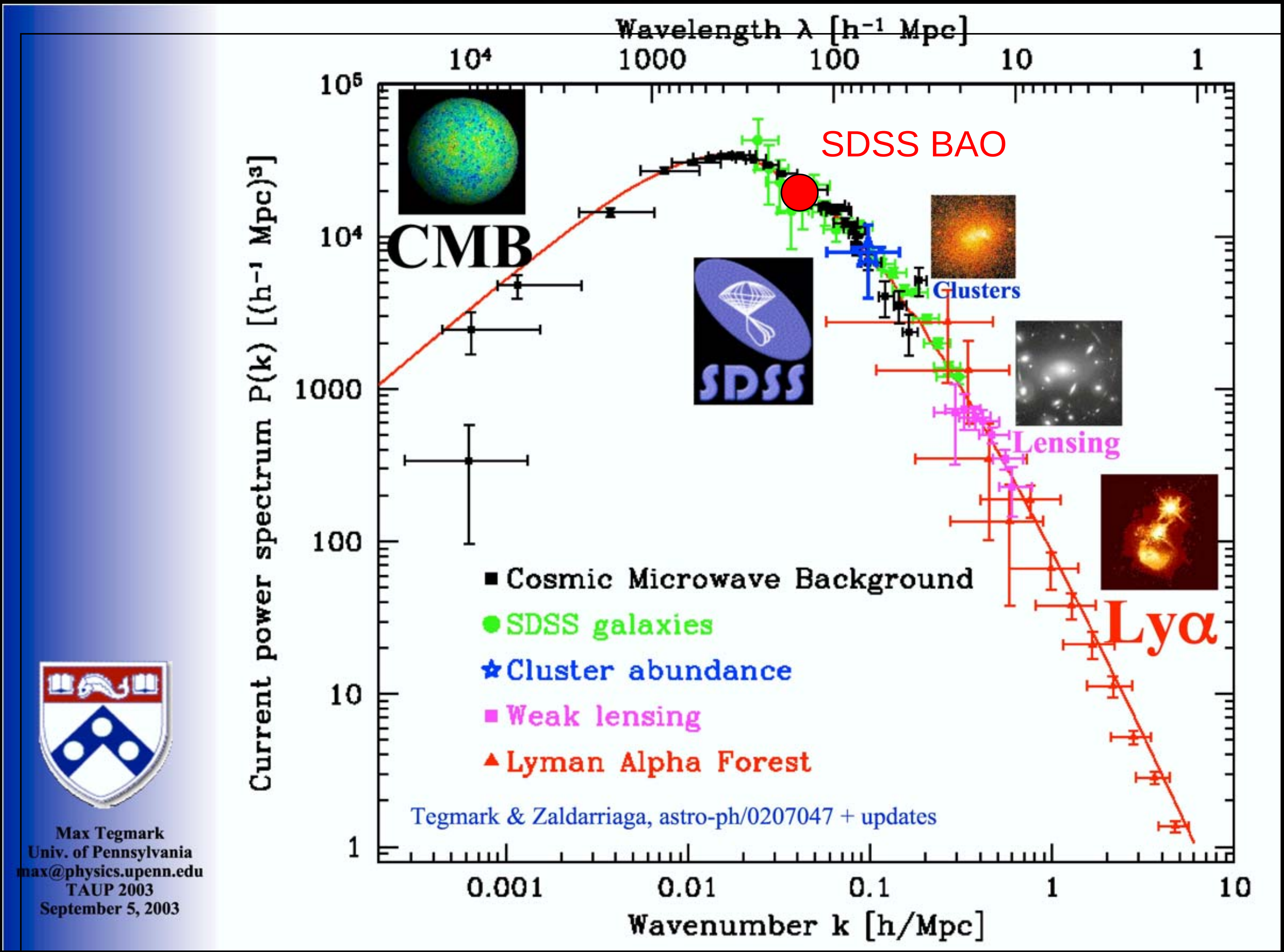


FROM MAX TEGMARK

ESSENTIALLY, STRUCTURE IS MEASURED ON ALL SCALES FROM SUB-GALACTIC TO THE HUBBLE HORIZON

SO, WHAT IS MISSING?

1) THE REDSHIFT DEPENDENCE OF STRUCTURE

2) PRECISION!

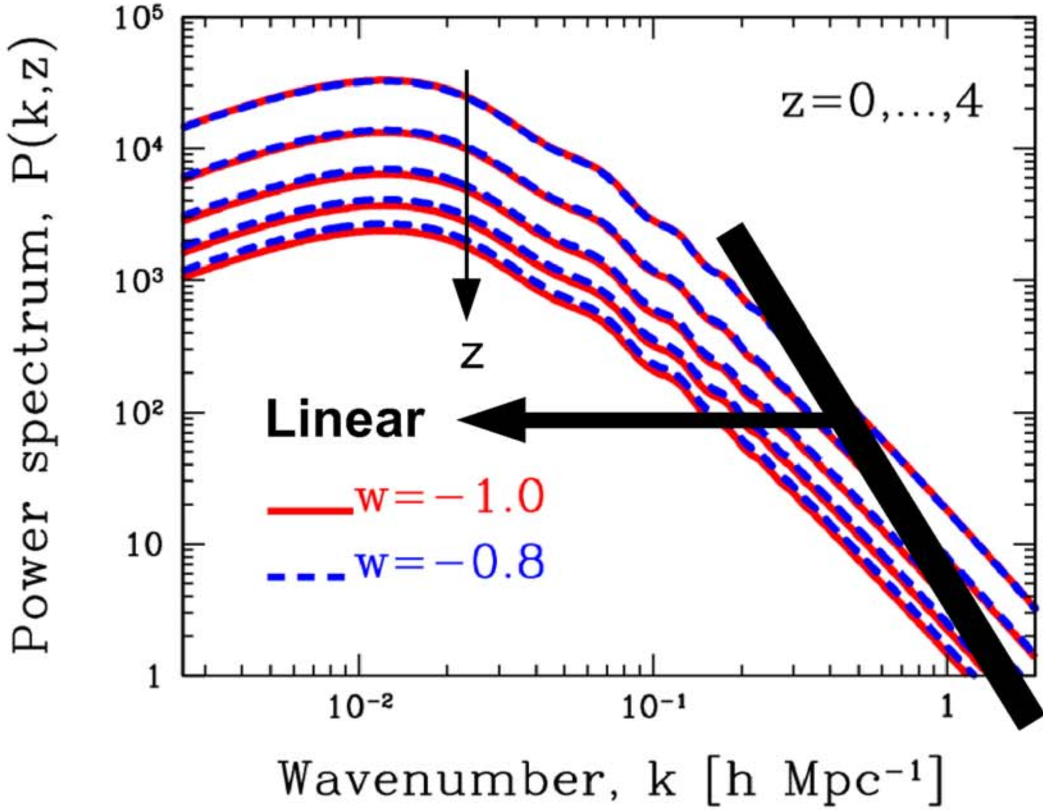
- Linear perturbation theory is applicable when:

$$\Delta(k,z) \equiv \frac{k^3 P(k,z)}{2\pi^2} \ll 1$$

Dimensionless power spectrum

  - At z = 0: $k \ll 0.2\,h\,\mathrm{Mpc}^{-1}$
  - At z = 3: $k \ll 2\,h\,\mathrm{Mpc}^{-1}$

- Higher z = larger k range calculable from linear theory.

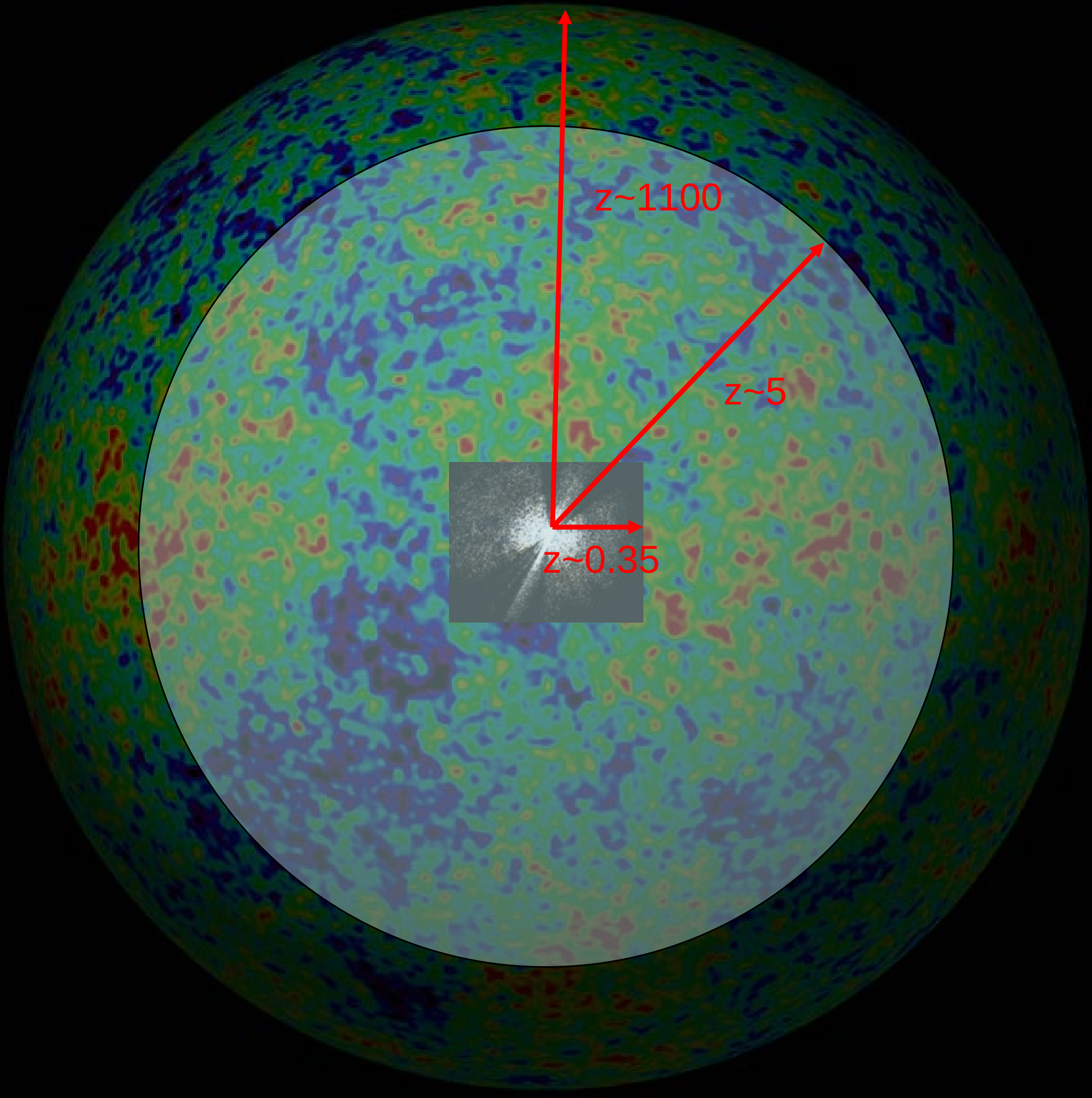


ADVANTAGES OF PROBING STRUCTURE AT HIGH REDSHIFT

- STRUCTURES ARE MORE LINEAR
- VOLUME IS LARGER (THE HORIZON VOLUME IS ~ 1000 TIMES LARGER THAN THE SDSS-LRG VOLUME)

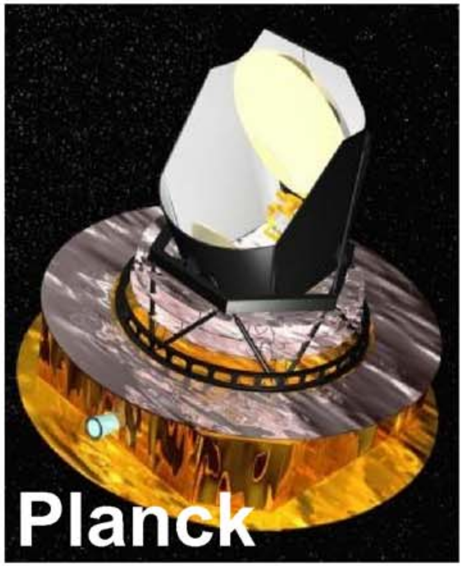
HOW TO DO IT?

- LYMAN-ALPHA?
- BAO? (WFMOS)
- GALAXIES? (LSST)
- 21-CM? (LOFAR, SKA)


z~1100
z~5
z~0.35

WHAT IS IN STORE FOR THE FUTURE?

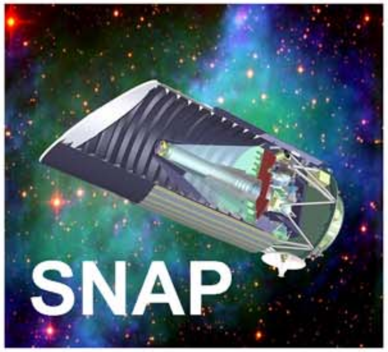
- BETTER CMB TEMPERATURE AND POLARIZATION MEASUREMENTS (PLANCK)
- LARGE SCALE STRUCTURE SURVEYS AT HIGH REDSHIFT
- MEASUREMENTS OF WEAK GRAVITATIONAL LENSING ON LARGE SCALES
- MEASUREMENTS OF 21-CM EMISSION FROM HYDROGEN AT VERY HIGH REDSHIFT



AAΩ

HETDEX

Pan-STARRS



Dark Energy Survey

LSST
Large Synoptic Survey Telescope

DUNE

SKA
SQUARE KILOMETRE ARRAY

CMB POLARIZATION ANISOTROPY MEASUREMENT

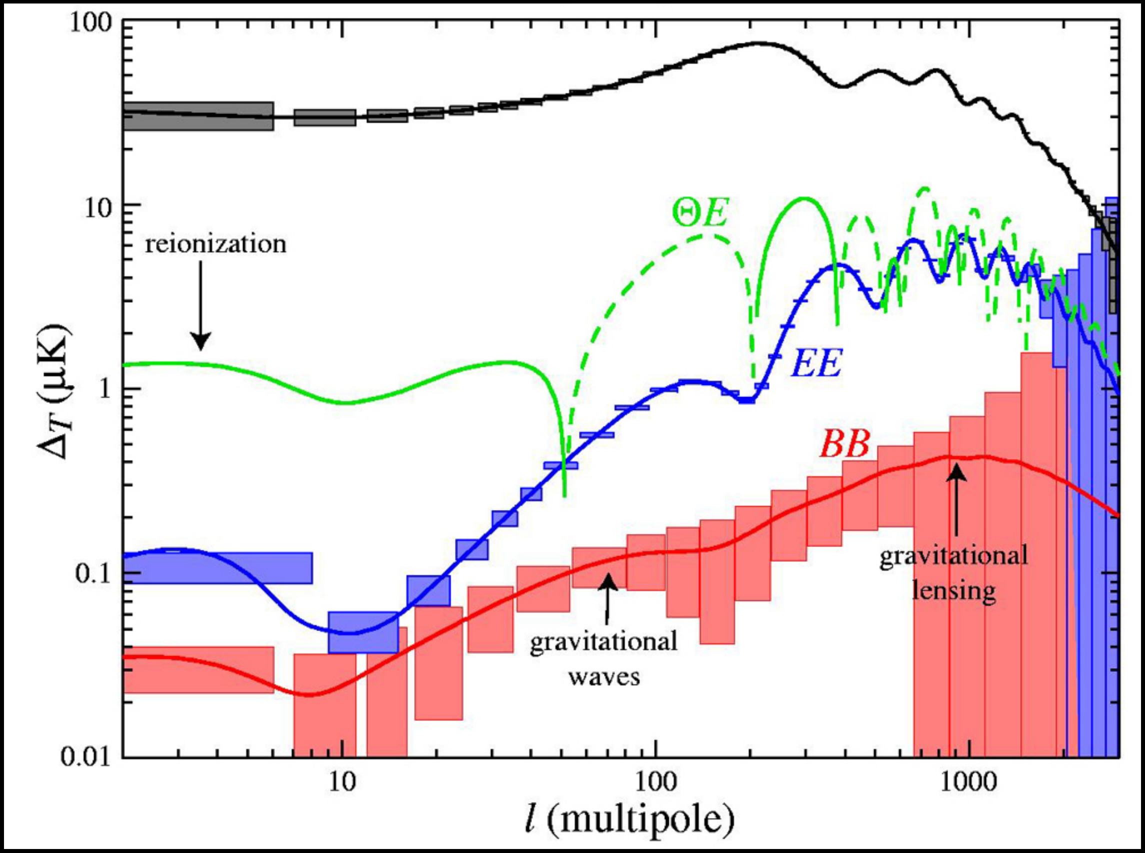
$$\frac{P_{ab}}{T}(\theta,\phi)=\sum_{lm} a^{E}_{lm}Y^{E}_{lm,ab}(\theta,\phi)+a^{B}_{lm}Y^{B}_{lm,ab}(\theta,\phi)$$

Gives a new sequence of power spectra

$$C_l^{ET} \equiv \left\langle a_{lm}^{E*} a_{lm}^{T} \right\rangle$$

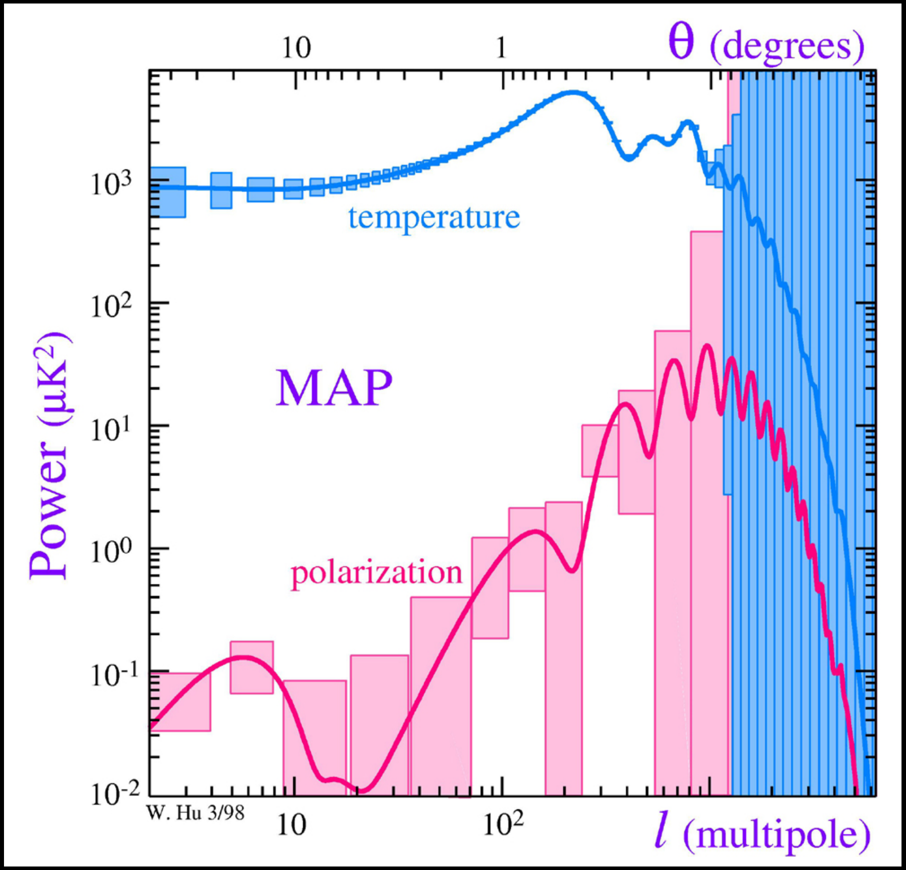
$$C_l^{EE} \equiv \left\langle a_{lm}^{E*} a_{lm}^{E} \right\rangle$$

$$C_l^{BB} \equiv \left\langle a_{lm}^{B*} a_{lm}^{B} \right\rangle$$

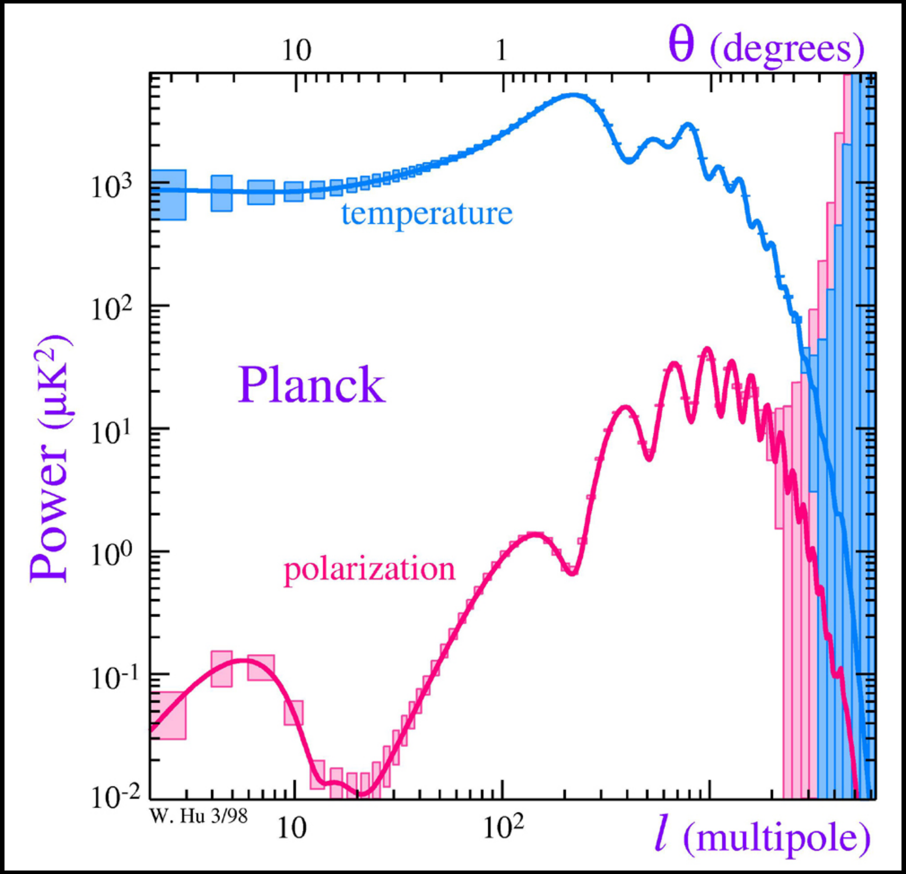


Dodelson & Hu ’02
Wayne Hu arXiv:0802.3688

PROJECTED OBSERVATIONAL ERRORS FOR MAP AND PLANCK



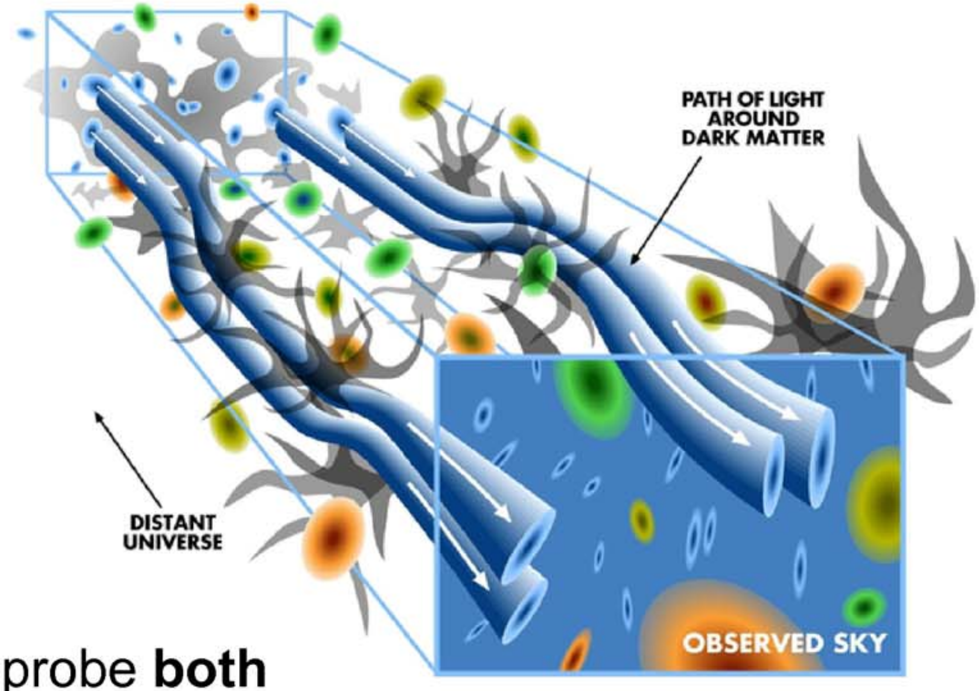
WMAP FINAL DATA



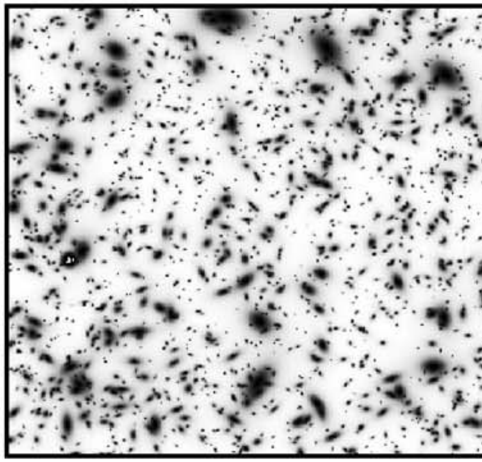
PLANCK

Weak lensing of galaxies/Cosmic shear...

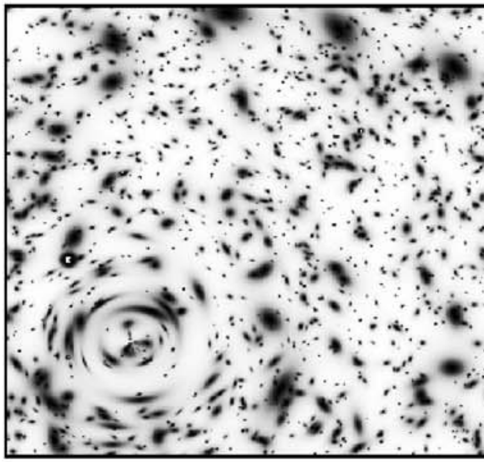
- Distortion (magnification or stretching) of distant galaxy images by **foreground matter**.



Distortions probe **both** luminous and dark matter.

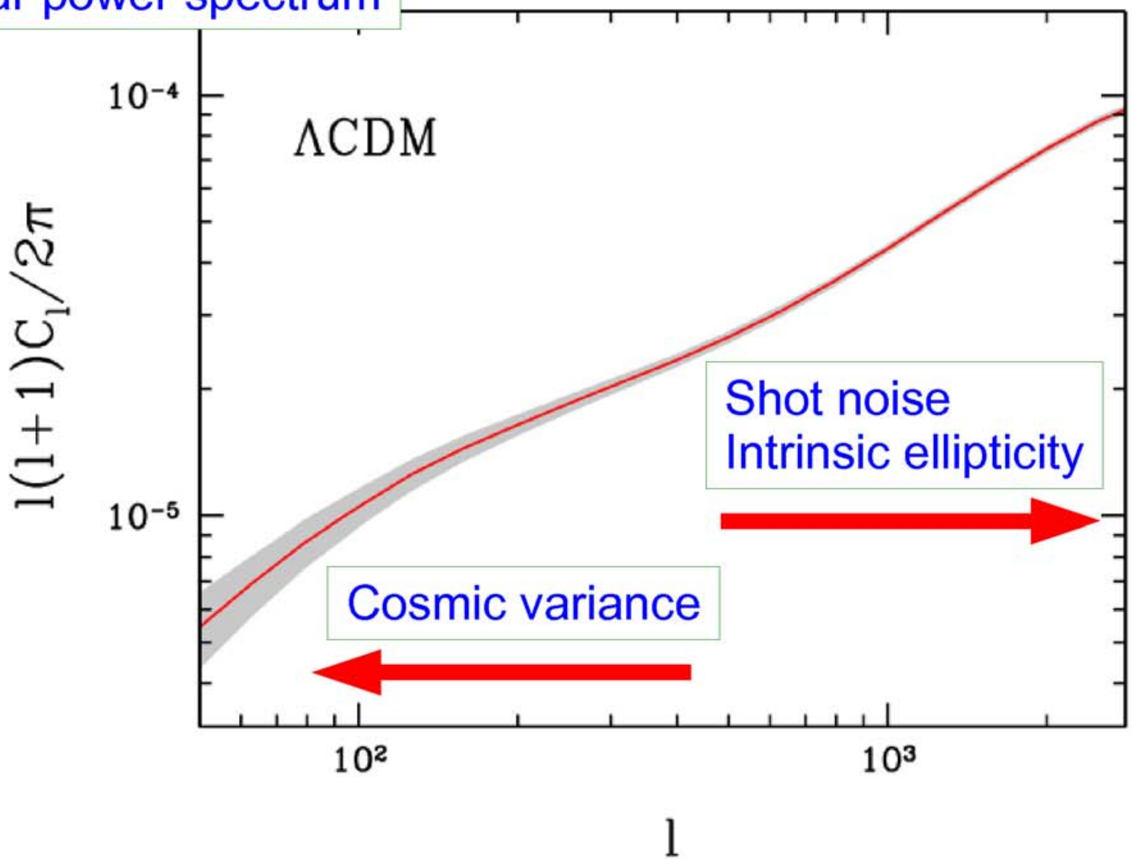


Unlensed



Lensed

Shear power spectrum

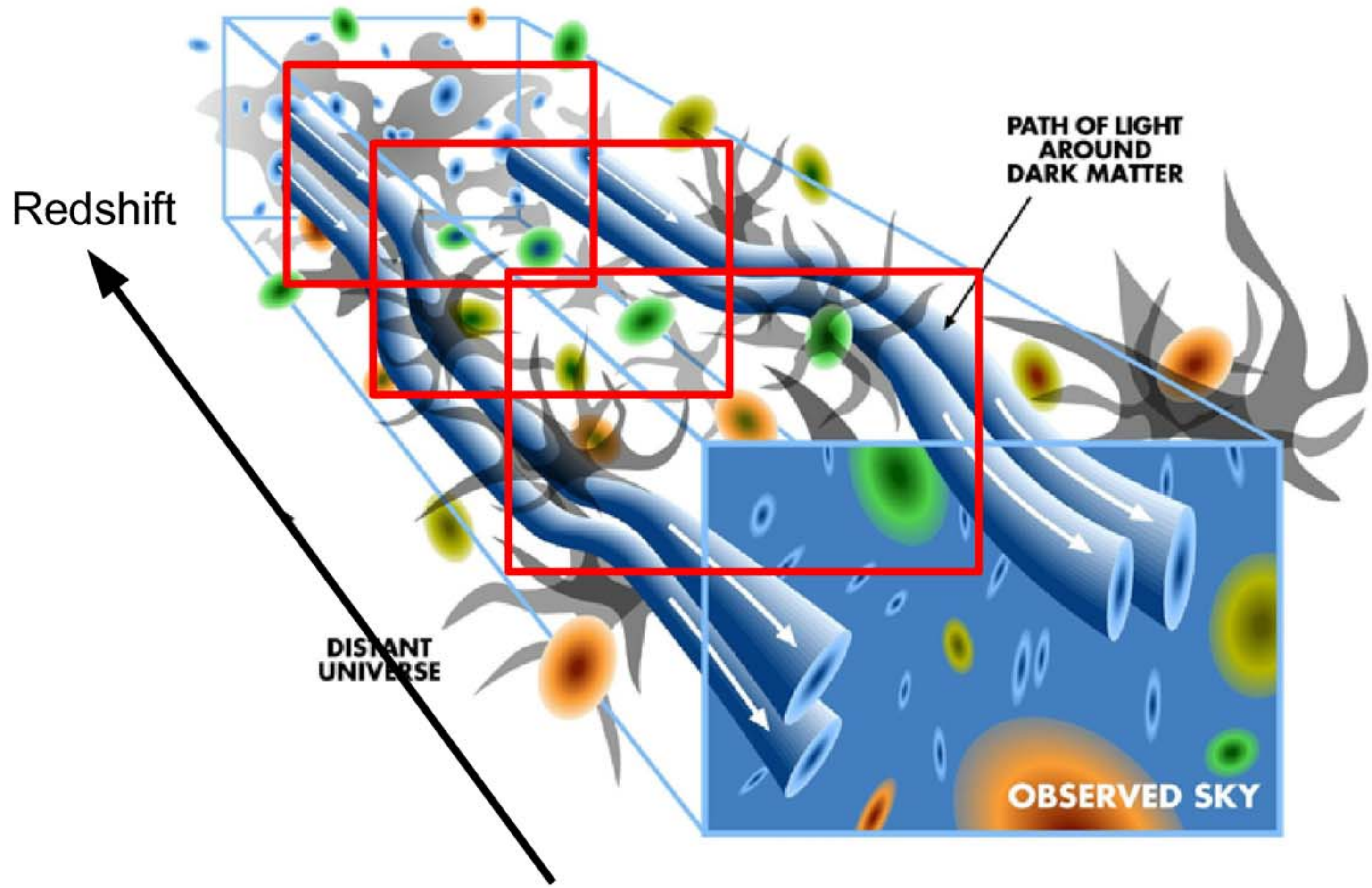


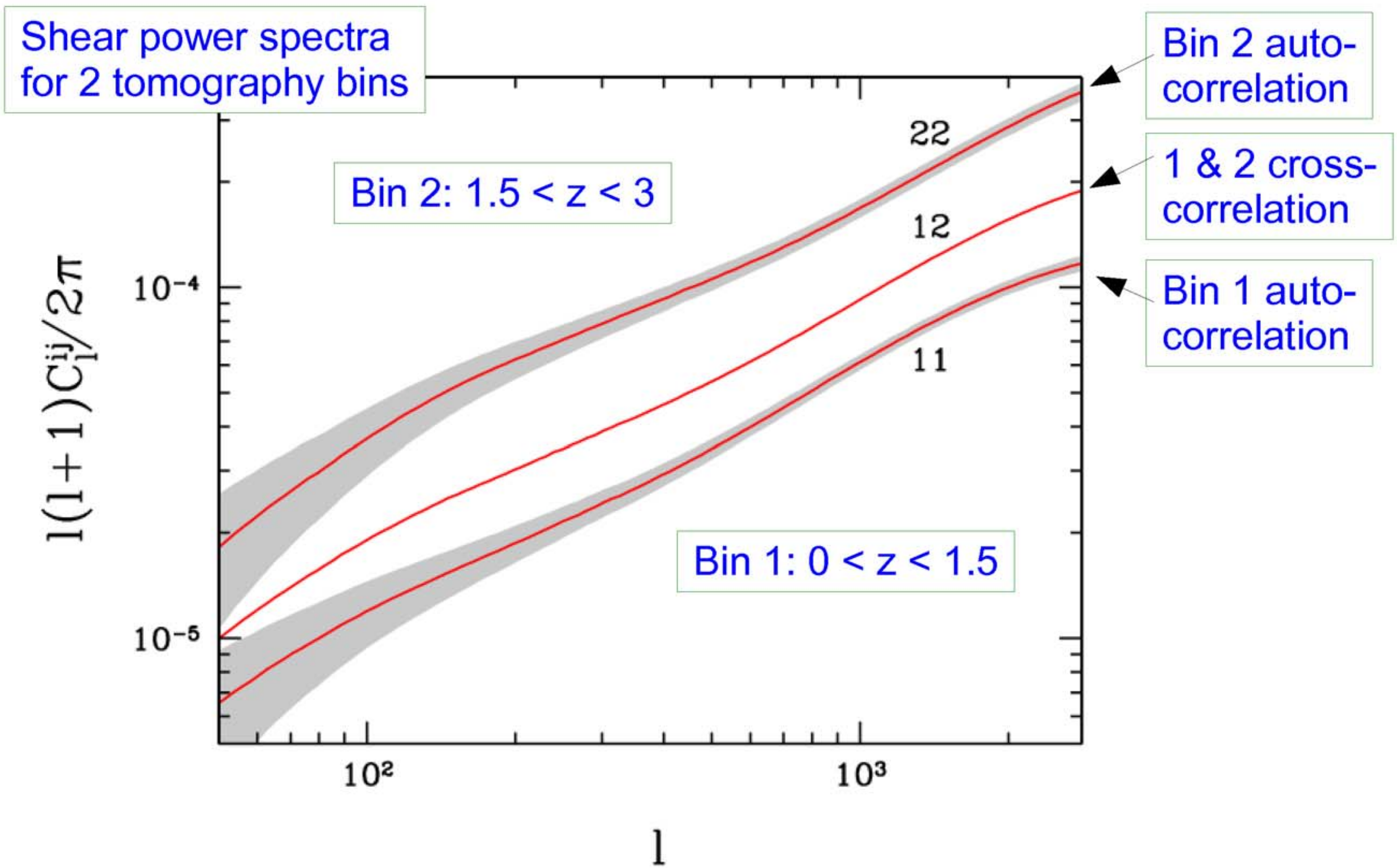
Shear power spectrum

Matter power spectrum

$$C_l \propto \int_0^\infty d\chi\, a^{-2} \left[\int_\chi^\infty d\chi'\, n_{\rm gal}(\chi') \frac{D(\chi'-\chi)}{D(\chi')} \right]^2 P(k = l/D(\chi))$$

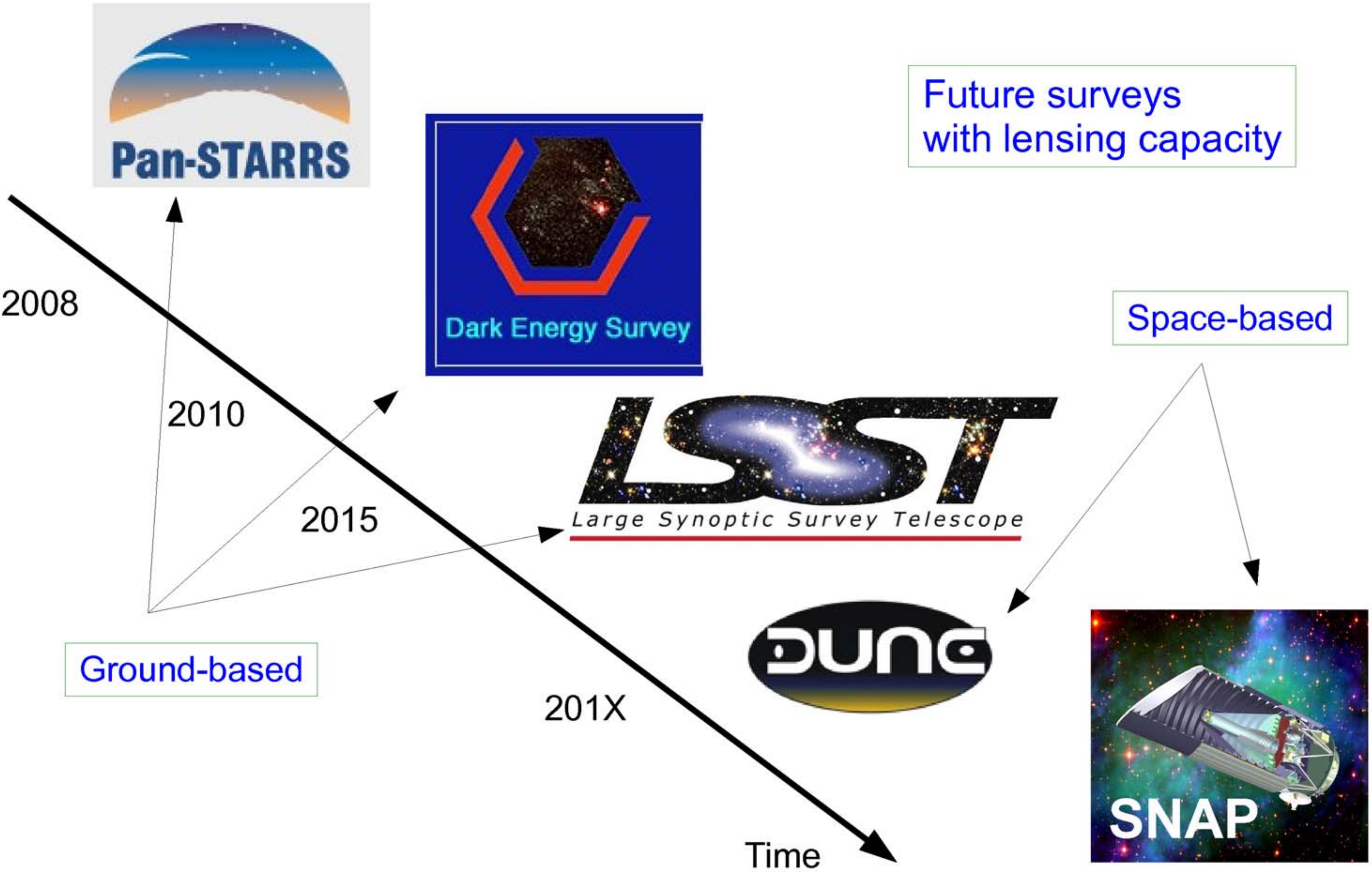
- **Tomography** = bin galaxies by redshift



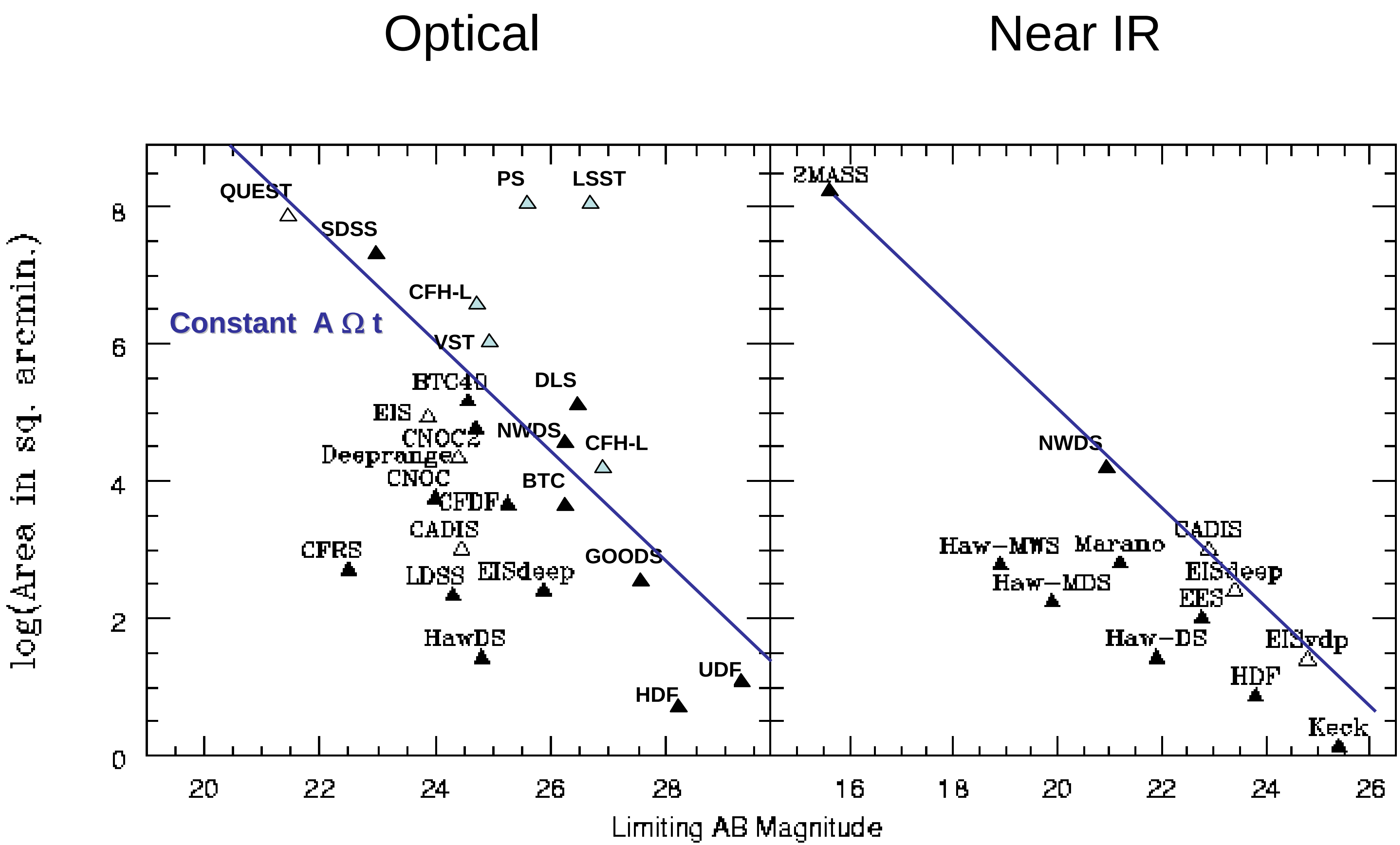


STH, TU, WONG 2006

- **Past**:
  - Cosmic shear first detected in 2000.
- **Present**:
  - There are some ongoing surveys (e.g., CFHTLS).
- **Future**:
  - Dedicated lensing surveys with capacity for tomography.


Future surveys
with lensing capacity
Pan-STARRS
Dark Energy Survey
2008
2010
2015
201X
LSST
Large Synoptic Survey Telescope
Space-based
Ground-based
DUNE
SNAP
Time

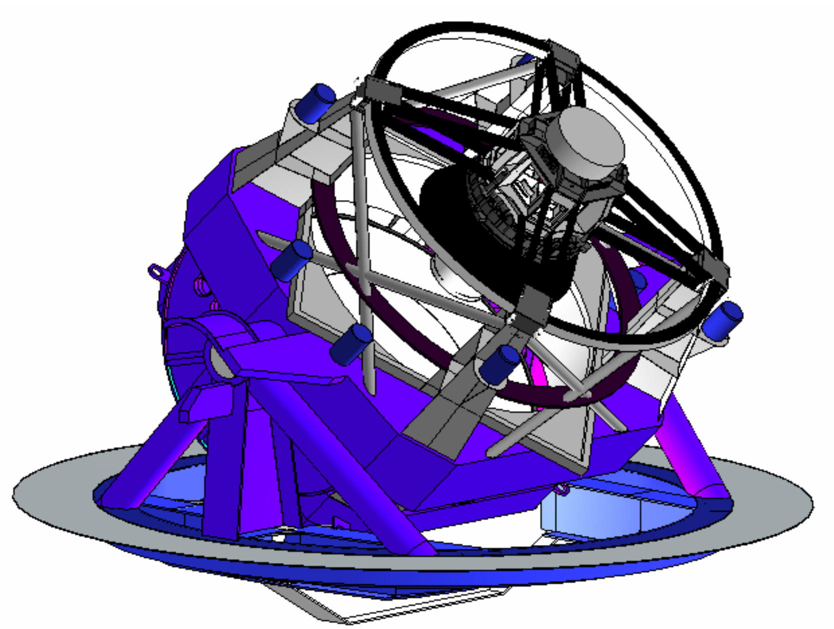
Some Recent Optical and Near IR Surveys



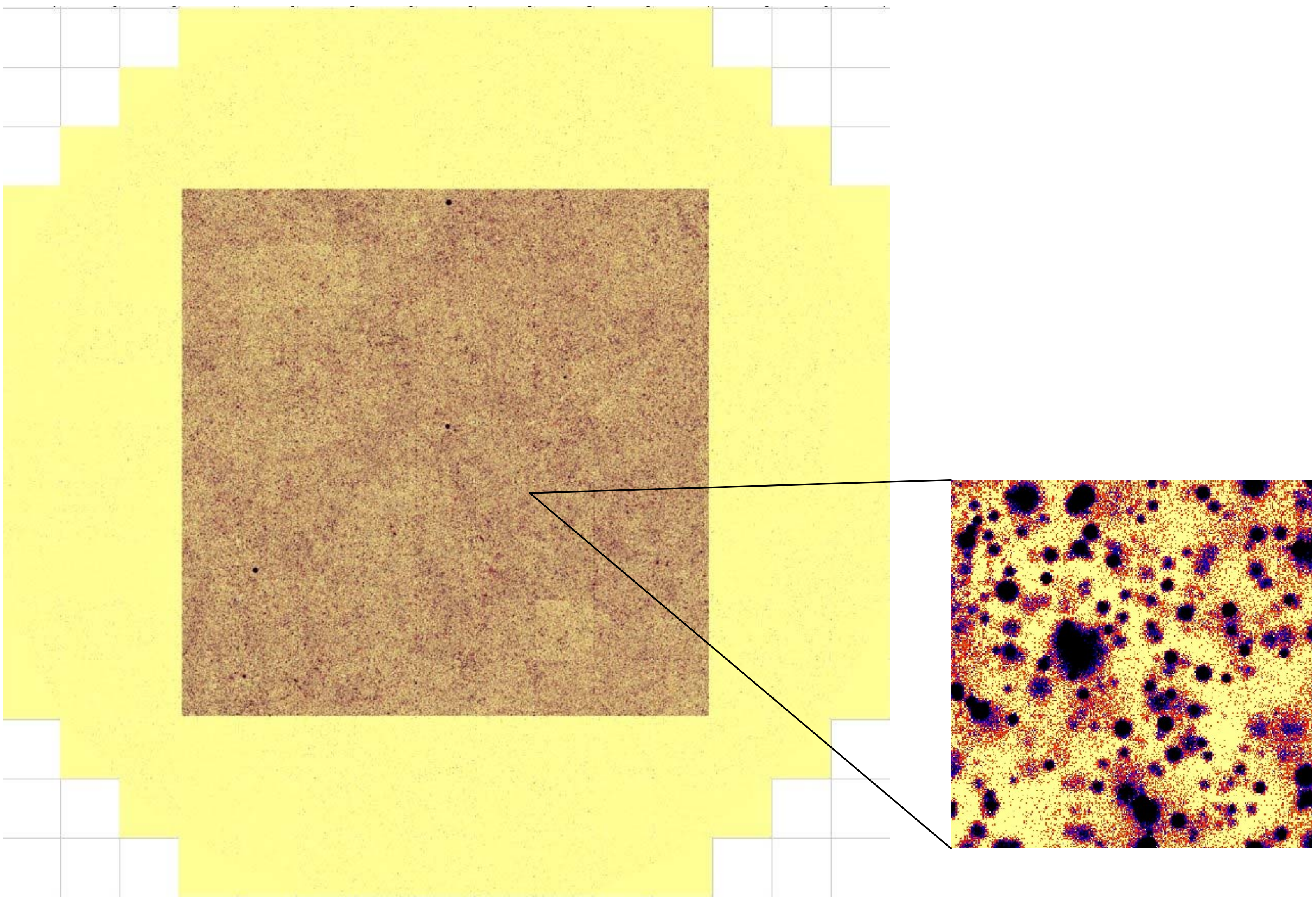
The Large Synoptic Survey Telescope (LSST)

- It incorporates an 8.4 m diameter primary mirror, with a 9.6 square degree camera.

- LSST will observe 20,000 square degrees of sky down to ~ 27th magnitude, yielding a sample of a few billion galaxies out to z ~ 1 - 1.5.

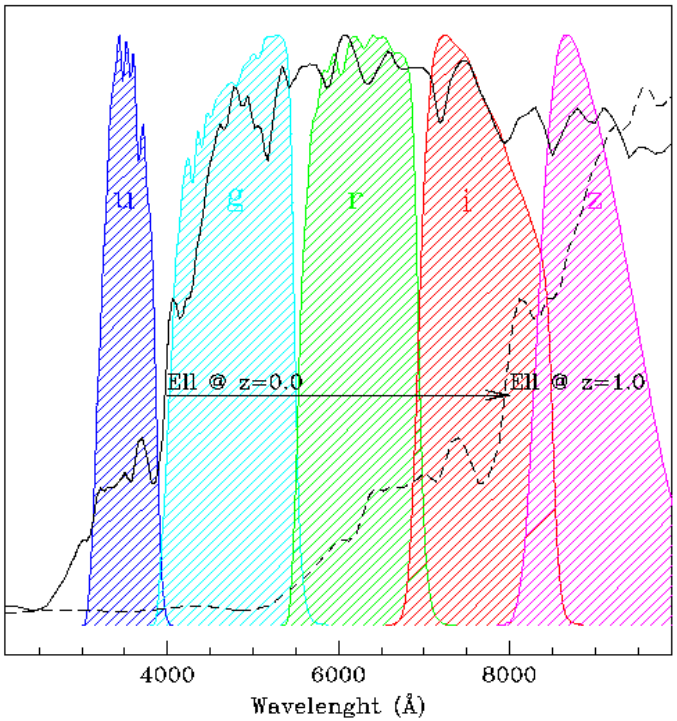


LSST Simulation



Getting the Distances - Photometric Redshifts

- Galaxies have distinct spectra, with characteristic features at known rest wavelengths.
- Accurate redshifts can be obtained by taking spectra of each galaxy. But this is impractical for the billions of galaxies mapped by LSST.
- Instead, we can use the colors of the galaxies obtained from the images themselves. This requires accurate calibration of both the photometry and of the intrinsic galaxy spectra as a function of redshift.



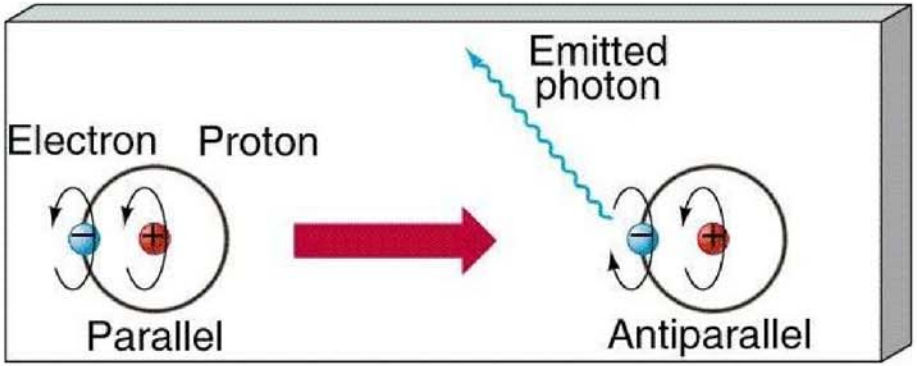
- Planck+LSST tomography (5 bins) sensitivities (based on a 11-parameter model):

	1σ sensitivities
– **Neutrino mass**, Σm_ν	0.043 eV
– **Dark energy density**, Ω_{de}	1%
– **Dark matter density**, $\Omega_c h^2$	1%
– **Baryon density**, $\Omega_b h^2$	0.6%
– **DE equation of state**, w	3%
– **Optical depth to reionisation**, τ	8%
– **Scalar spectral index**, n_s	1%
– **Number of neutrino species**, N_ν	2%

Hannestad, Tu & Y^3W, 2006

Neutral hydrogen 21cm spin-flip...

- Use intensity of the emission to map neutral hydrogen distribution.

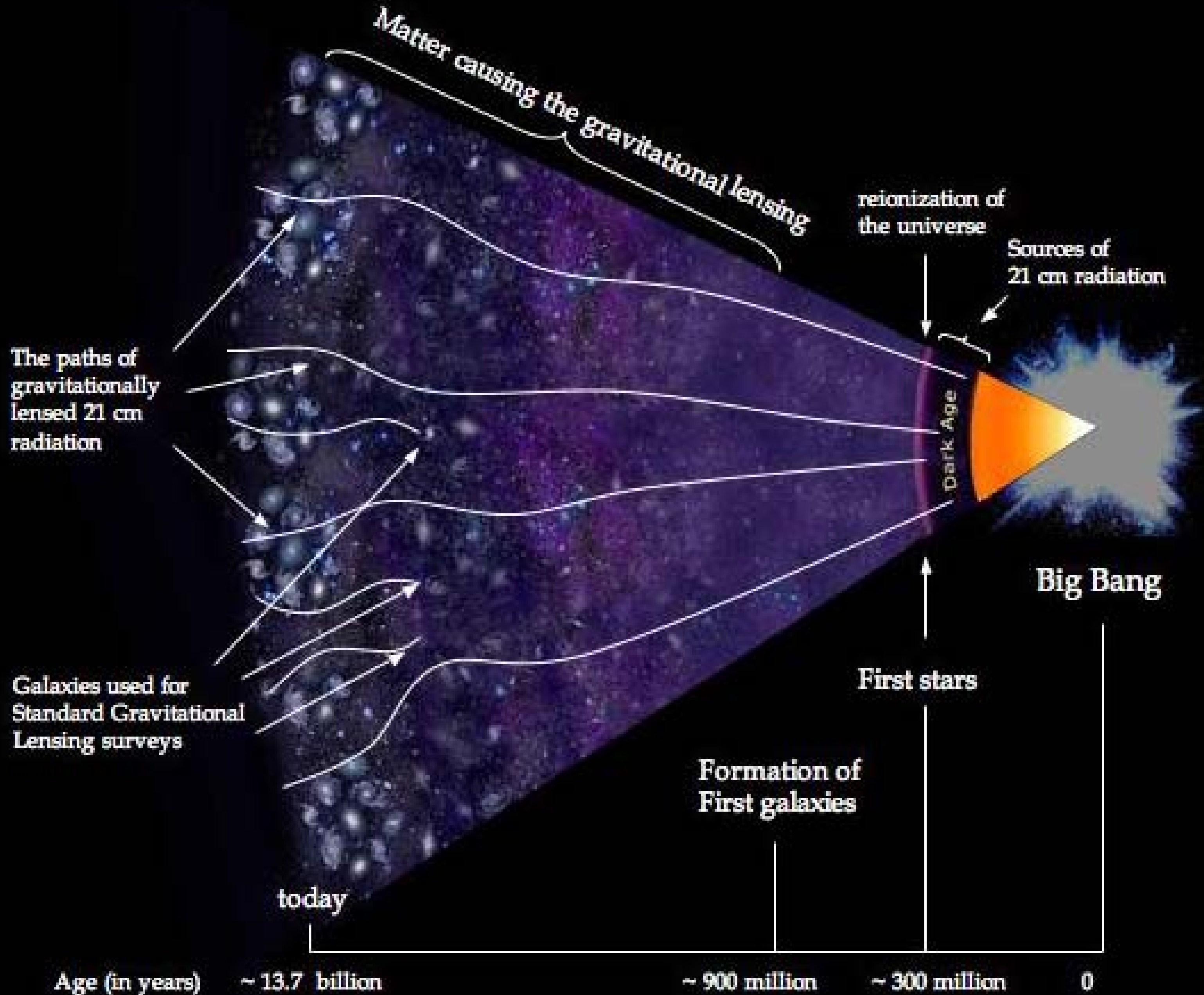


Probed by radio telescope arrays e.g., **LOFAR**, **MWA**, **SKA** (z < 20).

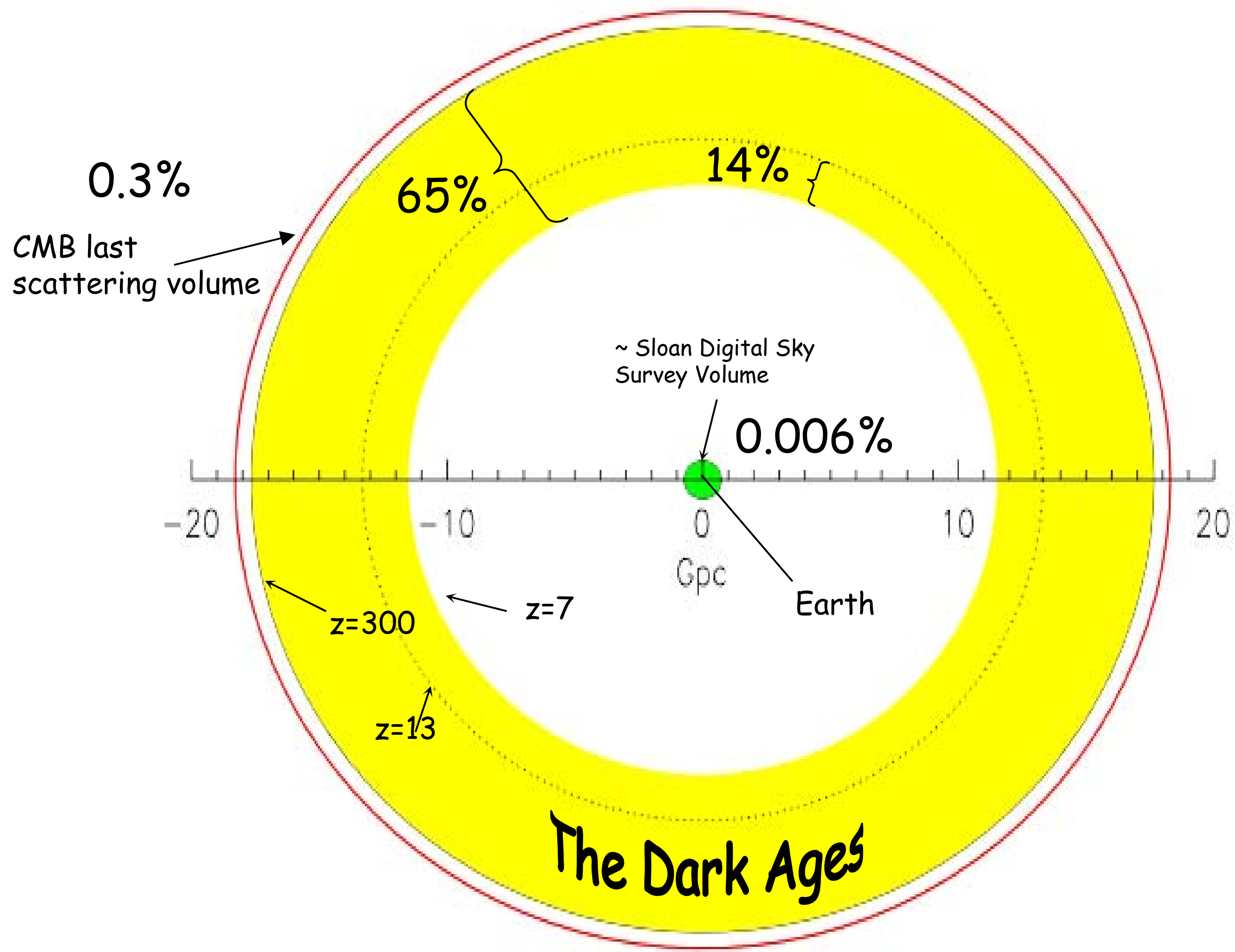
21cm intensity power spectrum

At 6 < z < 20 (reionisation epoch)

$$P_{21\,\mathrm{cm}}(k,z) \propto P_{\mathrm{matter}}(k,z) + \mathrm{reionisation\ \ physics}$$

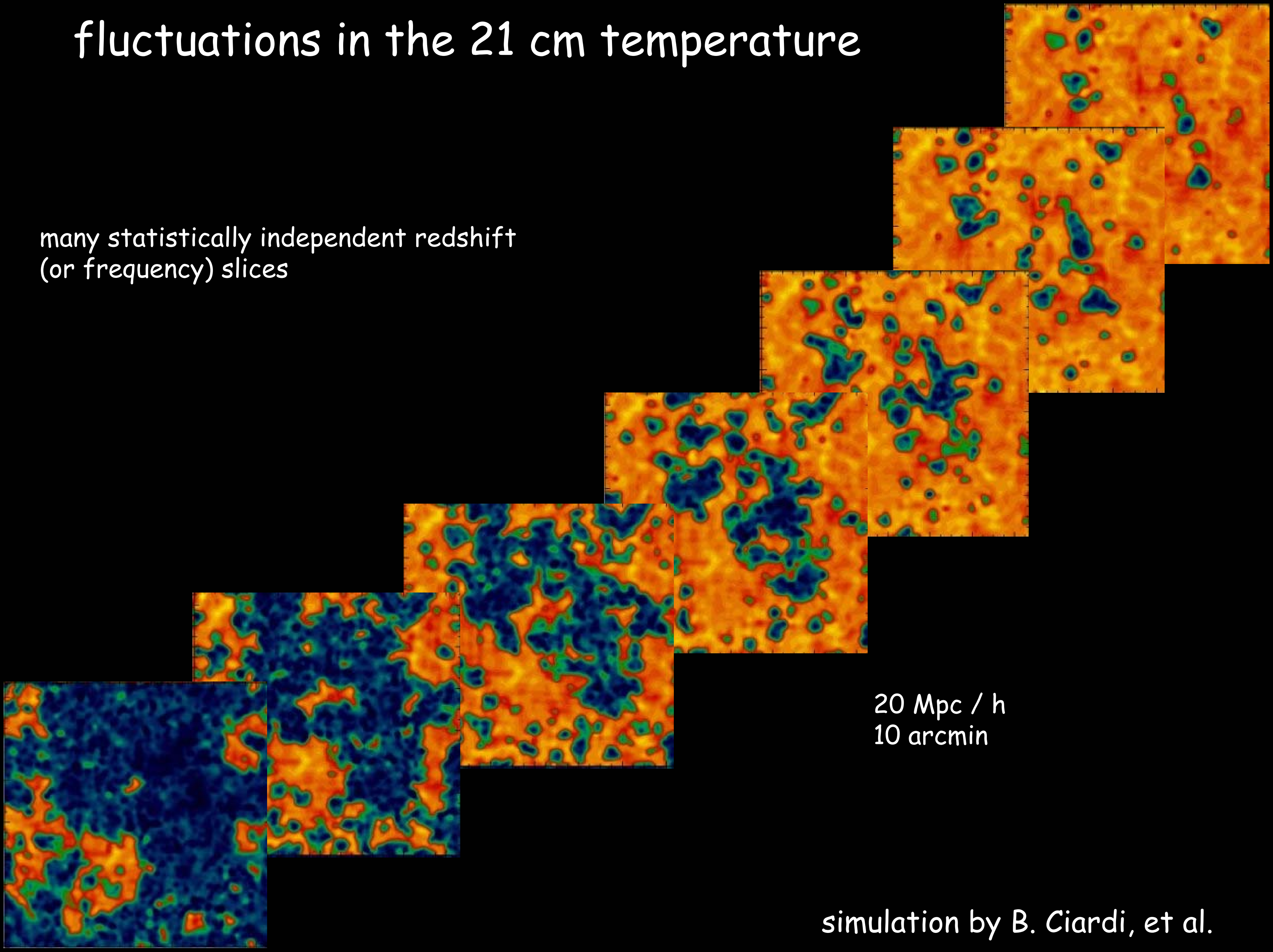

Matter causing the gravitational lensing
reionization of the universe
Sources of 21 cm radiation
The paths of gravitationally lensed 21 cm radiation
Dark Age
Big Bang
Galaxies used for Standard Gravitational Lensing surveys
First stars
Formation of First galaxies
today
Age (in years)
~ 13.7 billion
~ 900 million
~ 300 million
0

The Comoving Volume of the Universe



fluctuations in the 21 cm temperature

many statistically independent redshift
(or frequency) slices



20 Mpc / h
10 arcmin

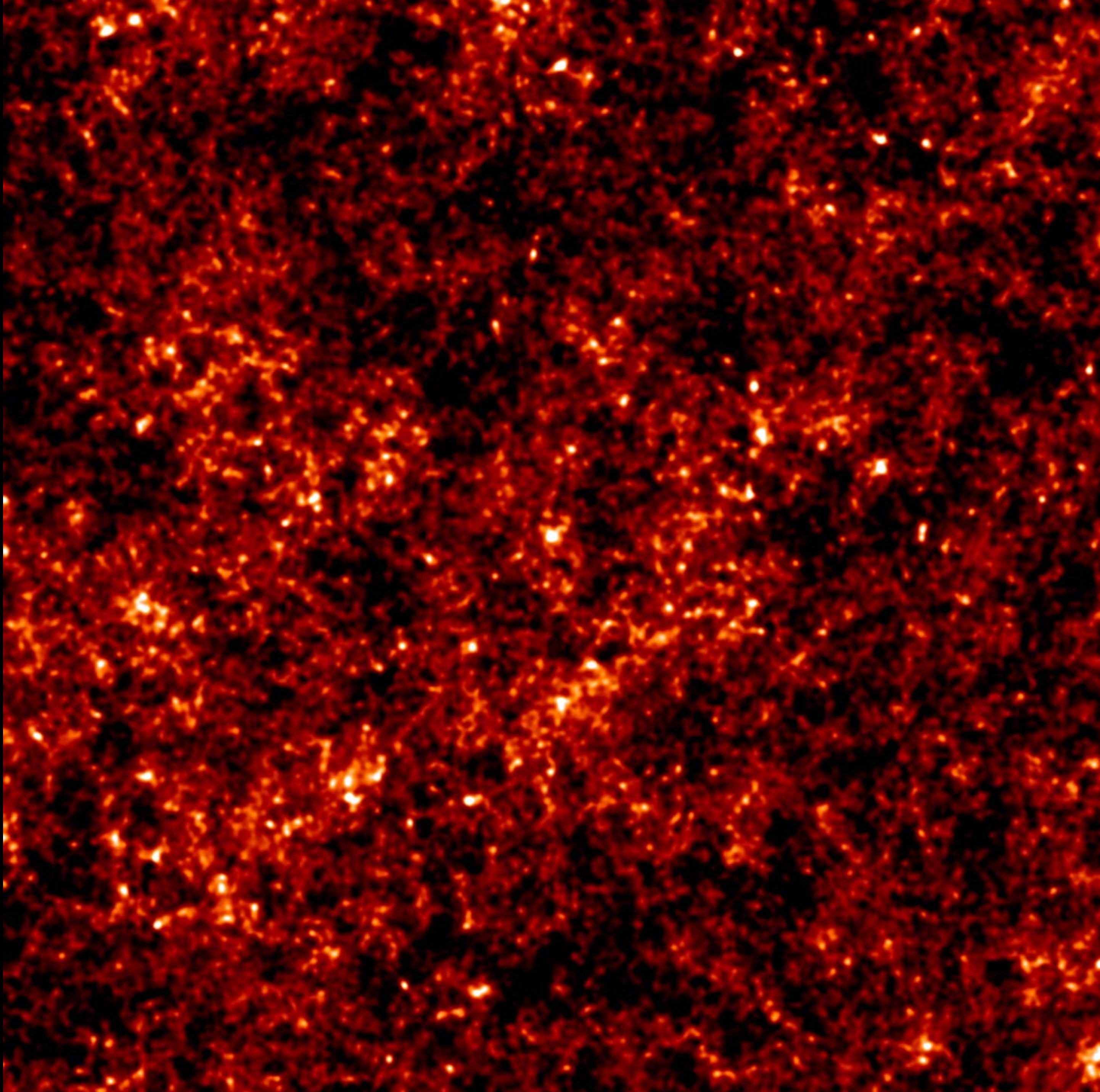
simulation by B. Ciardi, et al.

4 X 4 deg

Lensing through
The Millennium Simulation

21 cm Sources at z = 12
1' pixels

Hilbert, Metcalf
& White (2007)



2015

Under construction

Time

SKA
SQUARE KILOMETRE ARRAY

- **Planck+SKA** sensitivity:

Reionisation can be modelled and marginalised.

$$\Delta\left(\sum m_\nu\right) \sim 0.03 \rightarrow 0.1 \rightarrow 0.4\,\text{eV} \quad (95\,\%\,\text{C.L.})$$

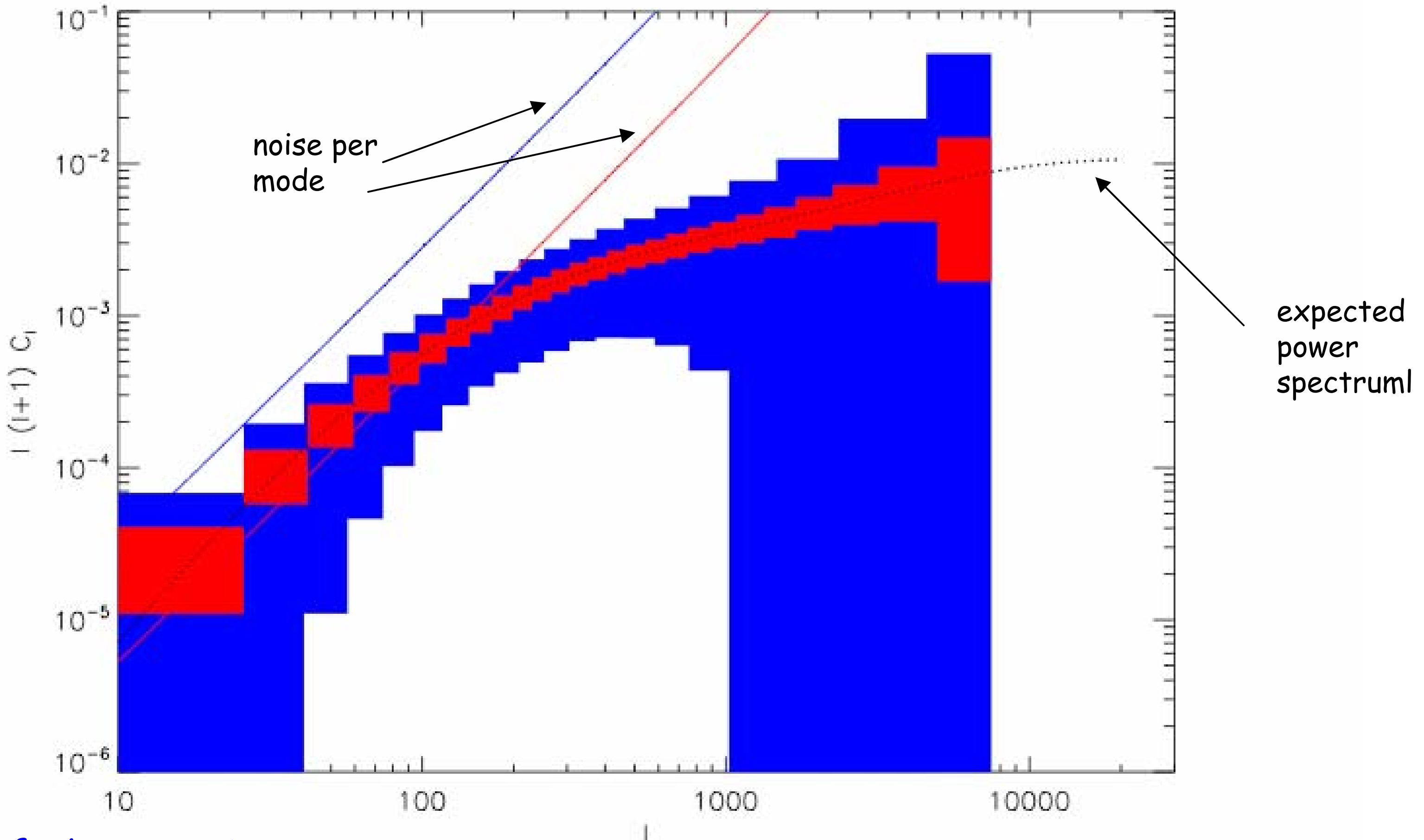
Precise knowledge of reionisation

No knowledge of reionisation

Mao, Tegmark, McQuinn, Zaldarriaga & Zahn, 2008

Convergence Power Spectrum Estimation

telescope like the core array of LOFAR



30 days of observations
90 days of observations

10% of the sky surveyed

D = 2 km with covering fraction of 1.6% ν_{min} = 110 Mhz
reionization at z=7