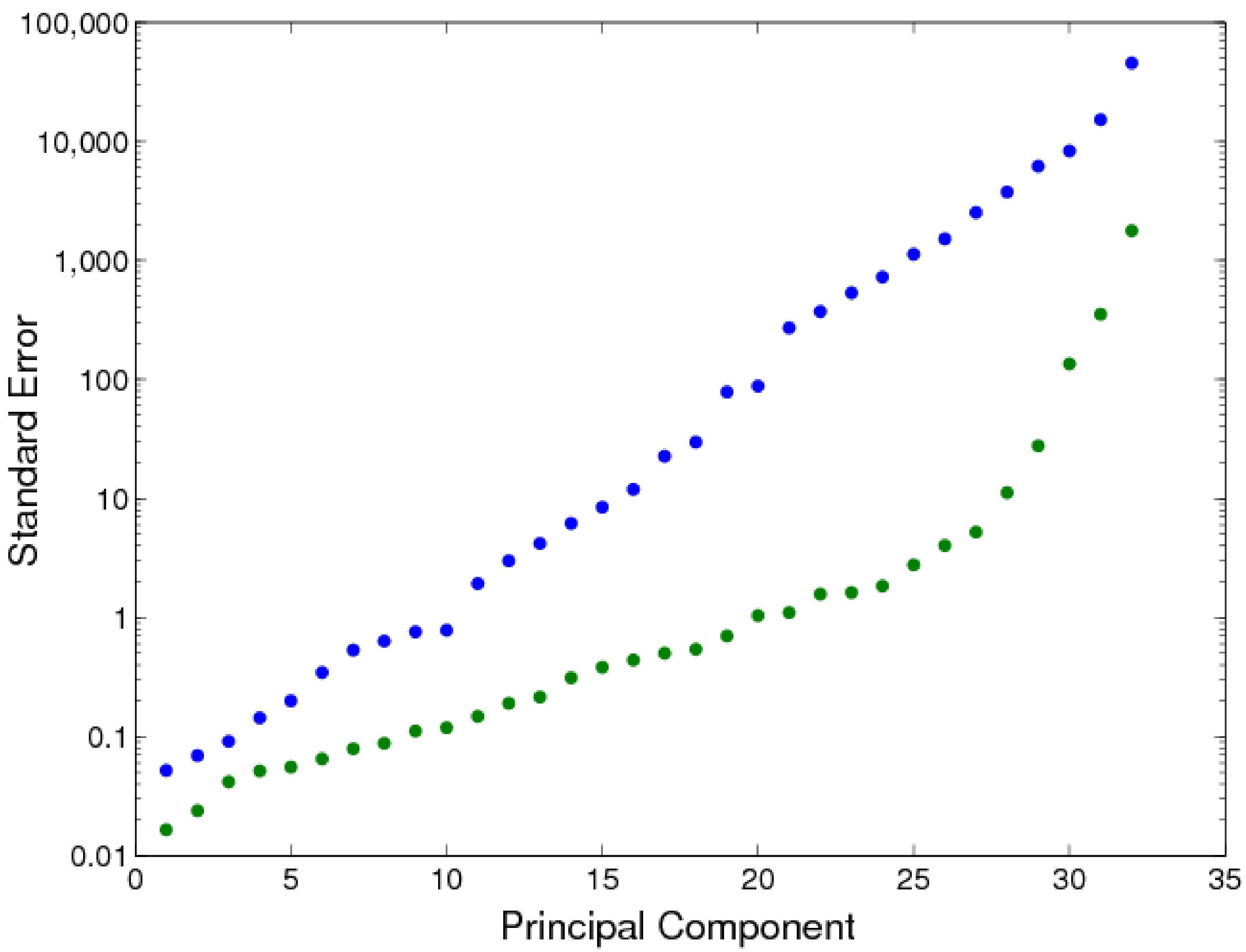


$\Sigma(\mathbf{n}, z)$



Eigenvalues

- CMB
- CMB+21cm



Conclusion

- 21cm intensity mapping provides a new way to map **large-scale structure**.

- Thanks to the high redshift precision and the fact that we look at a collective emission, 21cm can easily produce **3D maps** of large volume of the universe.

- **Redshift-space distortion** is enhanced in 21cm intensity mapping.

- A **principal component analysis** indicates that a typical experiment like CHIME can constrain 25 independent modes of the free functions μ and Σ