Title: Cosmology present status and future prospects

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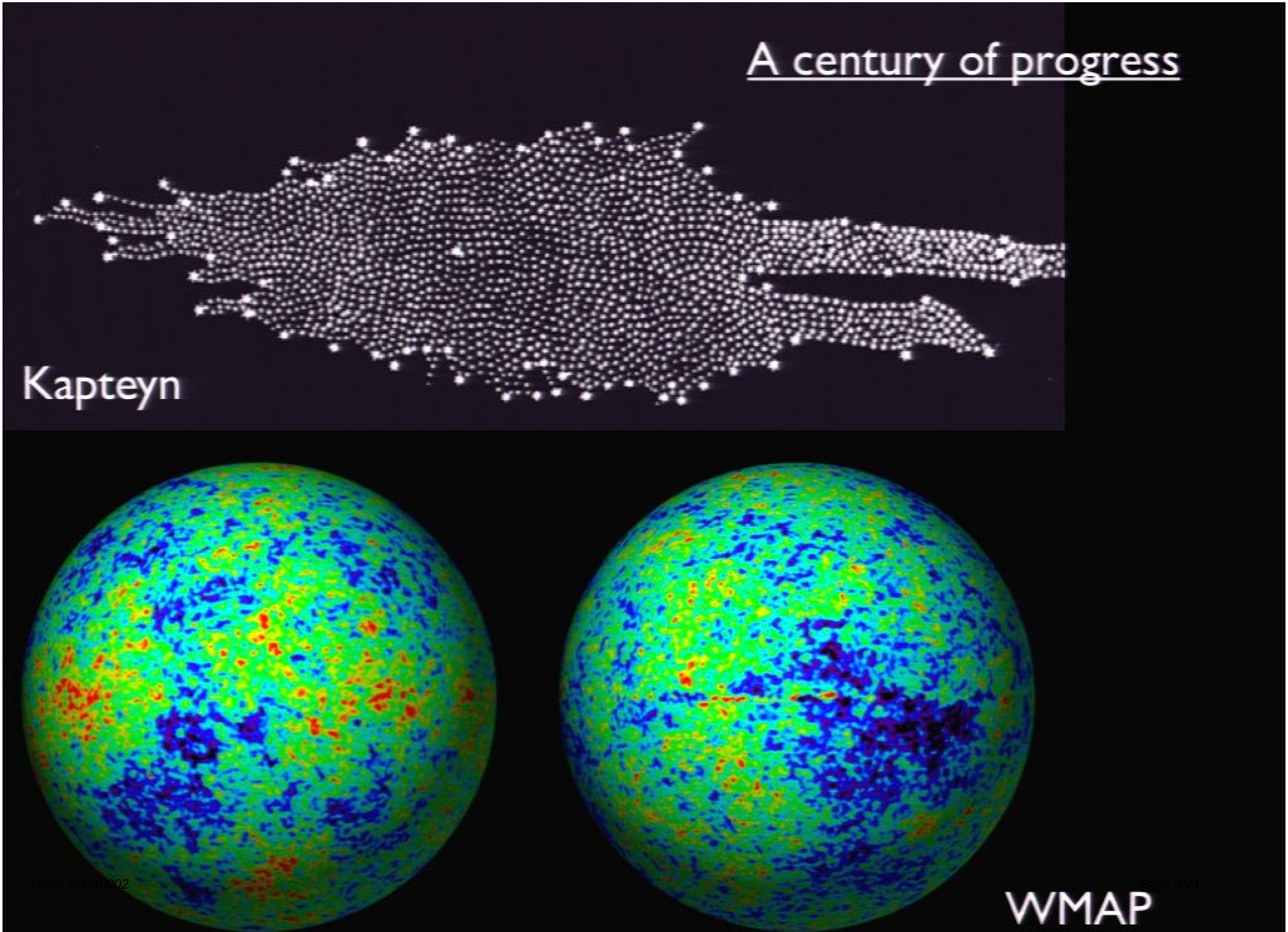
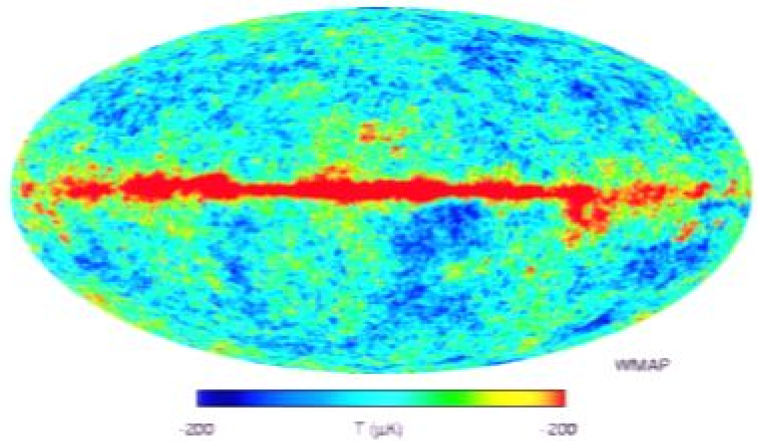
Abstract: I will summarize current observational constraints in cosmology with emphasis on what we have learned about the properties of the primordial density perturbations. I will describe future directions including observations of high redshift neutral hydrogen through is 21 cm line.

Cosmology: Present status and future prospects

Matias Zaldarriaga


A century of progress
Kapteyn
WMAP

The Era of Precision Cosmology



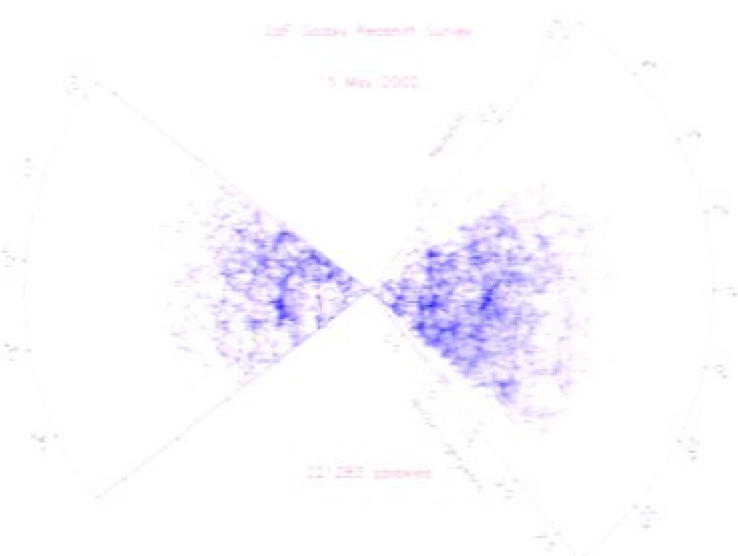


Table 6. Cosmological Parameter Summary

Description	Symbol	WMAP-only	WMAP+BAO+SN
Parameters for Standard ΛCDM Model [a]			
Age of universe	t_0	13.69 ± 0.13 Gyr	13.73 ± 0.12 Gyr
Hubble constant	H_0	$71.9^{+2.6}_{-2.7}$ km/s/Mpc	70.1 ± 1.3 km/s/Mpc
Baryon density	Ω_b	0.0441 ± 0.0030	0.0462 ± 0.0015
Physical baryon density	$\Omega_b h^2$	0.02273 ± 0.00062	0.02265 ± 0.00059
Dark matter density	Ω_c	0.214 ± 0.027	0.233 ± 0.013
Physical dark matter density	$\Omega_c h^2$	0.1099 ± 0.0062	0.1143 ± 0.0034
Dark energy density	Ω_Λ	0.742 ± 0.030	0.721 ± 0.015
Curvature fluctuation amplitude, $k_0 = 0.002$ Mpc^{-1} [b]	$\Delta^2_{\mathcal{R}}$	$(2.41 \pm 0.11) \times 10^{-9}$	$(2.457^{+0.092}_{-0.093}) \times 10^{-9}$
Fluctuation amplitude at $8h^{-1}$ Mpc	σ_8	0.796 ± 0.036	0.817 ± 0.026
$l(l+1)C^{TT}_{220}/2\pi$	C_{220}	5756 ± 42 μK^2	5748 ± 41 μK^2
Scalar spectral index	n_s	$0.963^{+0.014}_{-0.015}$	$0.960^{+0.014}_{-0.013}$
Redshift of matter-radiation equality	z_{eq}	3176^{+151}_{-150}	3280^{+88}_{-89}
Angular diameter distance to matter-radiation eq.[c]	$d_A(z_{eq})$	14279^{+186}_{-189} Mpc	14172^{+141}_{-139} Mpc
Redshift of decoupling	z_*	1090.51 ± 0.95	$1091.00^{+0.72}_{-0.73}$
Age at decoupling	t_*	380081^{+5843}_{-5841} yr	375938^{+3148}_{-3115} yr
Angular diameter distance to decoupling [c,d]	$d_A(z_*)$	14115^{+188}_{-191} Mpc	14006^{+142}_{-141} Mpc
Sound horizon at decoupling [d]	$r_s(z_*)$	146.8 ± 1.8 Mpc	145.6 ± 1.2 Mpc
Acoustic scale at decoupling [d]	$l_A(z_*)$	$302.08^{+0.83}_{-0.84}$	$302.11^{+0.84}_{-0.82}$
Reionization optical depth	τ	0.087 ± 0.017	0.084 ± 0.016
Redshift of reionization	z_{reion}	11.0 ± 1.4	10.8 ± 1.4
Age at reionization	t_{reion}	427^{+88}_{-65} Myr	432^{+90}_{-67} Myr
Parameters for Extended Models [e]			
Total density [f]	Ω_{tot}	$1.099^{+0.100}_{-0.085}$	1.0052 ± 0.0064
Equation of state [g]	w	$-1.06^{+0.41}_{-0.42}$	$-0.972^{+0.061}_{-0.060}$
Tensor to scalar ratio, $k_0 = 0.002$ Mpc^{-1} [b,h]	r	< 0.43 (95% CL)	< 0.20 (95% CL)
Running of spectral index, $k_0 = 0.002$ Mpc^{-1} [b,i]	$dn_s/d\ln k$	-0.037 ± 0.028	$-0.032^{+0.021}_{-0.020}$
Neutrino density [j]	$\Omega_\nu h^2$	< 0.014 (95% CL)	< 0.0065 (95% CL)
Neutrino mass [j]	$\sum m_\nu$	< 1.3 eV (95% CL)	< 0.61 eV (95% CL)
Number of light neutrino families [k]	N_{eff}	> 2.3 (95% CL)	4.4 ± 1.5

[a] The parameters reported in the first section assume the 6 parameter ΛCDM model, first using WMAP data only, then using WMAP+BAO+SN data.

[b] $k = 0.002$ Mpc^{-1} ⟷ $l_{eff} \approx 30$.

[c] Comoving angular diameter distance

"Cosmologists are often in error, though never in doubt." -- Lev Landau

Not everything is yet settled:

- Matter budget: Dark matter/Dark energy
- Early universe: How were the initial seeds created?
- Non-linear physics: Galaxy formation and evolution,

reionization, the first stars

The matter content

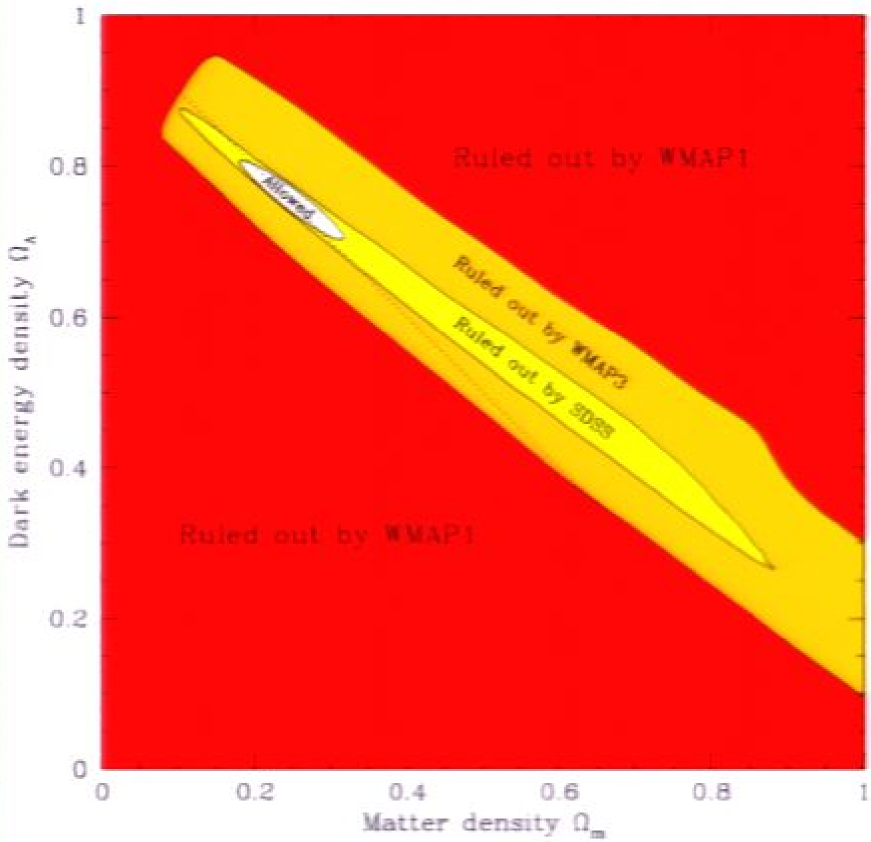


FIG. 15: 95% constraints in the $(\Omega_m, \Omega_\Lambda)$ plane. The large shaded regions are ruled out by WMAP1 (red/dark grey) and WMAP3 (orange/grey) when spatial curvature is added to the 6 vanilla parameters, illustrating the well-known geometric degeneracy between models that all give the same acoustic peak locations in the CMB power spectrum. The yellow/light grey region is ruled out when adding SDSS LRG information, breaking the degeneracy mainly by measuring the acoustic peak locations in the galaxy power spectrum. Models on the diagonal dotted line are flat, those below are open and those above are closed. Here the yellow banana has been cut off from below by an $h \gtrsim 0.4$ prior in the CosmoMC software.

The Universe appears to be flat with the energy density dominated by a fluid with equation of state

$$w = -1.004 \pm 0.089$$

0705.3323 (Percival et al.) using BAOs

Dark matter is required to explain the shape of the CMB peaks as well as LSS.
The baryon fraction inferred from the CMB is consistent with BBN.

Windows into the inflationary epoch:

We now know for a fact that perturbations had to be created during inflation. Which properties of the perturbations can be used to test the model?

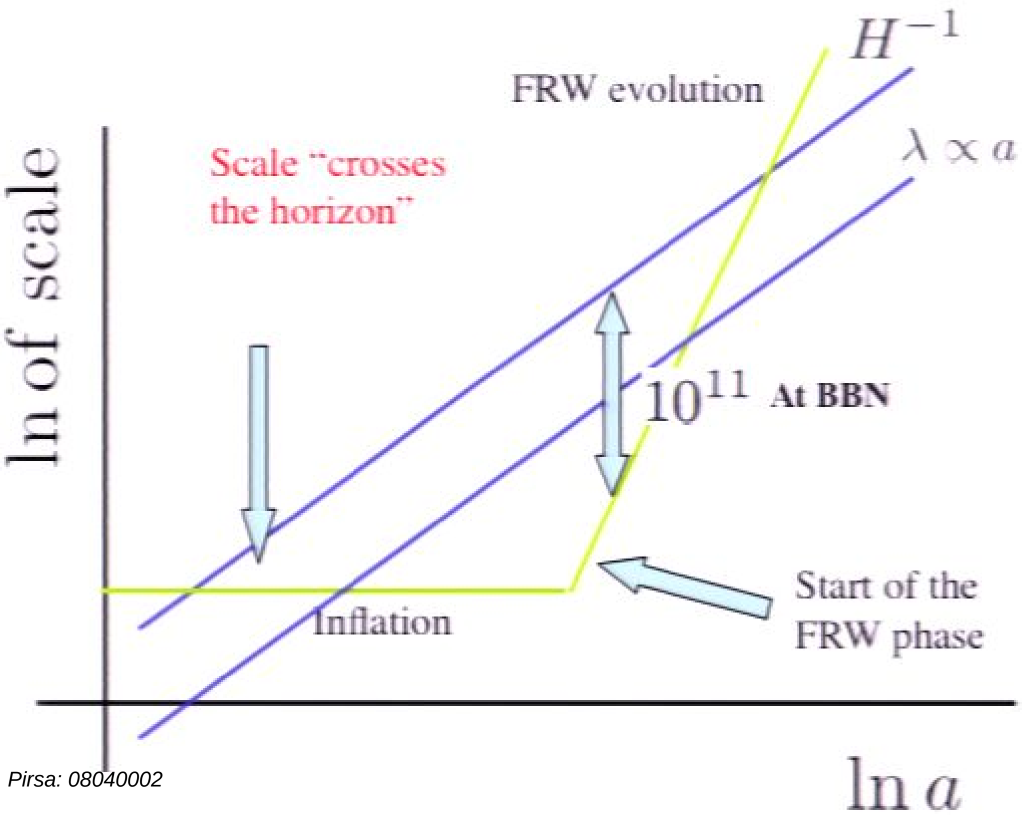
1. Departures from scale invariance of the density perturbations
2. Gravity waves
3. Departures from Gaussianity
4. Isocurvature fluctuations
5. Relics such as cosmic strings

- CMB experiments: WMAP, Planck, CMBPOL, SPT, ACT, etc
- Smaller scales from Lyman alpha forest, lensing, SZ, etc.

Push to smaller scales to have more modes and measure polarization to look for Gravity Waves

When were perturbations created?

The data definitively shows that they were created during Inflation



$$H = \frac{\dot{a}}{a}$$

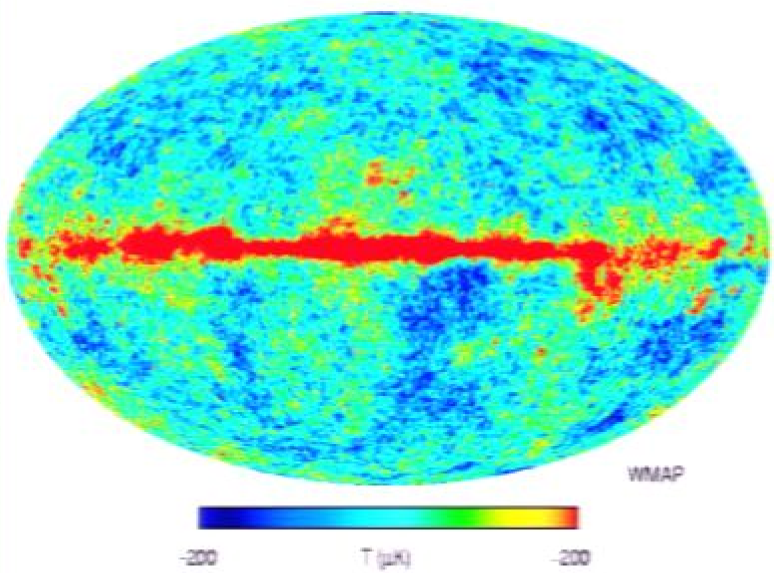
$$R_H \sim H^{-1}$$

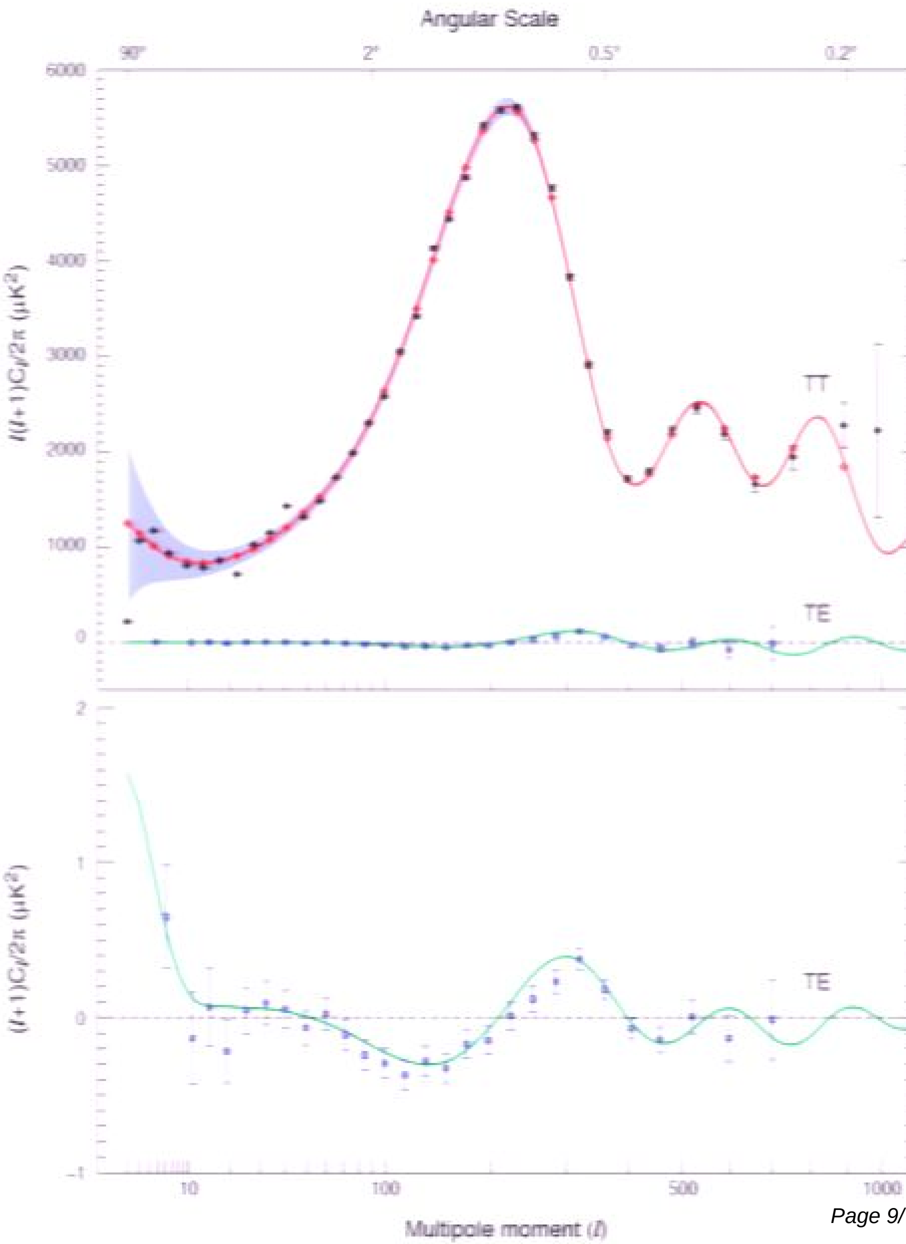
$$\lambda = \lambda_0 a$$

$$\frac{\lambda}{R_H} = \lambda_0 a H \propto \dot{a}$$

Gravity is attractive so $\dot{a}$ usually decreases

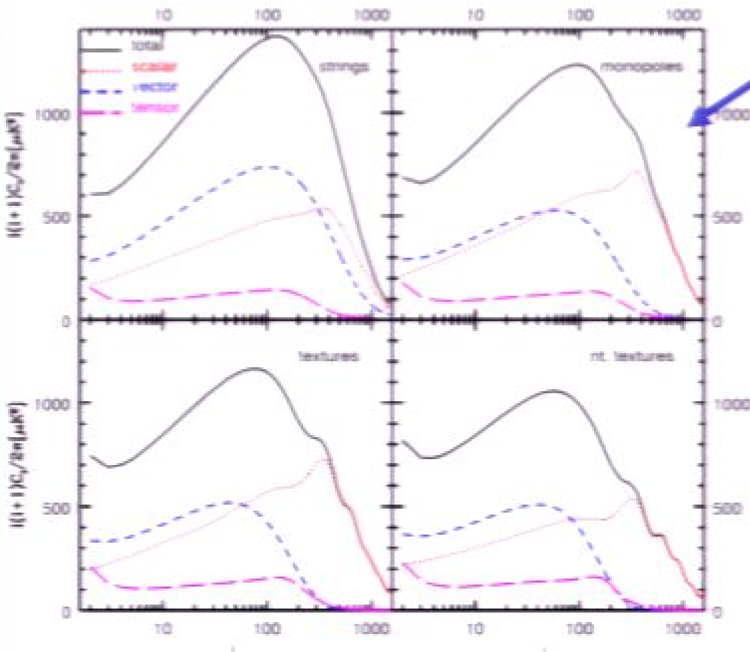
Power Spectrum





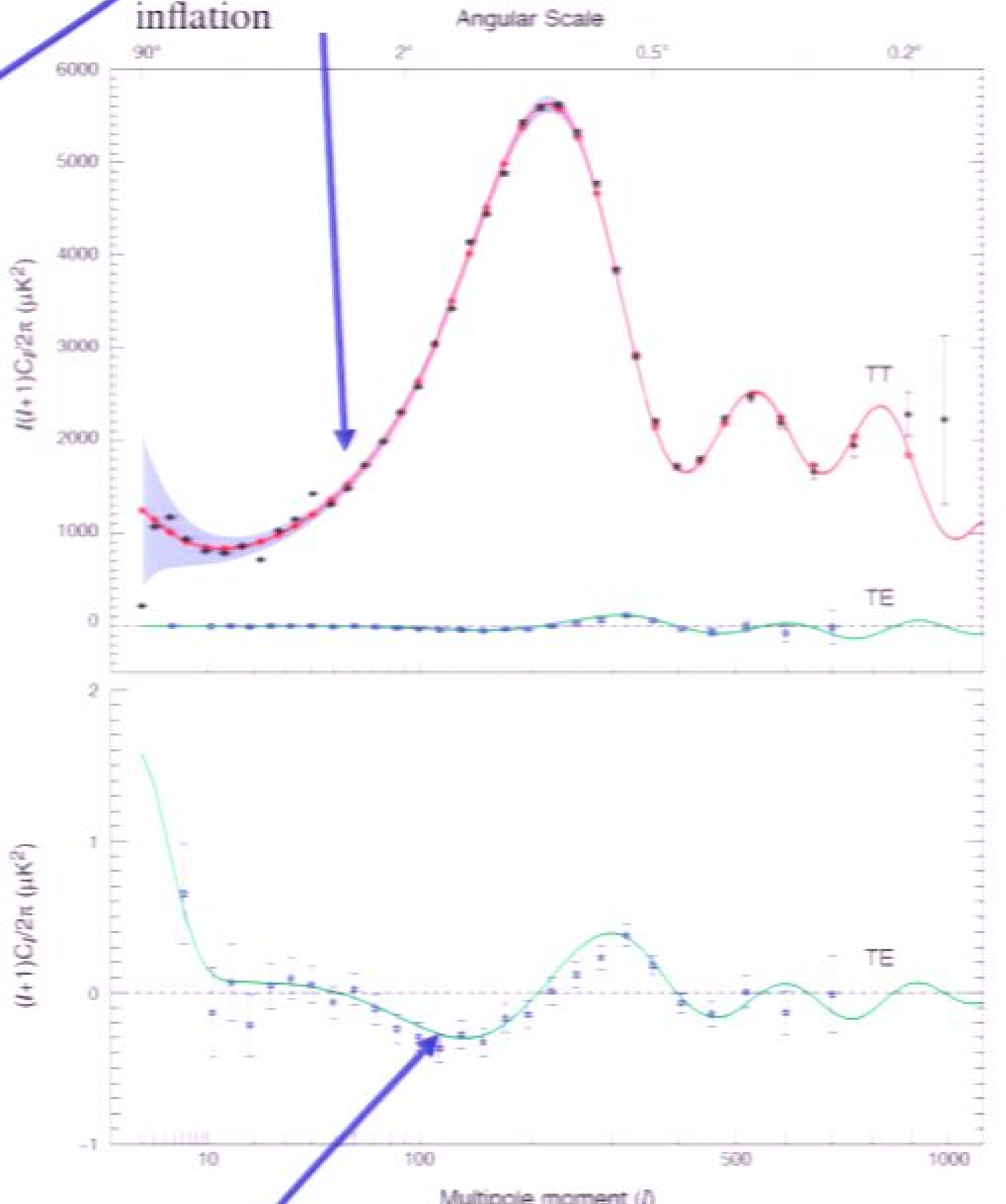
When were perturbations created?

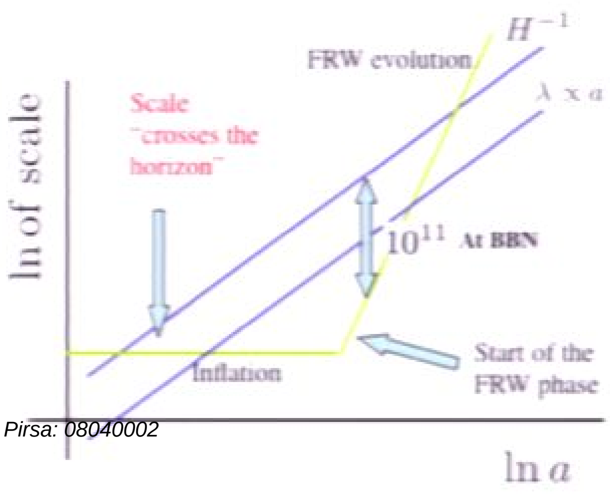
Causal Seeds Pen, Seljak & Turok (1997)



Sharp acoustic peaks are difficult to create without inflation

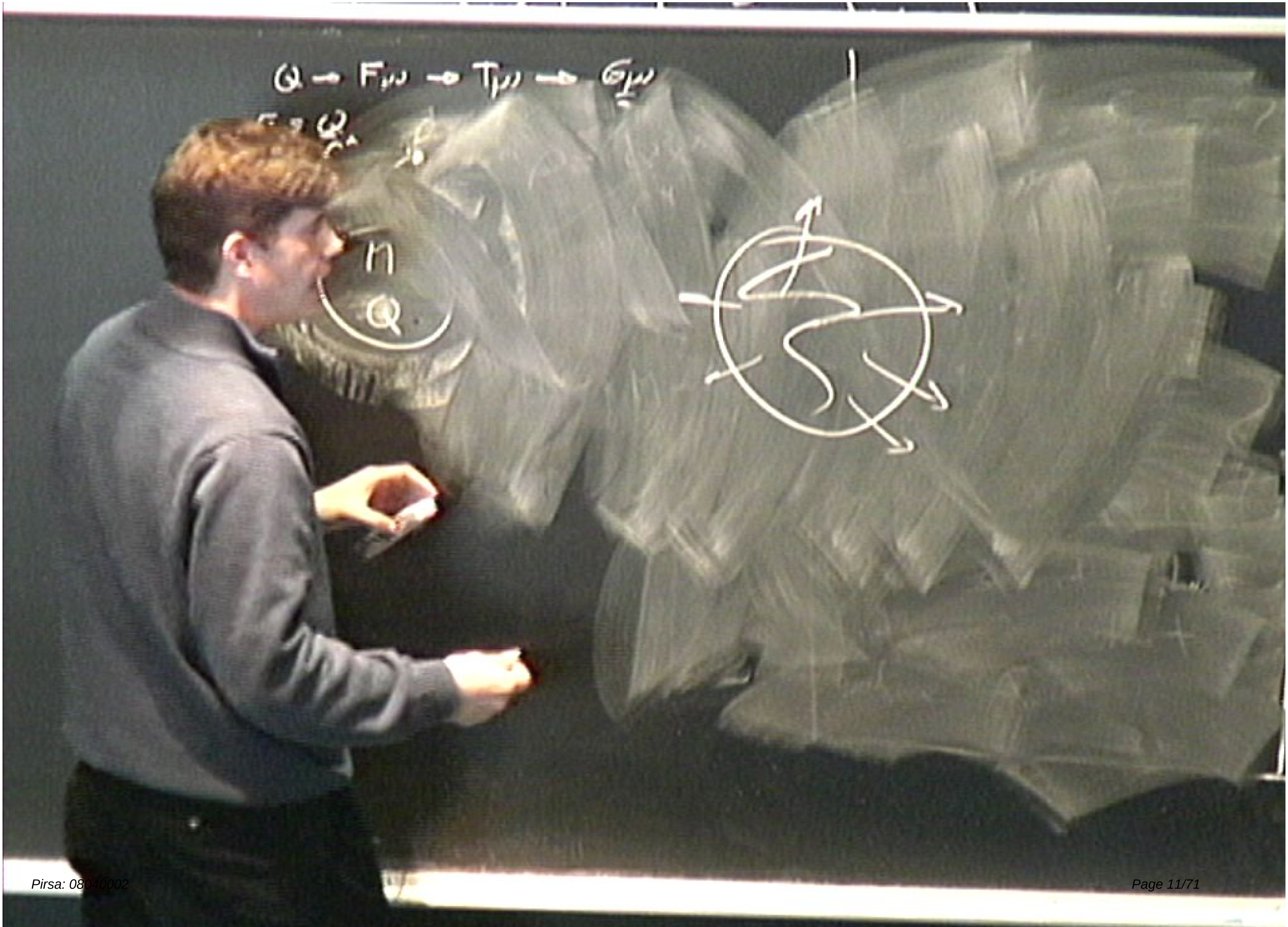
WMAP 3yrs





Negative peak imply fluctuations come from outside horizon

Hu & White (1996)
Spergel & MZ (1997)
Pieris et al WMAP (2003)


$Q \rightarrow F_{\mu\nu} \rightarrow T_{\mu\nu} \rightarrow G_{\mu\nu}$
M
Q

The shape of the power spectrum

Standard inflation predicts departures from scale invariance, although small

ratio of the size of fluctuations at two different scales, with wave-numbers k1 and k2

$$n - 1 \sim 1/N_{efold} \sim 0.02$$

$$\frac{P(k_1)}{P(k_2)} = (\frac{k_1}{k_2})^{n-1}$$

$(400)^{n-1} \sim 1.3$ $\quad (1500)^{n-1} \sim 1.4$ $\quad (10^4)^{n-1} \sim 1.6$

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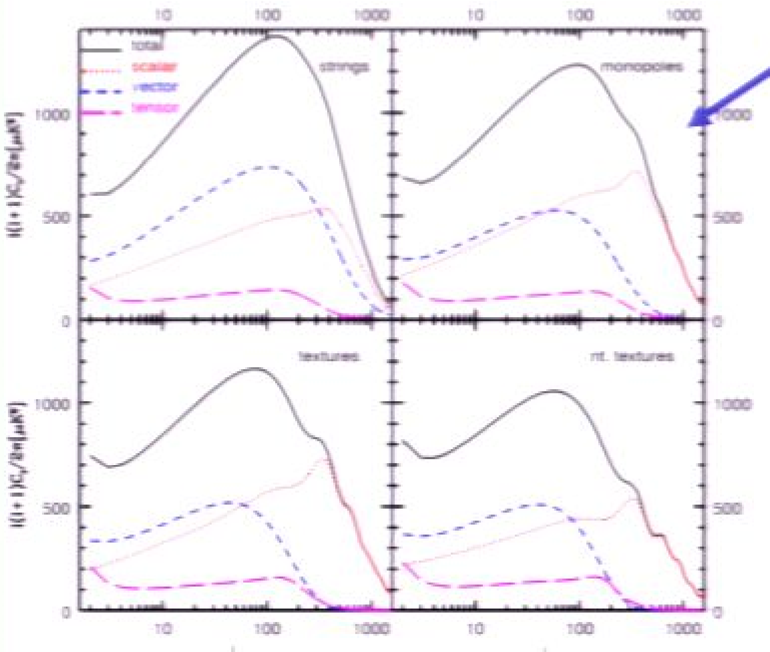

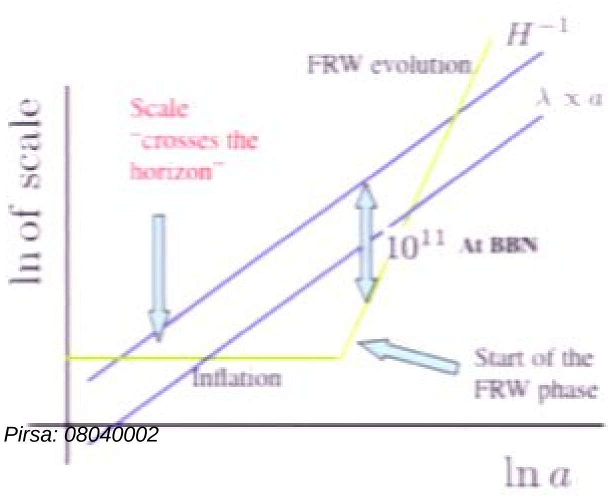

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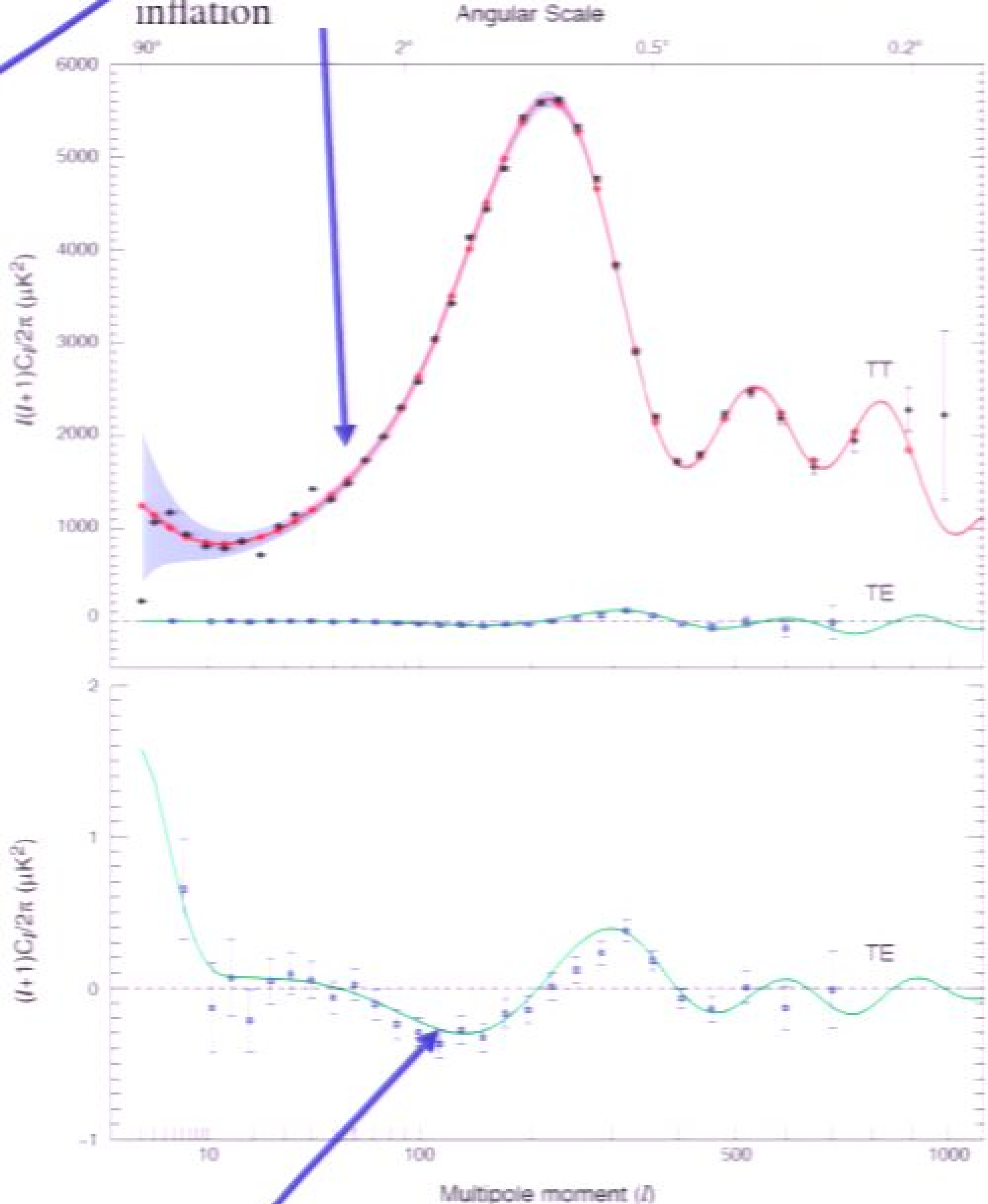

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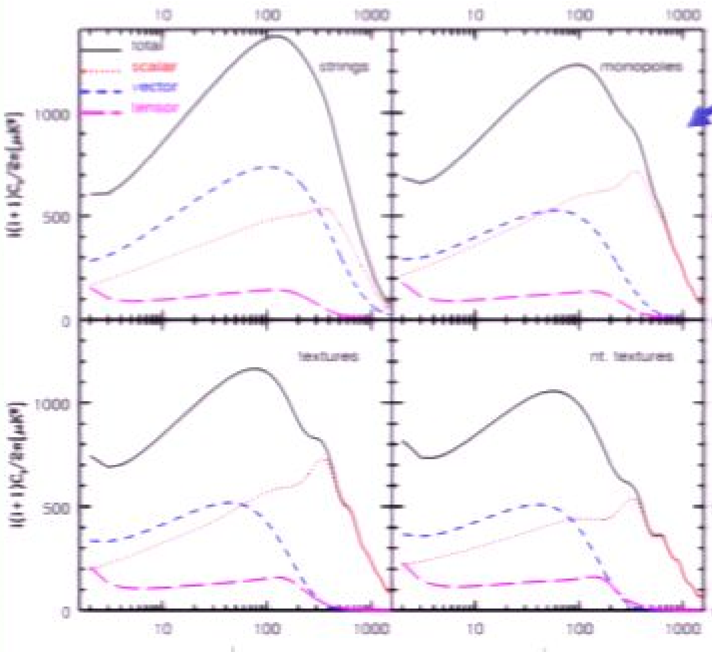

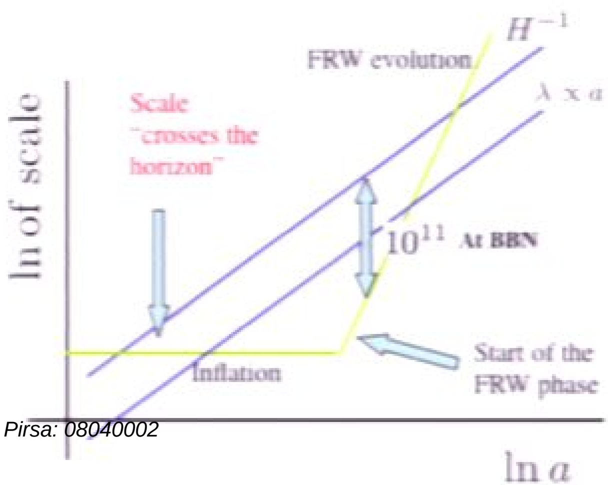

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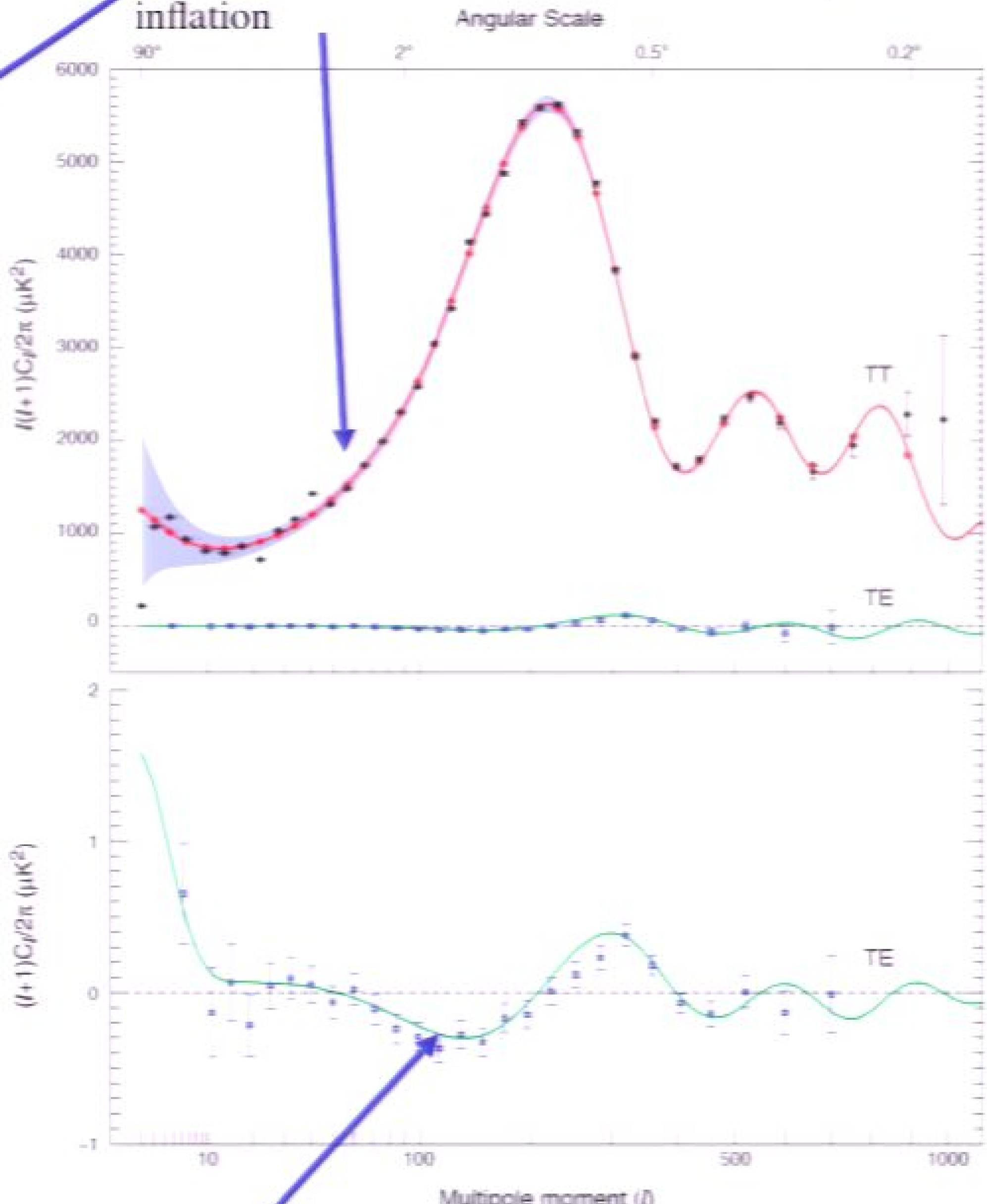

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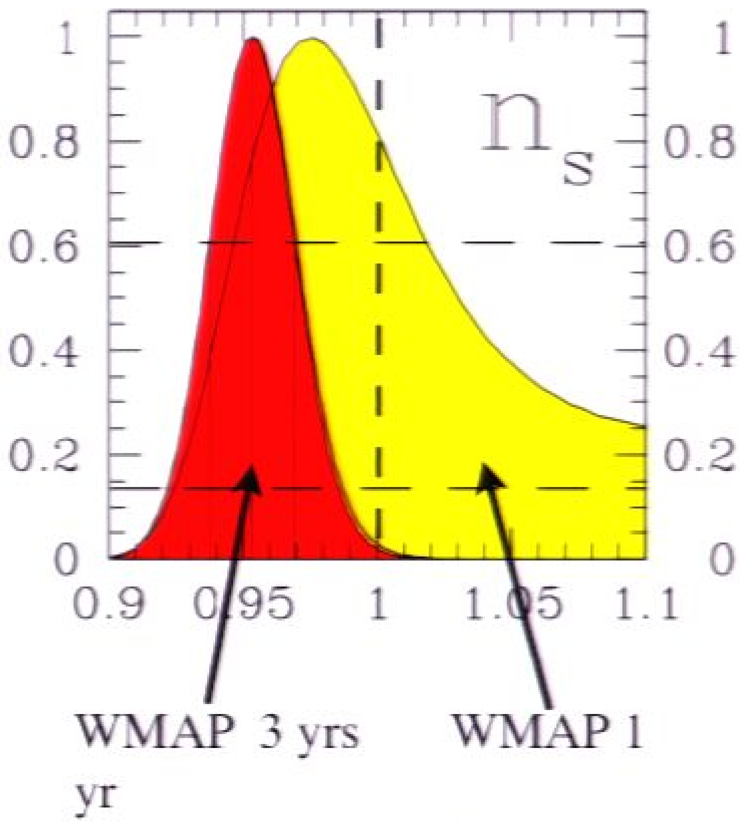
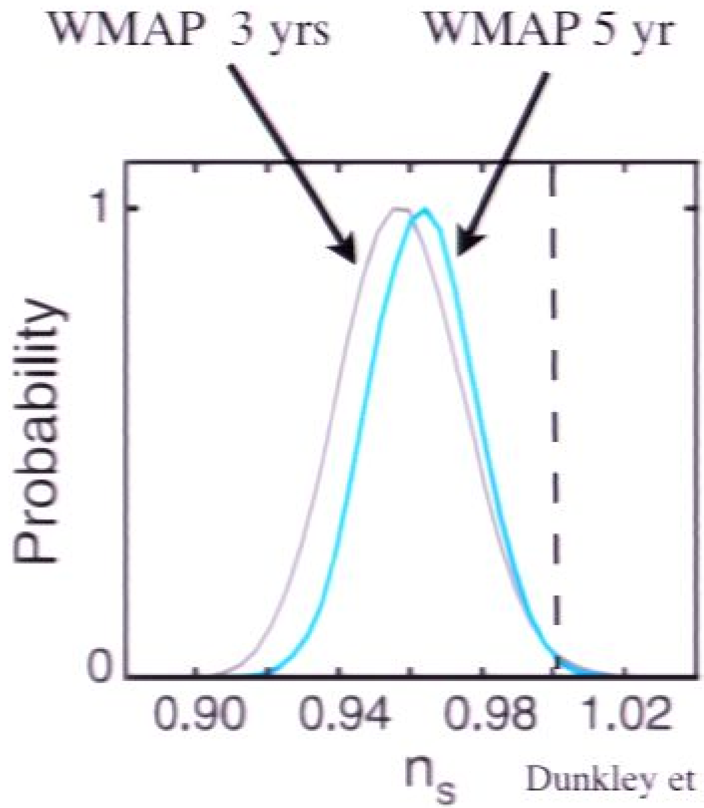
Departures from scale invariance after 3 yrs of WMAP



n_s	WMAP	$0.954^{+0.017}_{-0.016}$
	+SDSS	$0.953^{+0.016}_{-0.016}$

Tegmark et al astro-ph/0608632



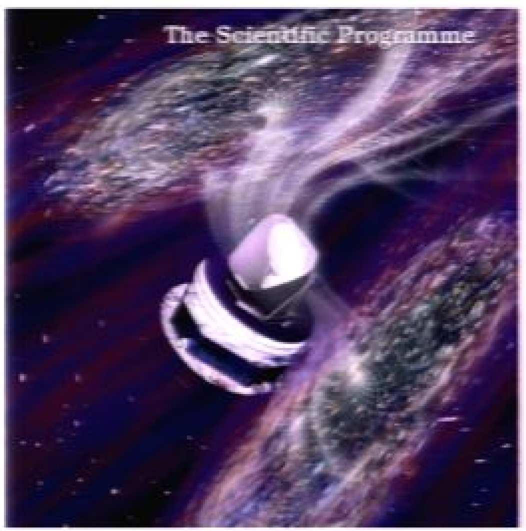
Dunkley et al WMAP 5 yrs

Several technical issues remain unsolved that appear to change the significance of this result (eg. different treatments of point sources can make n<1 be only a 1.8 σ result 0710.1873).

There are tensions between WMAP other probes such as the Lyman α forest, etc.

The future is even brighter: Ground base experiments, Planck

PLANCK



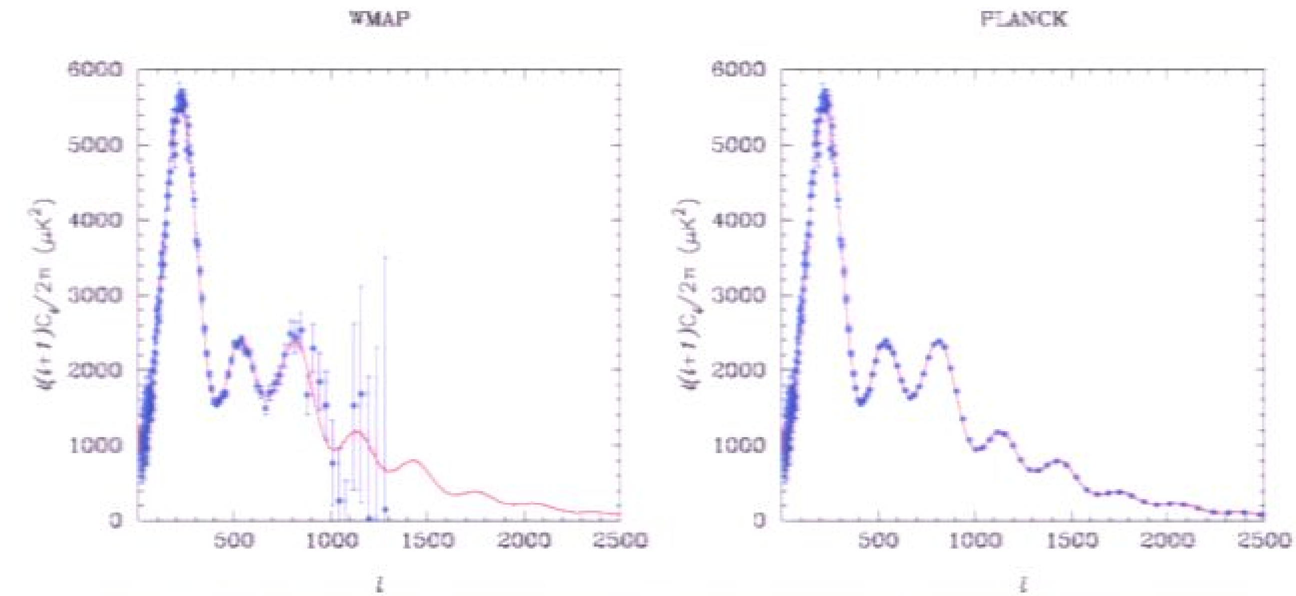
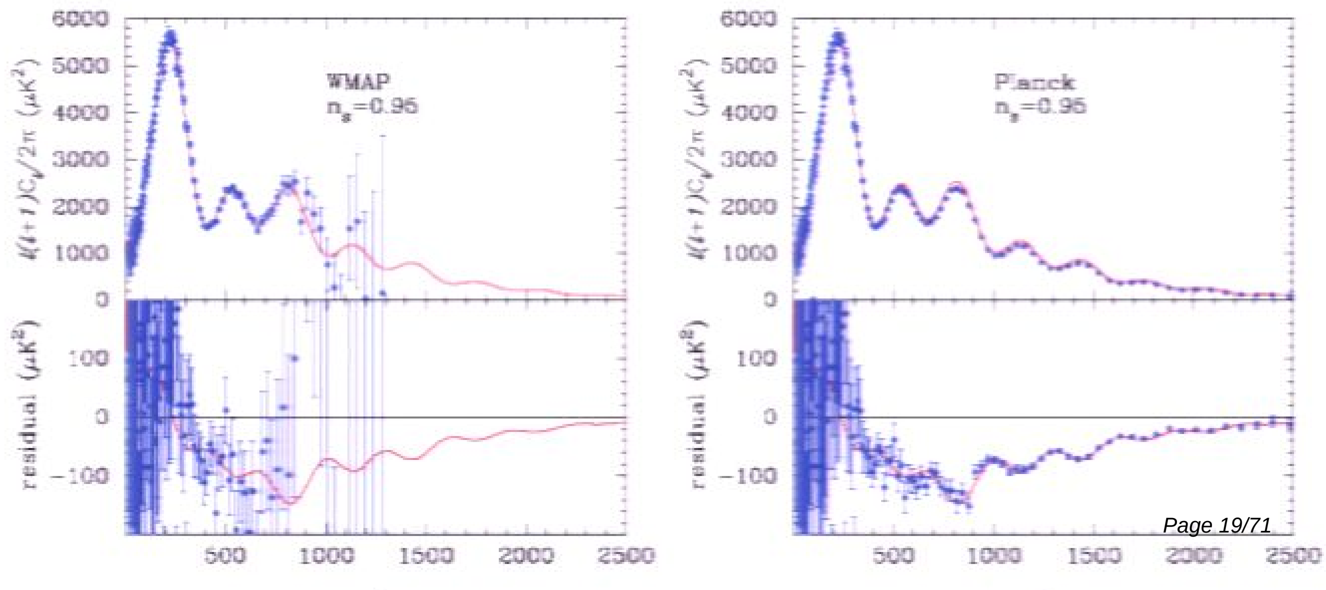


FIG 2.8.—The left panel shows a realisation of the CMB power spectrum of the concordance ΛCDM model (red line) after 4 years of *WMAP* observations. The right panel shows the same realisation observed with the sensitivity and angular resolution of *Planck*.



The energy scale of inflation: gravitational waves

Inflation predicts the presence of a stochastic Background of Gravitational Waves

$$h_{ij} \sim \frac{H}{M_{PL}}$$

If $\frac{H}{M_{PL}} \sim 10^{-5}$ → Comparable to density perturbations

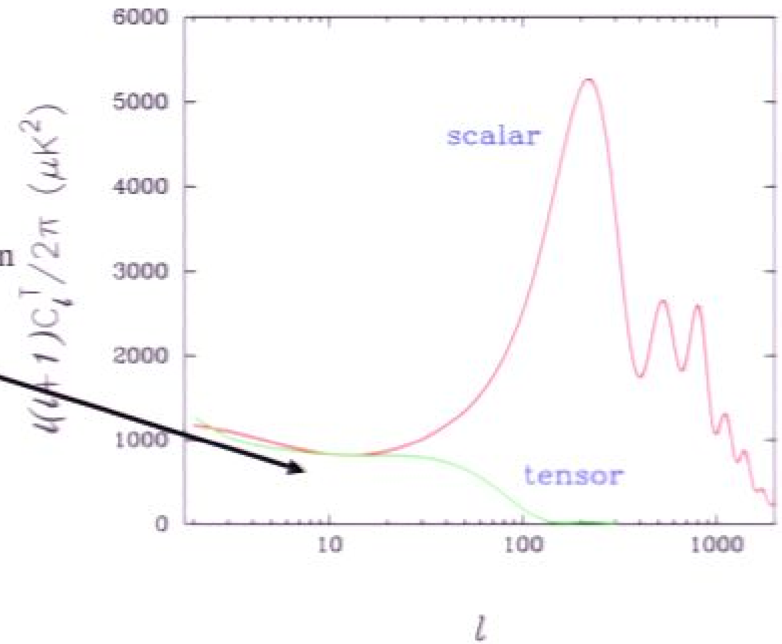
Directly measure the expansion rate during Inflation.

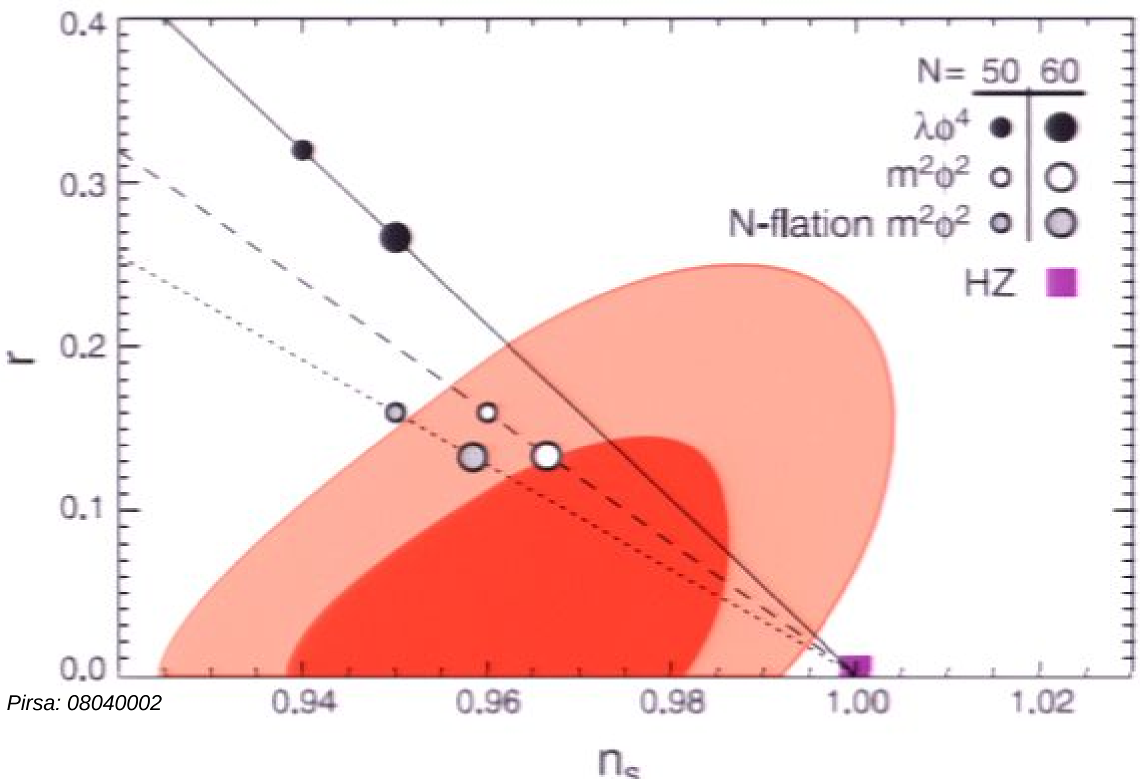
This measurement has taken a greater significance now that it appears that GW might not be observable in "string-inflation".

Current constraints from WMAP 5 yrs

Current constraints come from fitting the shape of the temperature power spectrum.

r is ratio of contributions on large scales

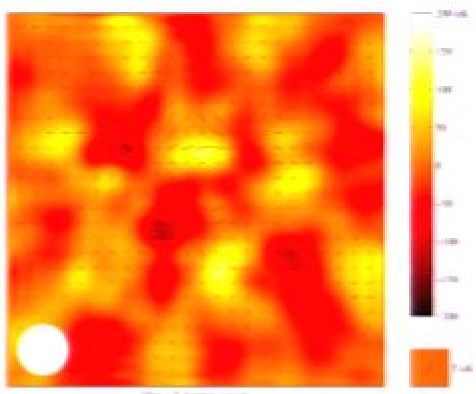




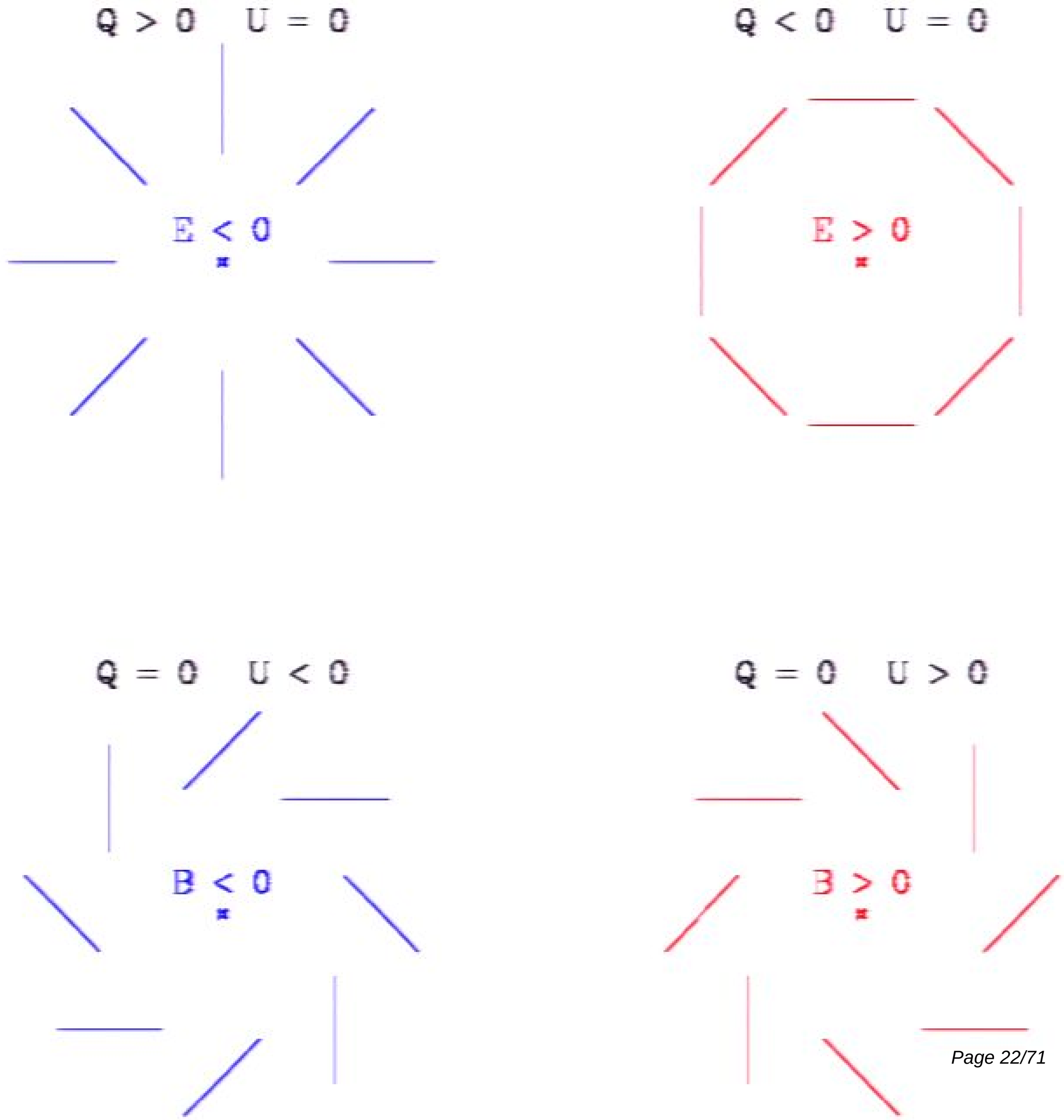
CMB probes a narrow range of energy scales

The future of GW constraints: Polarization

Density pert.
&
Gravity Waves

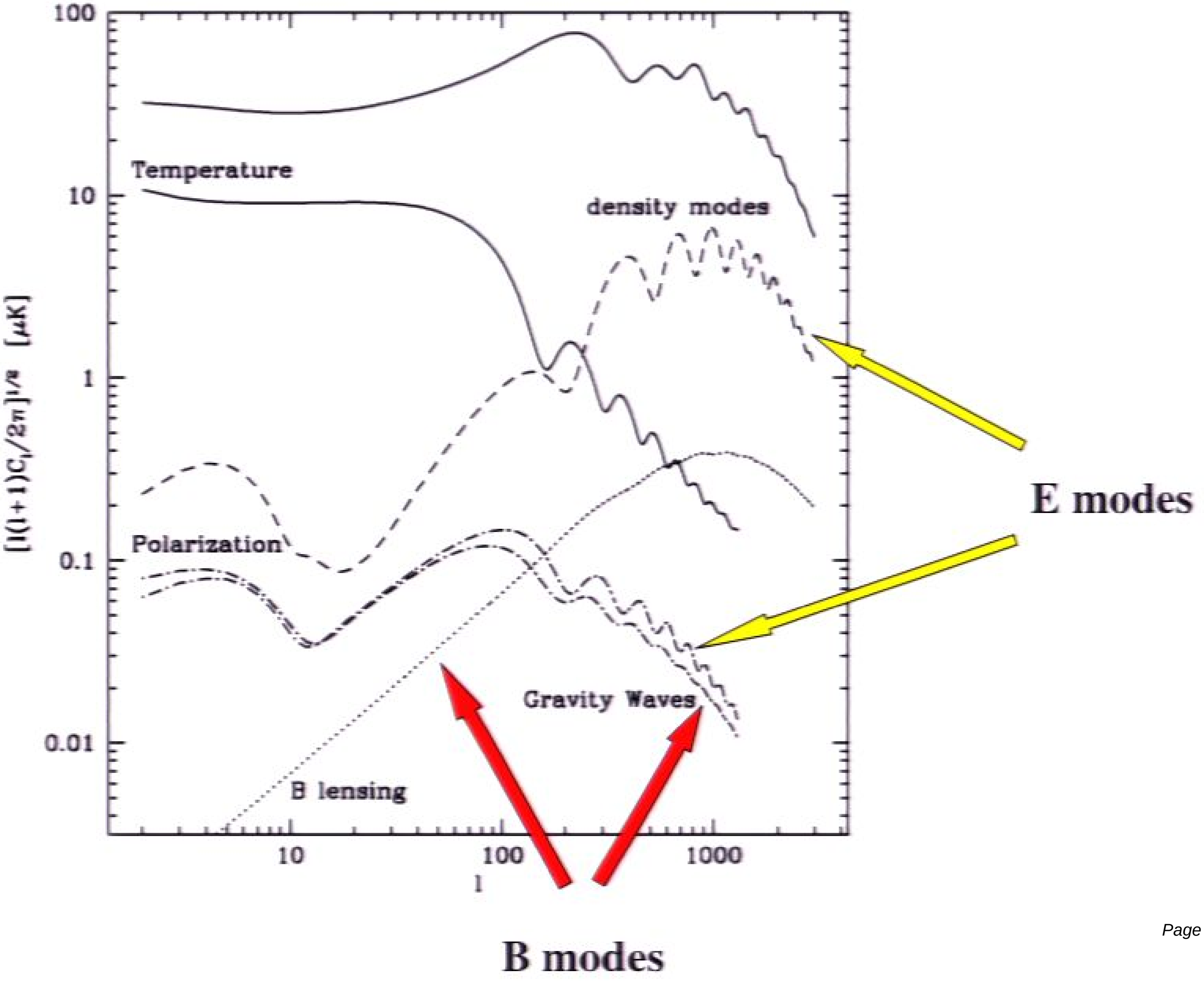


Gravity
Waves



Seljak & MZ
Kamionkowski Kosowsky & Stebbins

Power spectra of E & B



Which experiment will first constrain Gravity waves using B modes?

Examples

Running

Future

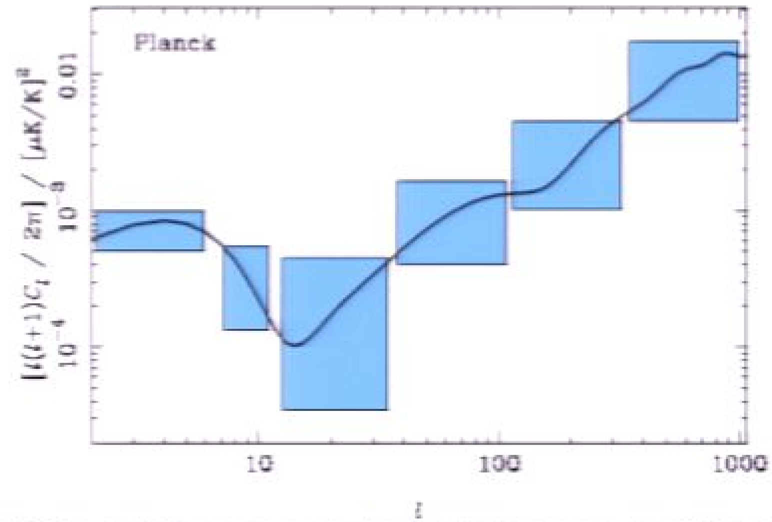
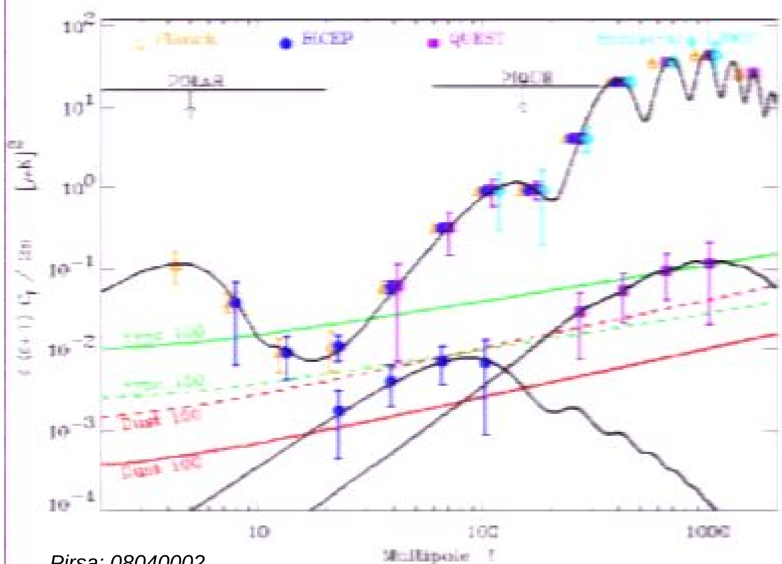


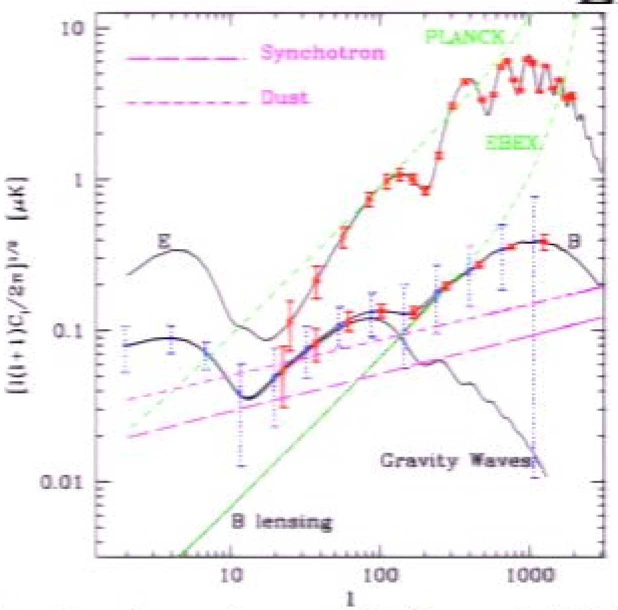
FIG 2.17.—Forecasts for the $\pm1\sigma$ errors on the B-mode polarisation power spectrum C_ℓ^B from *Planck* (for $r = 0.1$ and $r = 0.17$). Above $\ell \sim 150$ the primary spectrum is swamped by weak gravitational lensing of the E-polarisation produced by the dominant scalar perturbations. The cosmological model, and the assumptions about instrument characterisation, are the same as in Figure 2.13.

Bicep



1500 sq deg.. 42 arcmin res. 2 Freq. 100. 150 GHz

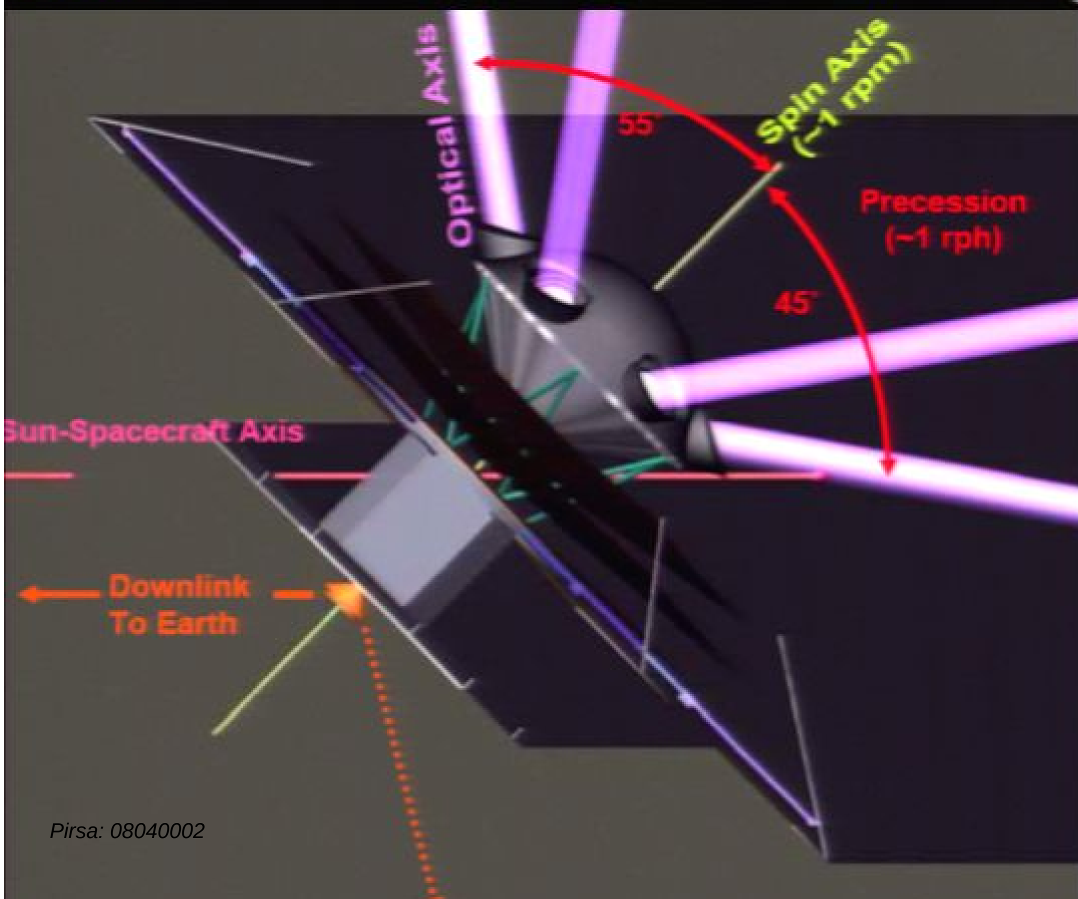
EBEX

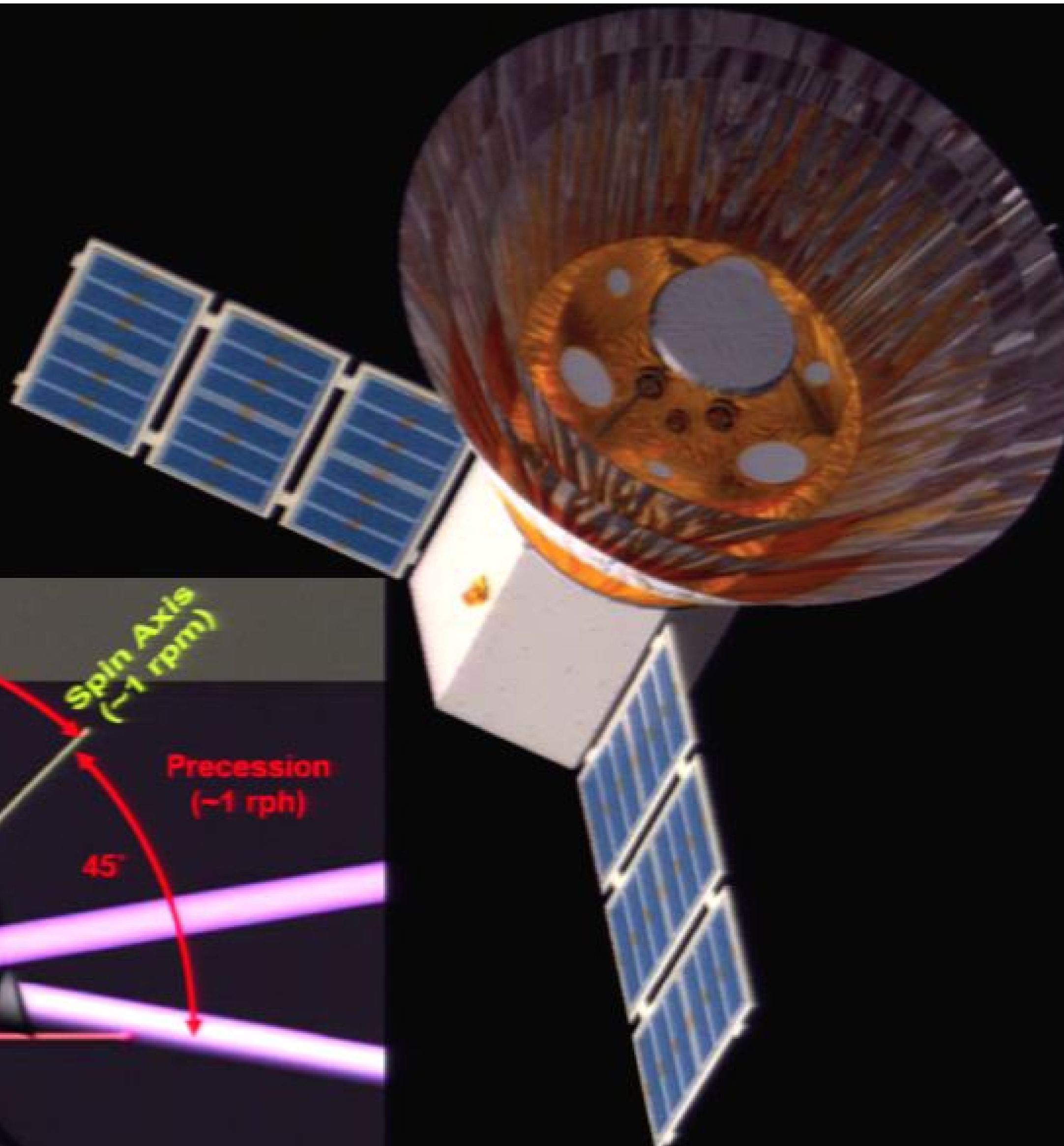


350 sq deg.. 8 arcmin res. 0.7 μK per pixel. 3 Freq. 150. 250 & 420 GHz

Future

Epic





CMBPOL

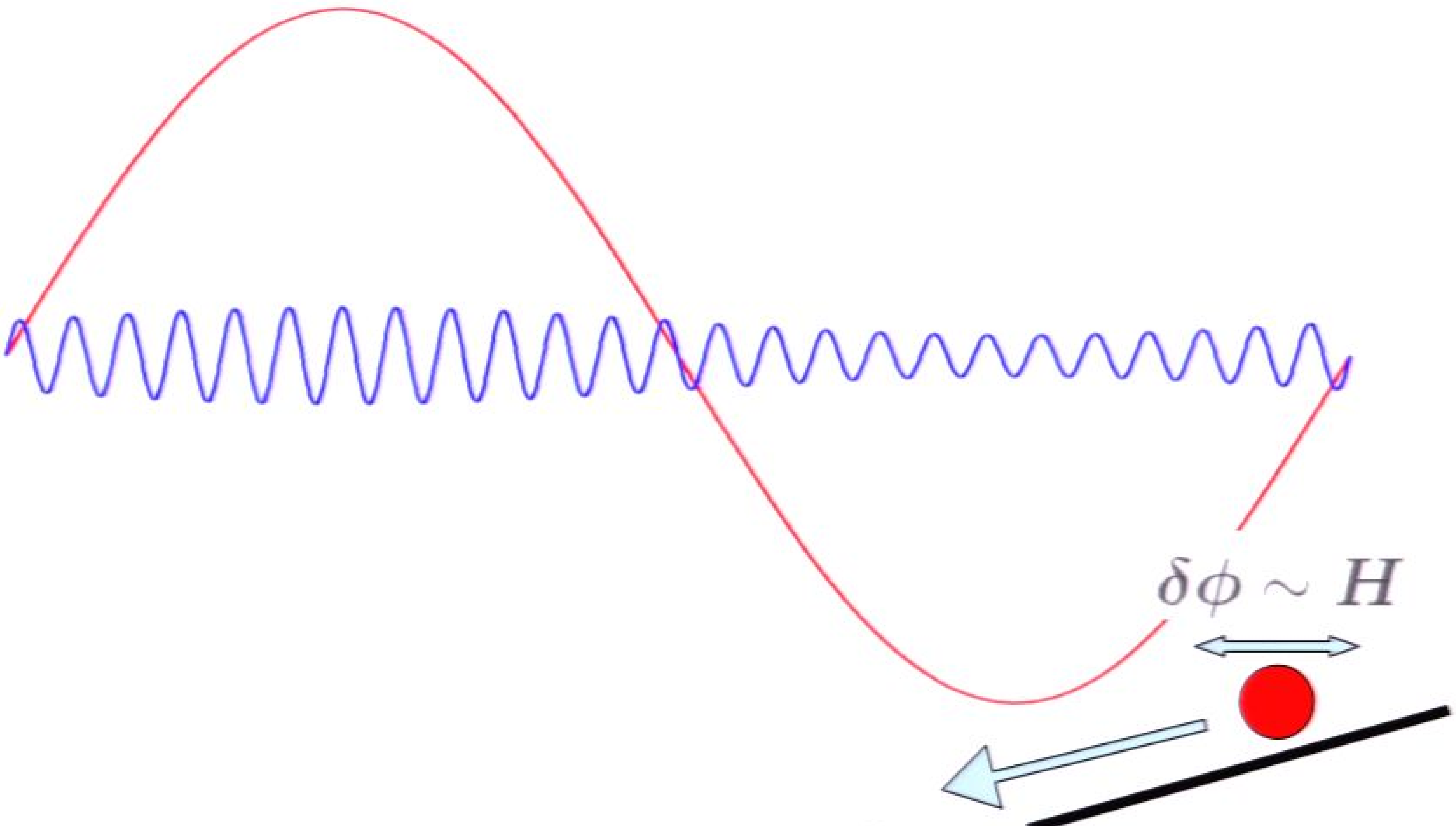
The statistics of the seeds

The simplest inflationary models predict very small (unobservable) departures from Gaussianity

Secondary anisotropies and residual foregrounds also lead to departures from Gaussianity.

The Size of non-Gaussianities :

There is a direct connection between the departures from scale invariance and the three point function



Non-Gaussianities $\sim (n-1)10^{-5}$

Maldacena 2002

Level of non-G in standard inflation

- $$\frac{\langle \delta^3 \rangle}{\langle \delta^2 \rangle^{3/2}} \sim (n-1)\delta \sim 10^{-2} \times 10^{-5}$$
- The ultimate level using CMB is around 10^{-4}

Komatsu & Spergel

- Current constraint is around 10^{-2}

WMAP first year data

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In models of inflation where the density perturbations we see were produced by fluctuations in a field other than the inflaton, and get converted into density fluctuations at reheating or later, non-Gaussianities of the local form are common.

$$\frac{\delta\rho}{\rho} = g + f_{NL}(g^2 - \langle g^2 \rangle) + \cdots$$

This is generic to all models where there is more than one field (or clock) so that it makes sense to talk about evolution outside the horizon (curvaton, multi-field models, variable decay rate).

 Typical expectation is $f_{NL} \sim 10$

Expected level

$$\frac{\langle\delta^3\rangle}{\langle\delta^2\rangle^{3/2}} \sim \frac{V^{(3)}}{H}$$

$$\frac{(\partial\phi)^4}{M^4} \rightarrow \frac{\dot{\phi}H^3}{HM^4} \sim f\delta \qquad f \sim \frac{\dot{\phi}^2}{M^4}$$

f can be >> (n-1) however if f is close to one the higher derivative operators will modify the homogeneous solution

$$\mathcal{L} = F[\frac{(\partial\phi)^2}{M^4}]$$

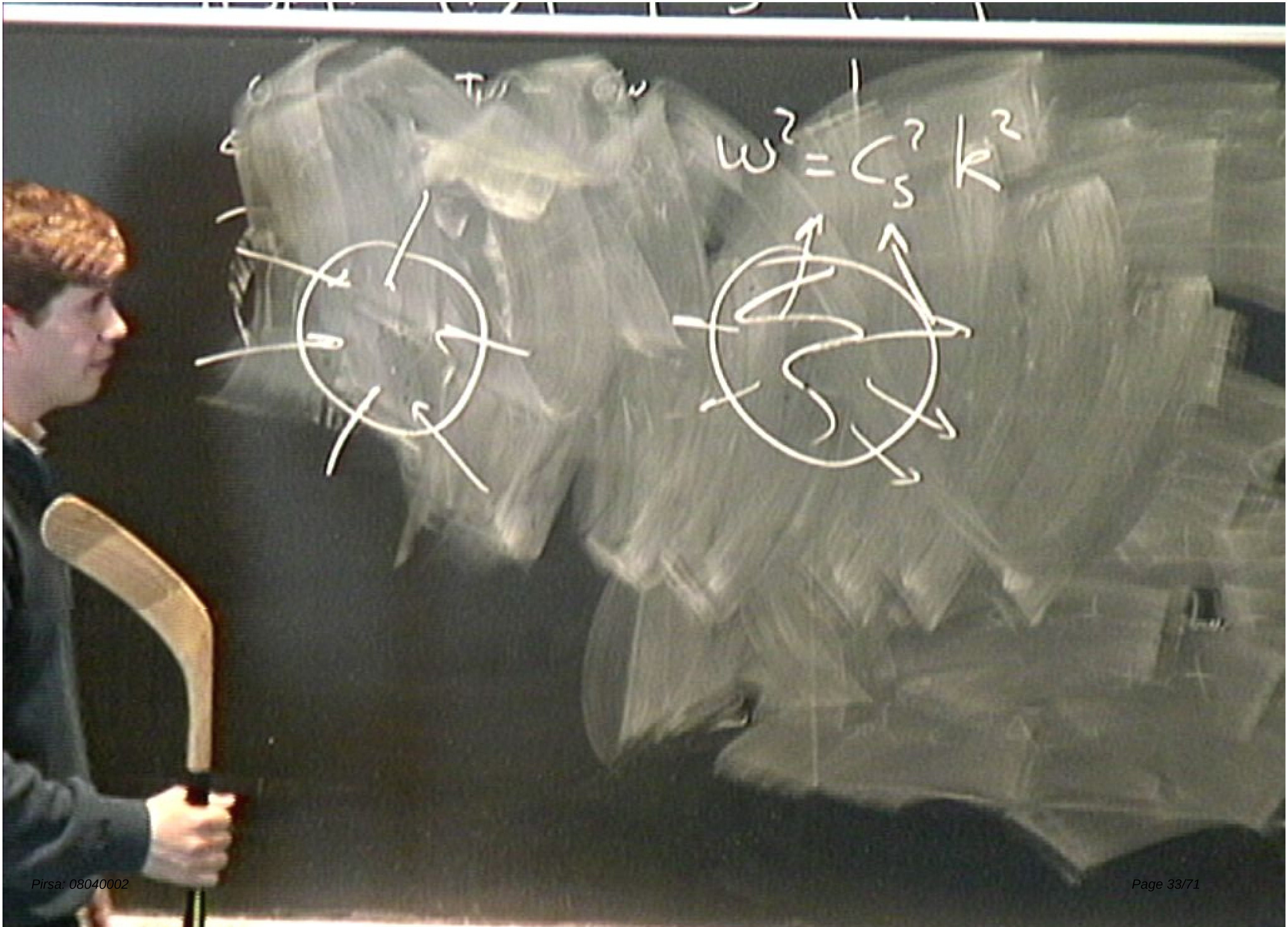
For detectable non-G the full function F is important for the dynamics.

Strongly coupled dynamics not traditional slow roll.

There are just two different things to look for, two distinct shapes of the three point function.

Multiple fields: evolution outside the horizon is meaningful	Only one clock but strongly coupled dynamics
Correlates large and small scales	Only correlates similar scales

In general we expect (= "can manage to get") departures from Gaussianity that are on the small side for WMAP but could be seen by Planck


$\omega^2 = c_s^2 k^2$

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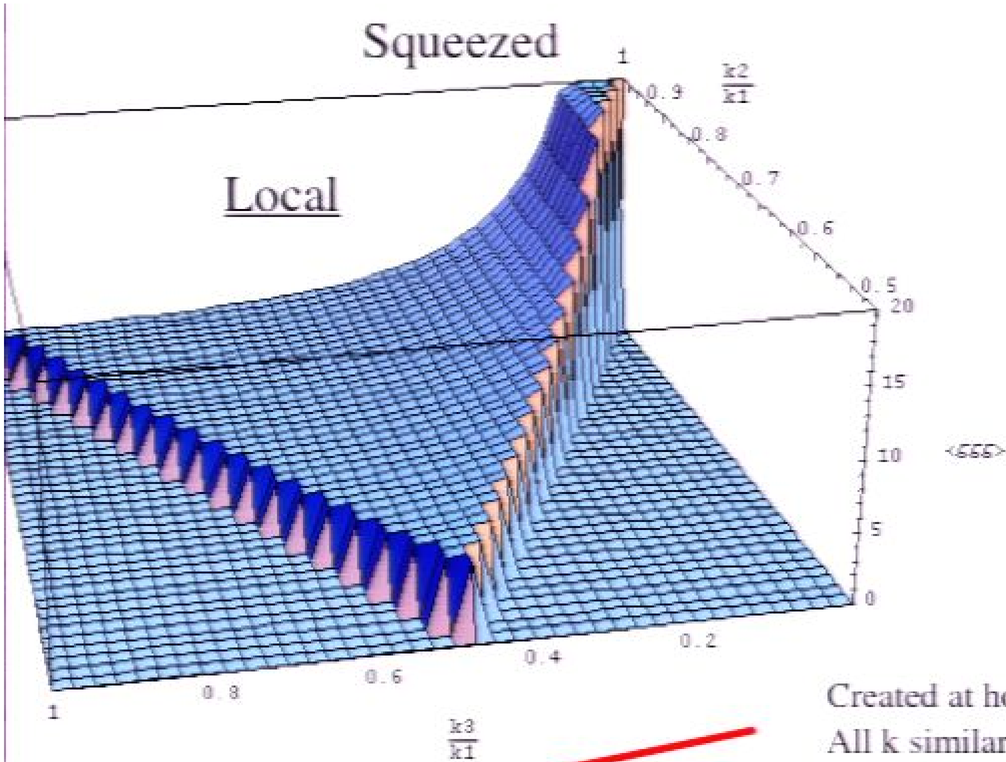
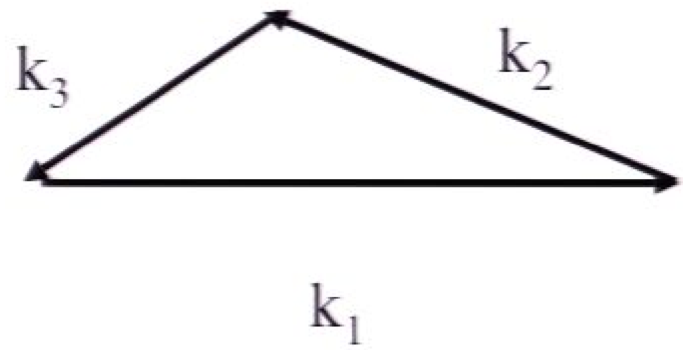
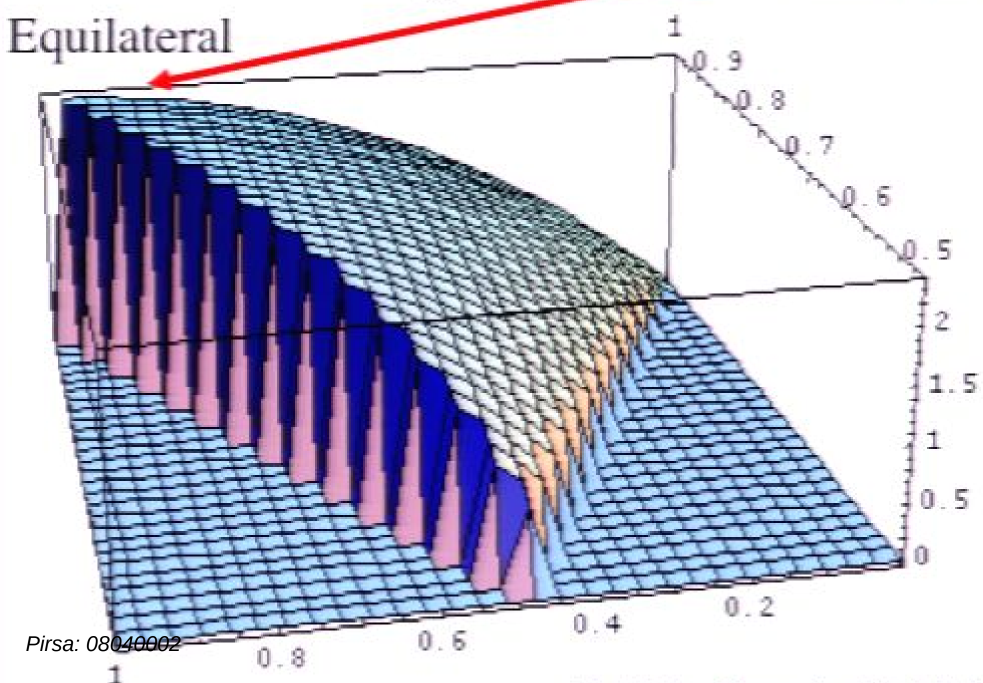
The 3-point function





Created at horizon crossing
All k similar in order to contribute

$$\langle \frac{\delta\rho}{\rho}(k_1)\frac{\delta\rho}{\rho}(k_2)\frac{\delta\rho}{\rho}(k_3)\rangle$$



Higher derivative operators

Babich, Creminelli & MZ

Searching for the signal

The best data set is the one with the largest number of high signal to noise measurements (pixels, Fourier modes). Constraints go as

$$N_{\rm pix}^{-1/2}$$

WMAP and future all sky CMB experiments are the most promising.

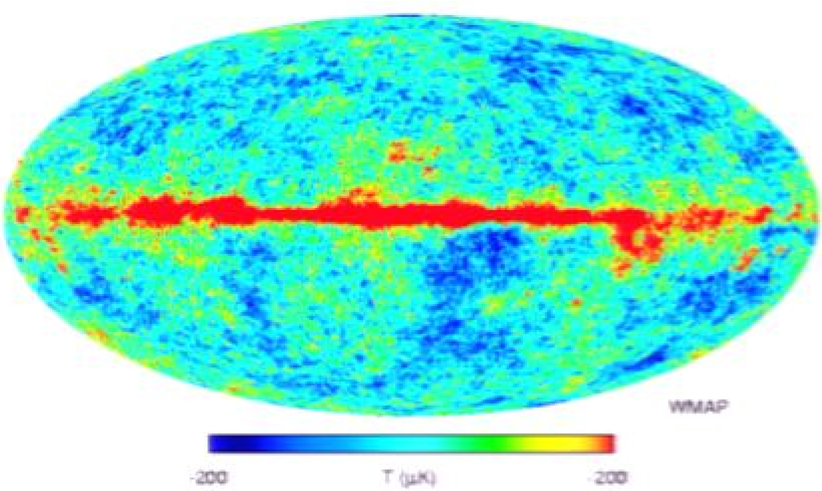
Surveys of hydrogen at high redshift using its 21 cm line could potentially do better.

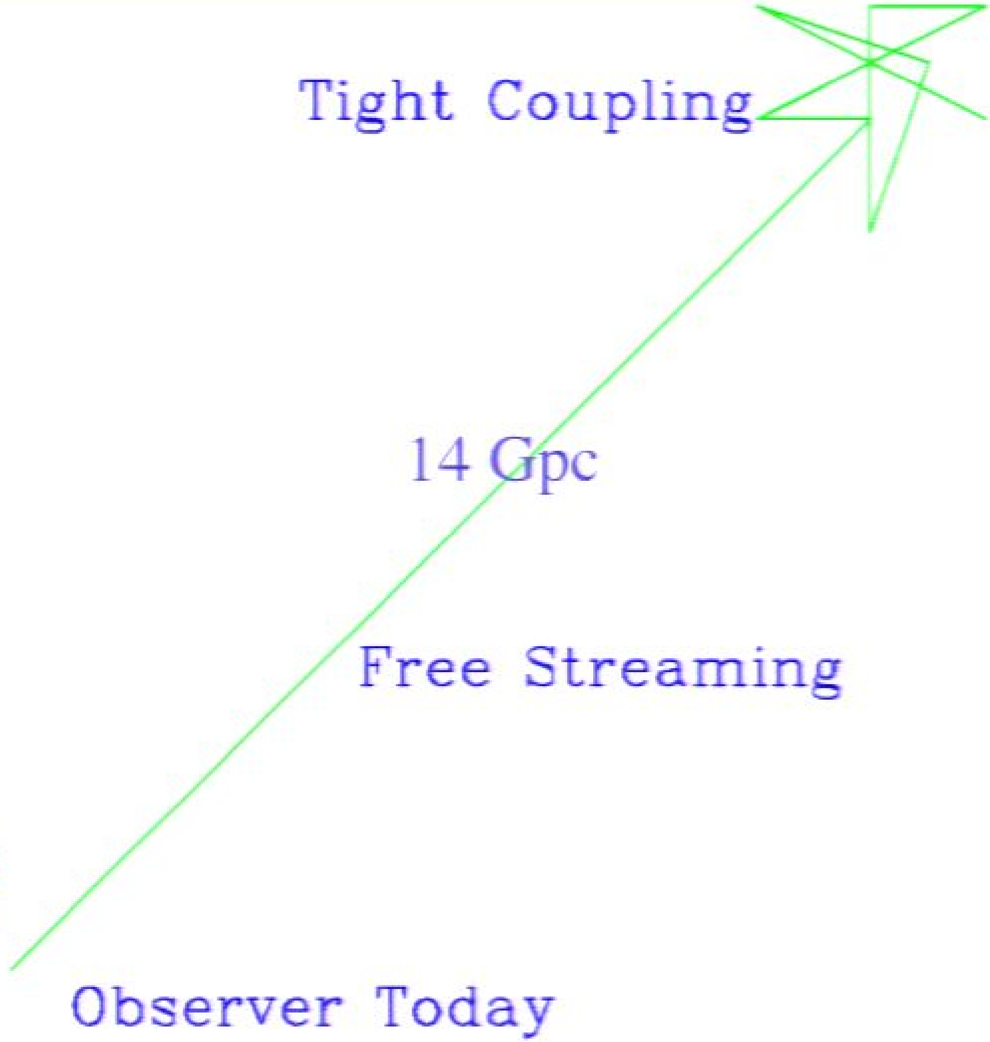
The basics of CMB Anisotropies

$$\frac{\delta T}{T} = \phi + \frac{\delta_\gamma}{4} + \frac{v_r}{c}$$

All 3 effects have the same origin

$$P \sim \lambda_T \nabla v$$





Summary so far

Experiments are beginning to constrain the characteristics of the primordial fluctuations at levels that are interesting for early universe physics.

- Small departures from scale invariance
- Stochastic background of GW
- Departures from Gaussianity

The best way to characterize the departures from Gaussianity is the three point function.

Departures come in just two types depending on the physical origin of the effect

The constraining power of a data set is just given by $N_{pix}^{1/2}$

The data is consistent with Gaussianity.

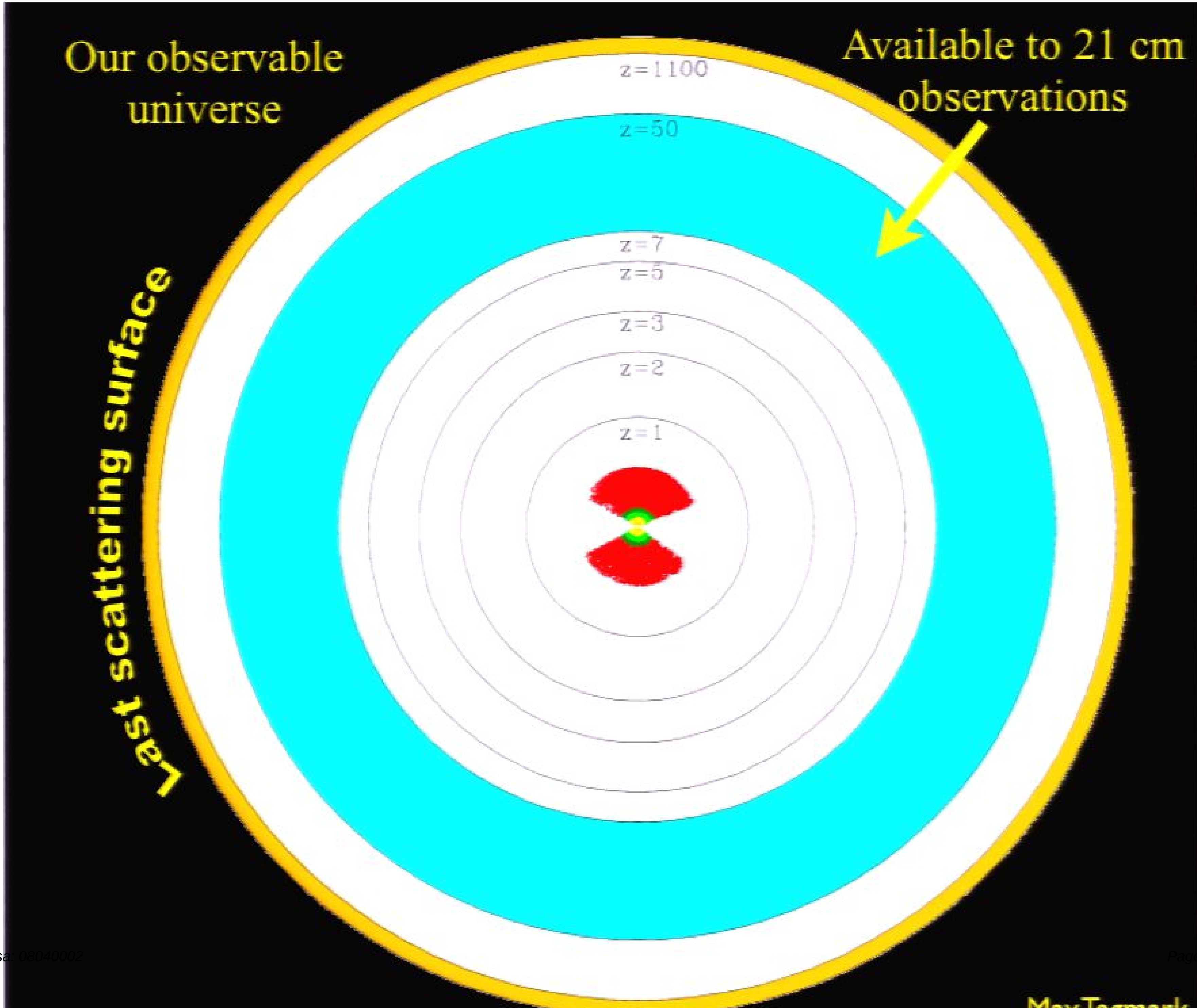
Upper limits are close to plausible levels.

21 cm fluctuations: a new window for Cosmology

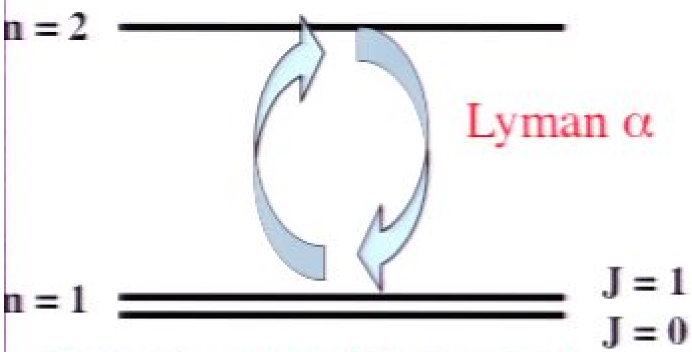
First Step

- Epoch of Reionization Science
- Fluctuations on small scales
- Gaussianity

Future


Our observable universe
Available to 21 cm observations
Last scattering surface
z=1100
z=50
z=7
z=5
z=3
z=2
z=1

21 cm transition: a new window



Ground state of hydrogen

$$\frac{n_1}{n_2} = \frac{g_1}{g_2} \; e^{-T_*/T_s}$$

$$T_* = 0.068 \text{ K}$$

Before reionization we can observe hydrogen using the 21 cm line

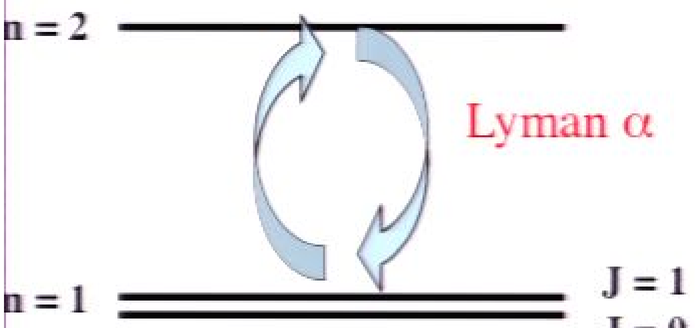
Coupling mechanisms

- 21 cm processes T_{CMB}
- Collisions T_K
- Lyman α T_K

$T_s > T_{CMB}$ Emission

$T_s < T_{CMB}$ Absorption

21 cm transition: a new window



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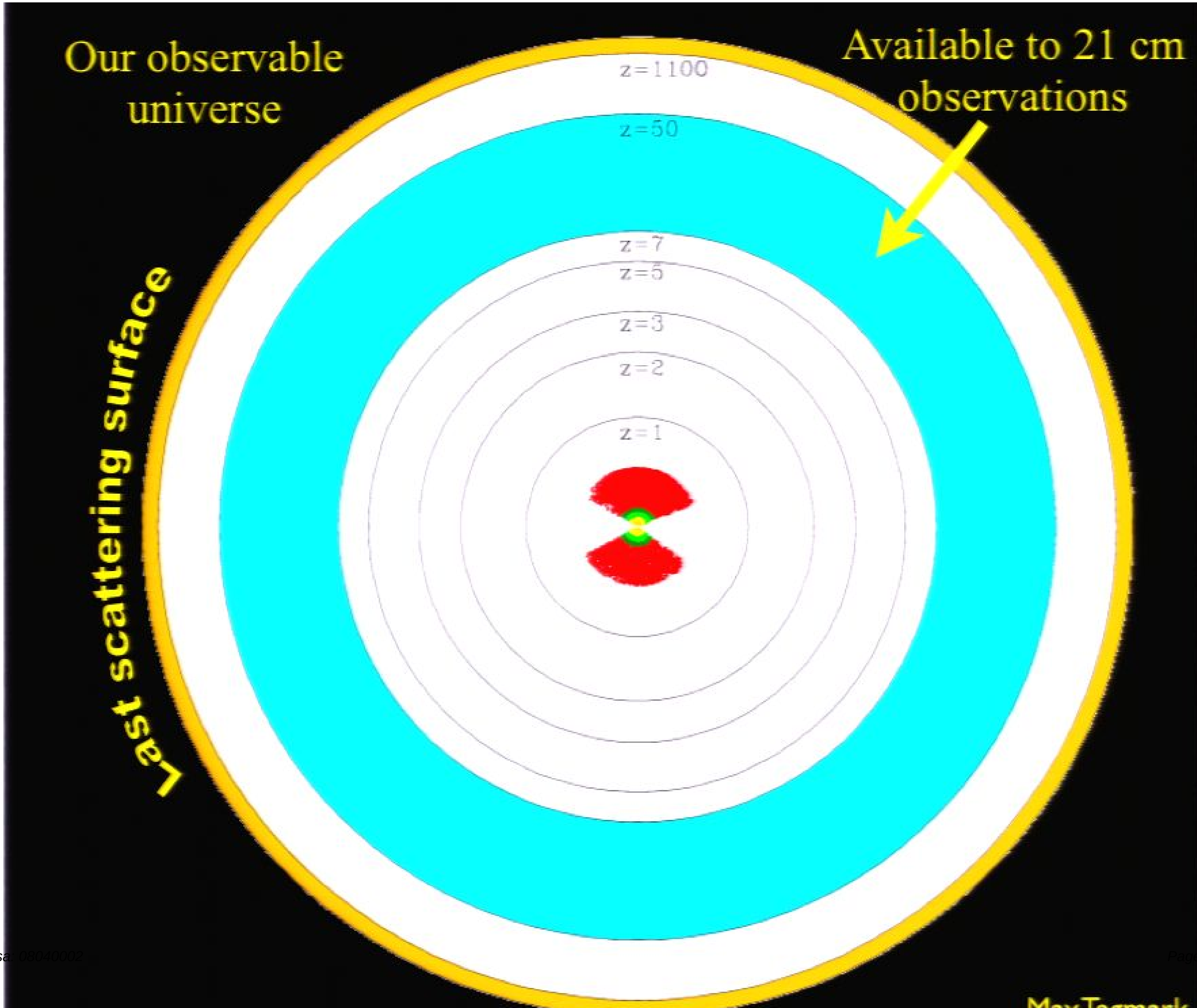
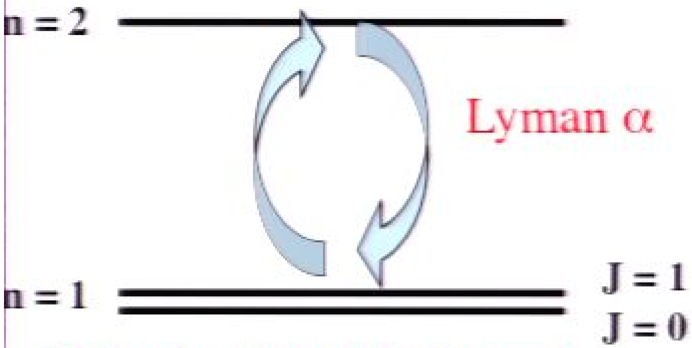

Our observable universe
Available to 21 cm observations
z=1100
z=50
z=7
z=5
z=3
z=2
z=1
Last scattering surface

21 cm transition: a new window



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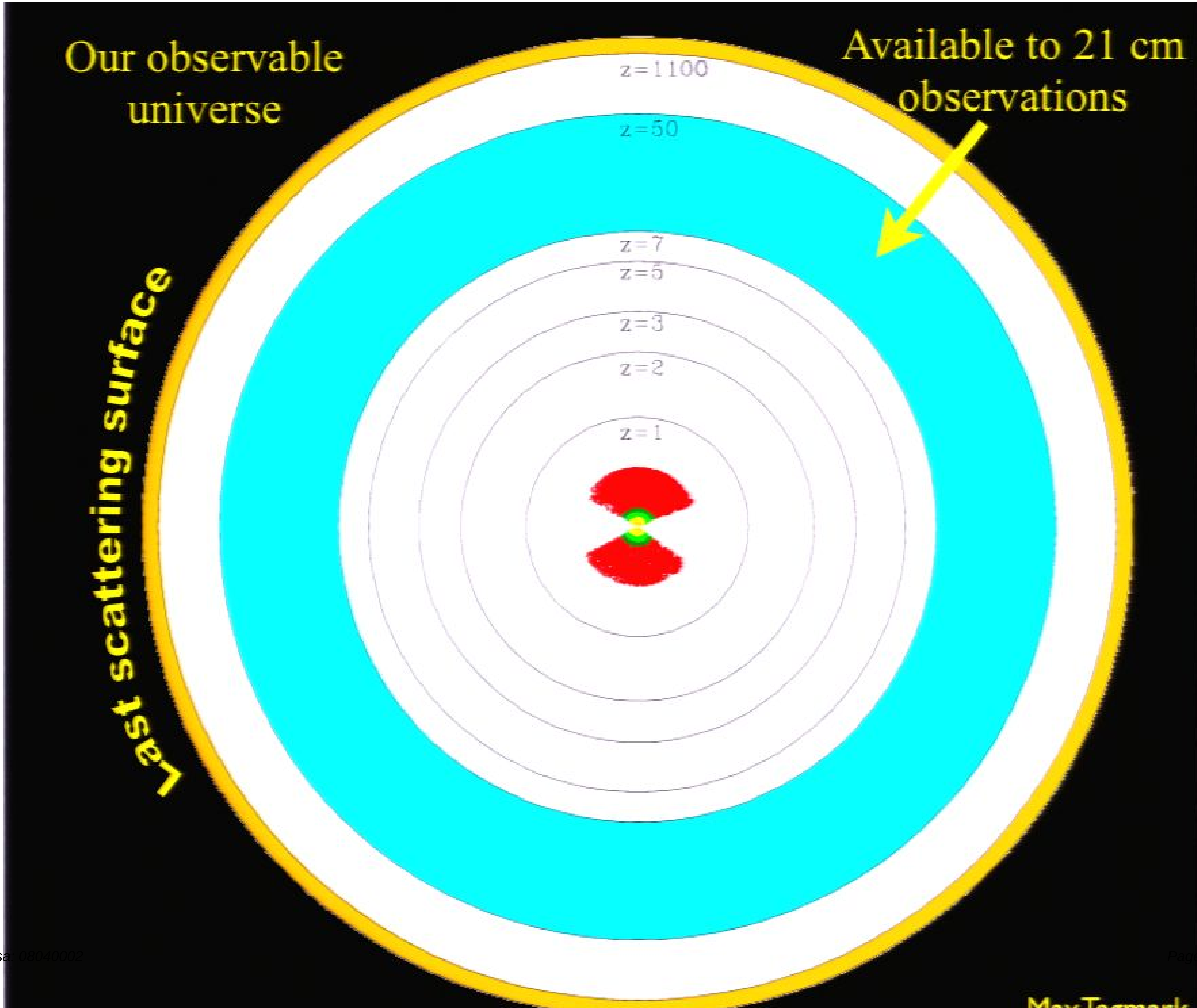

Our observable universe
Available to 21 cm observations
z=1100
z=50
z=7
z=5
z=3
z=2
z=1
Last scattering surface

Brightness fluctuations

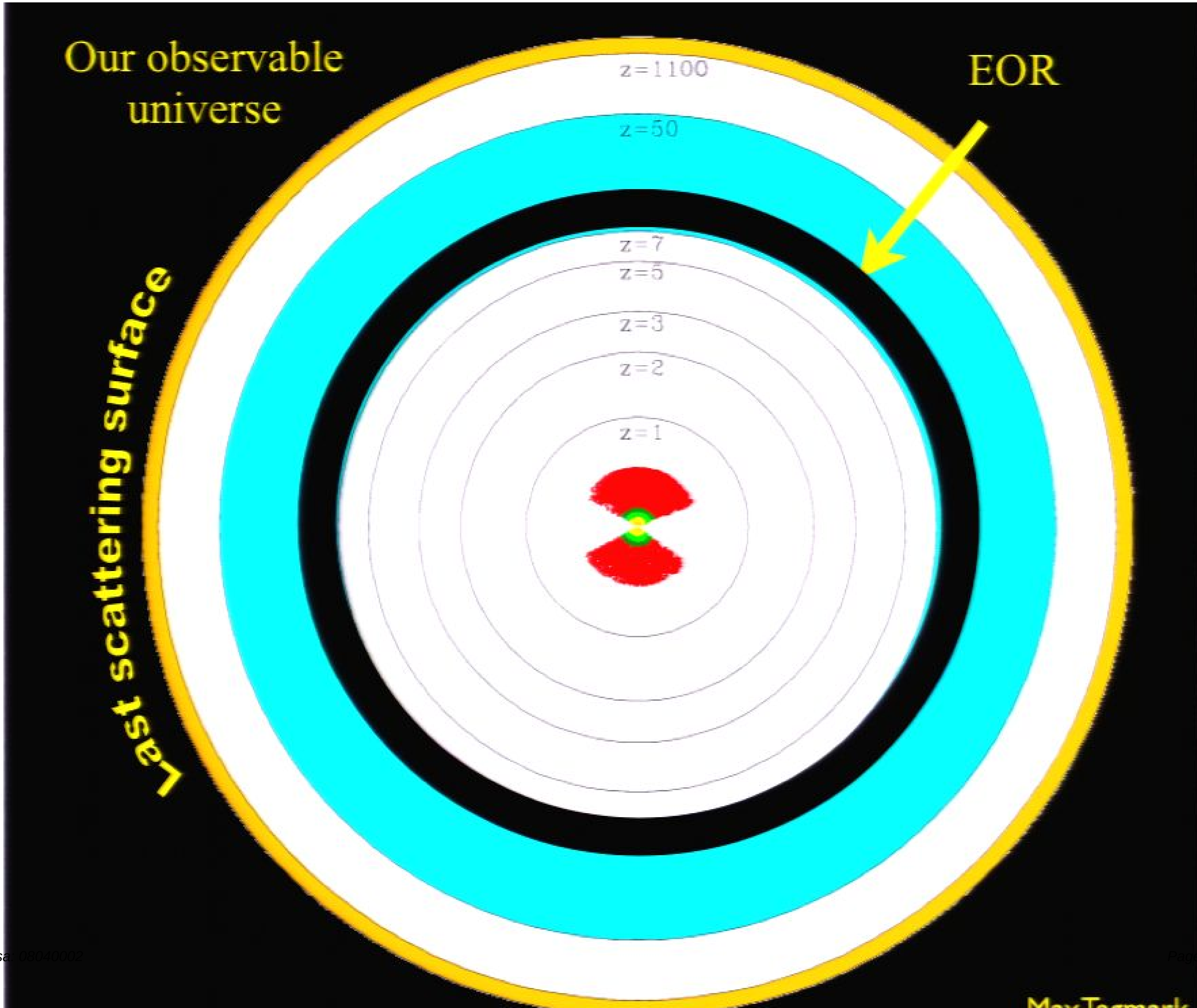
Fluctuation in the Neutral fraction

$$\psi = x_H(1+\delta)\left(\frac{T_S - T_{CMB}}{T_S}\right)$$

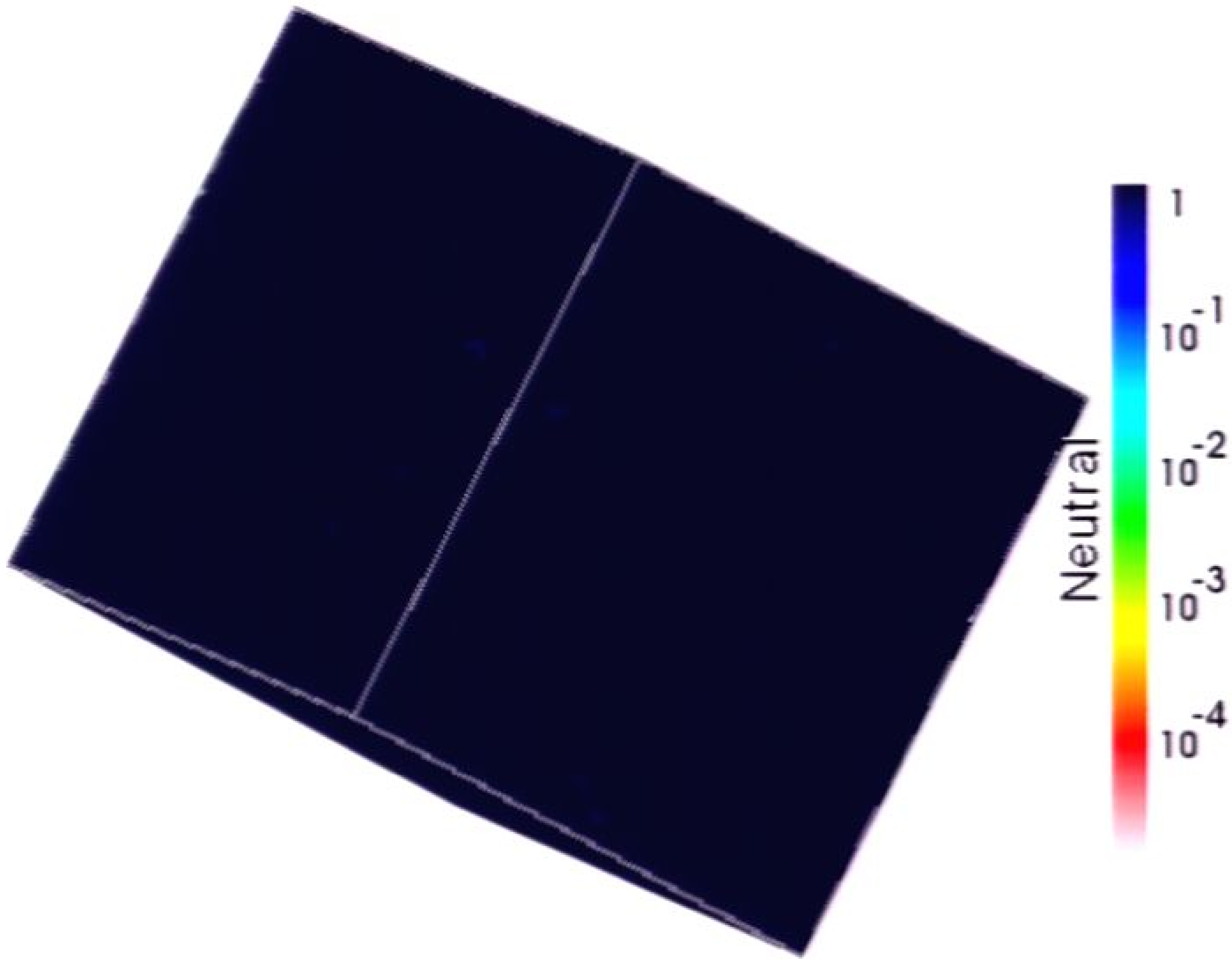
Fluctuation in the density

Fluctuation in the temperature:

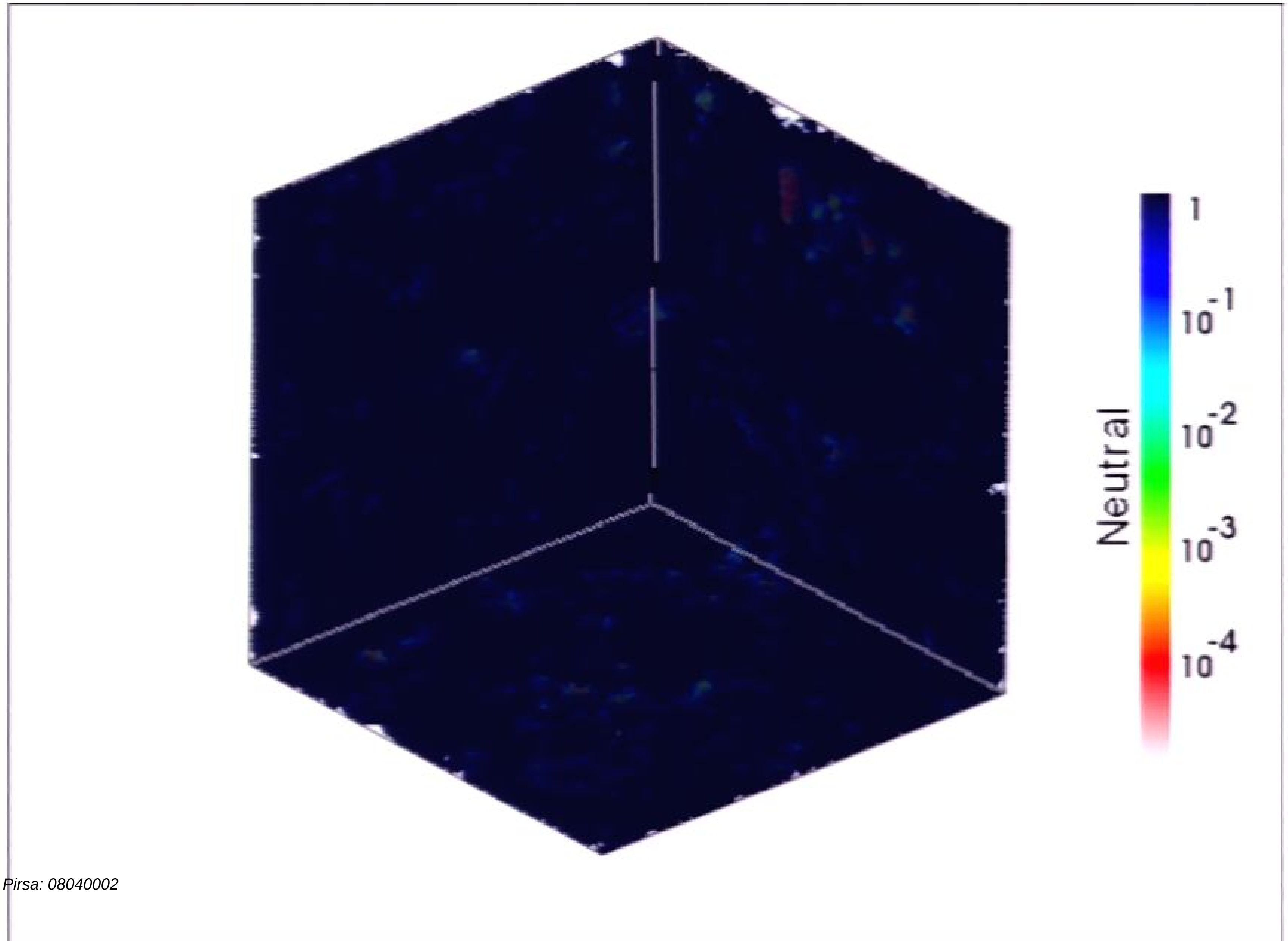
Unimportant for $T_s \gg T_{cmb}$ (reionization)


Our observable universe
EOR
z=1100
z=50
z=7
z=5
z=3
z=2
z=1
Last scattering surface
Max Tegmark

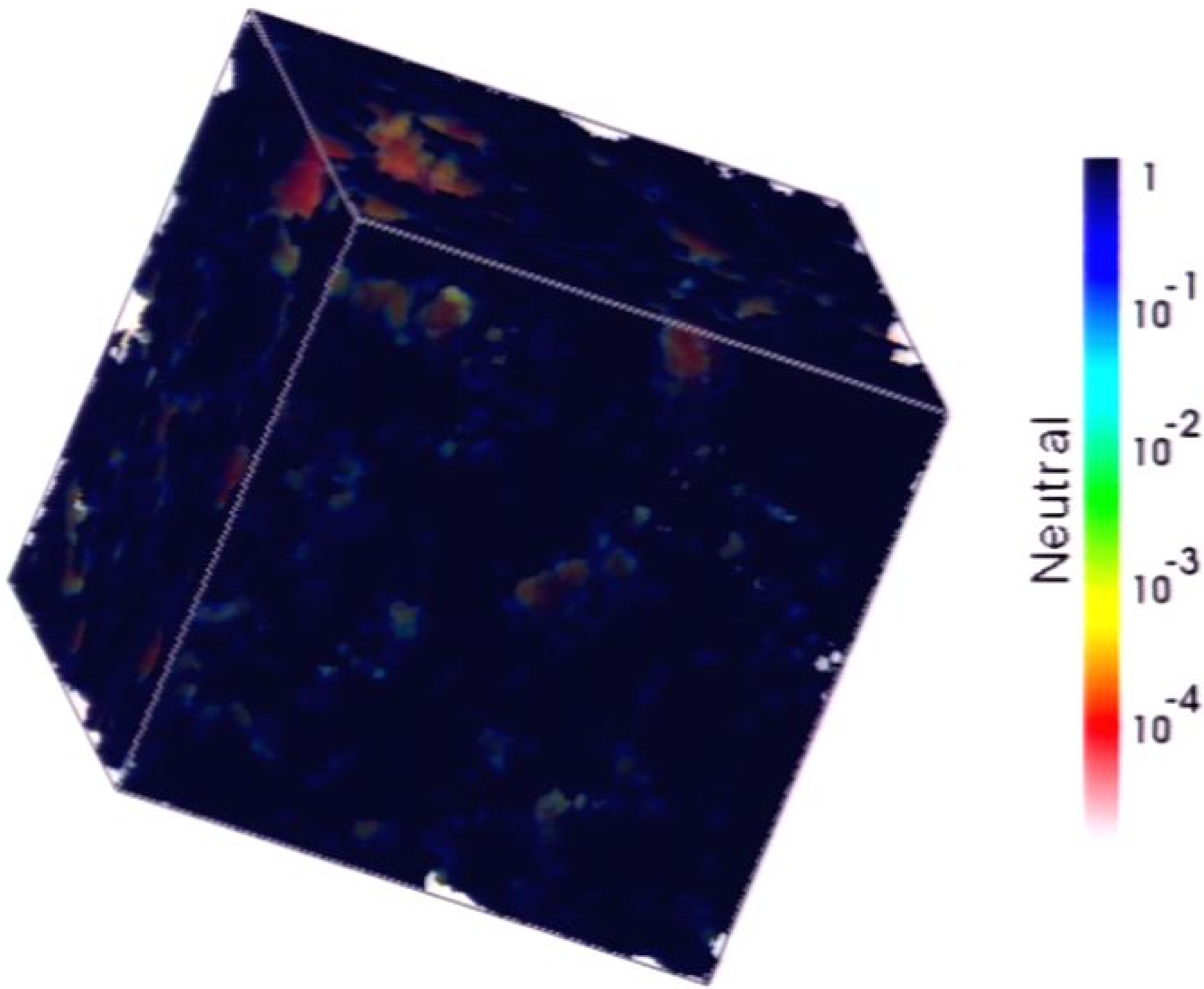
The epoch of reionization



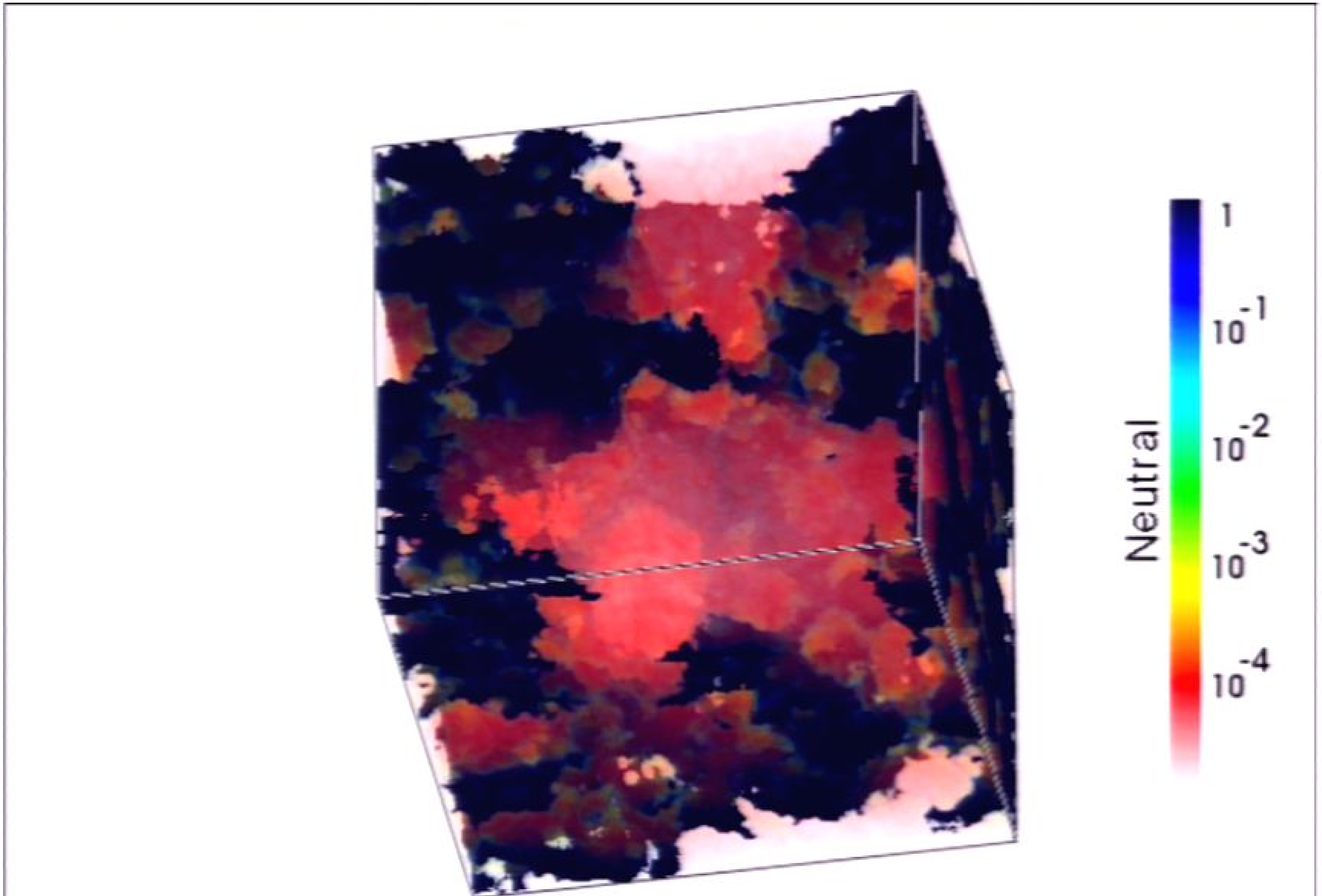
The epoch of reionization



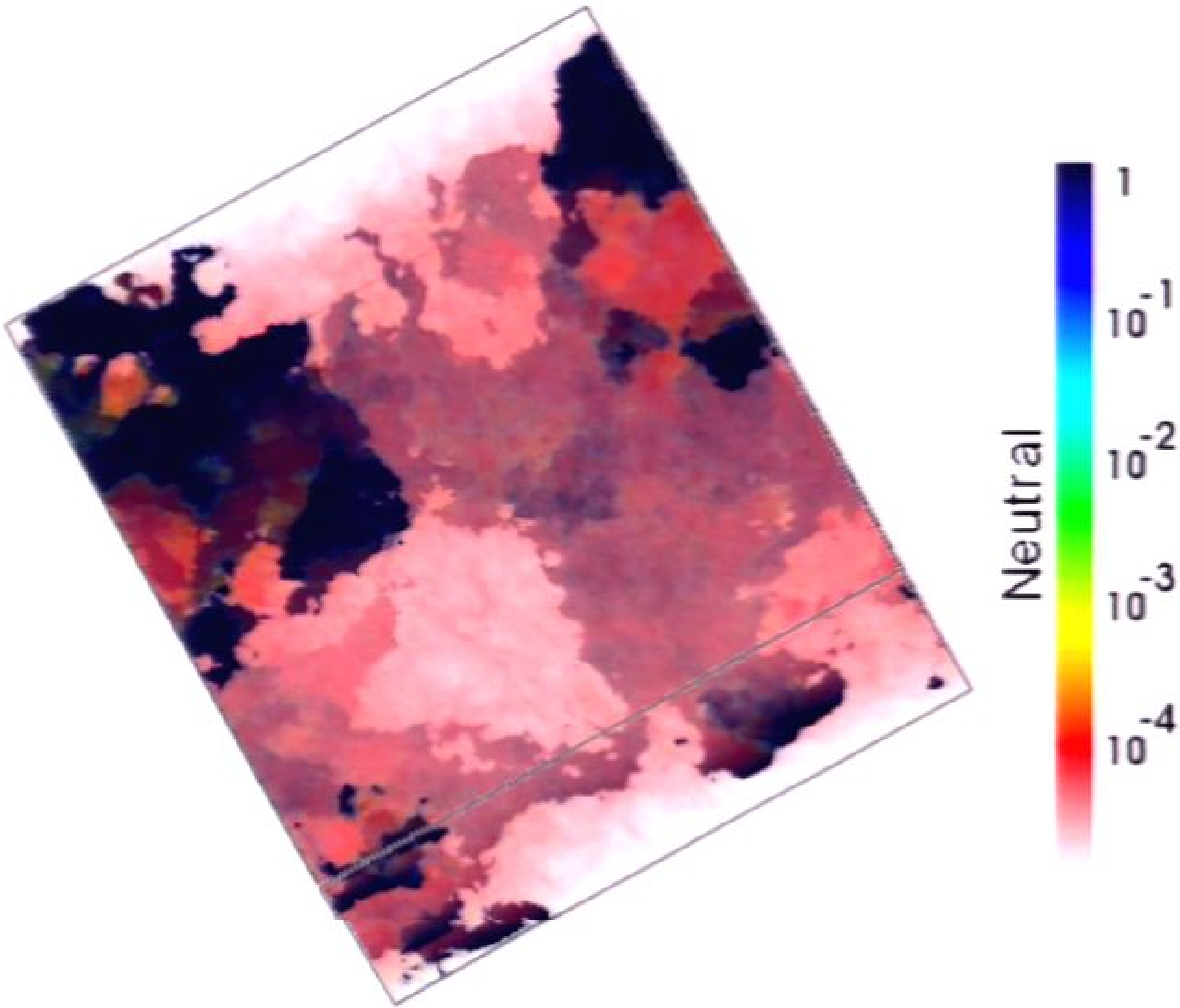
The epoch of reionization



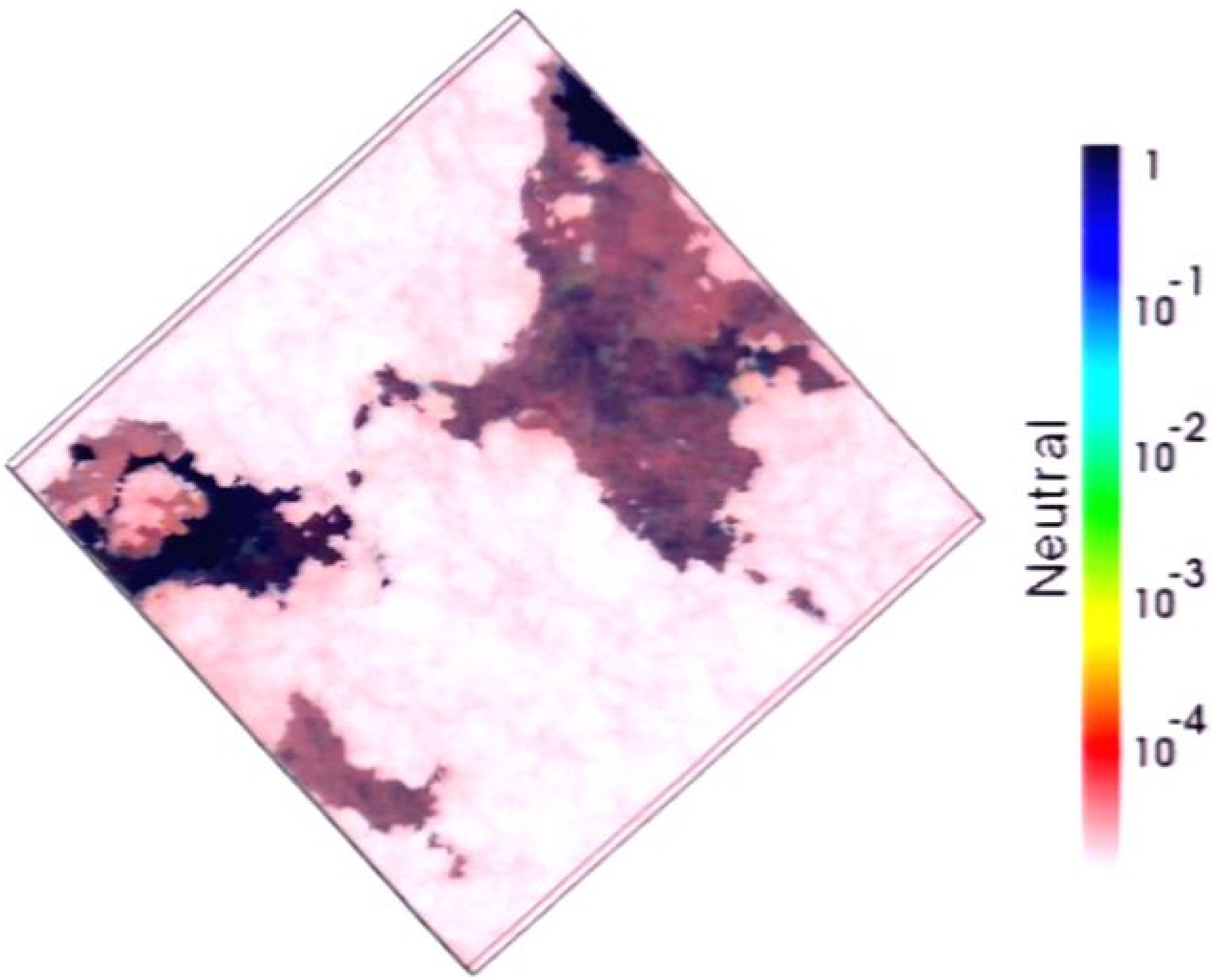
The epoch of reionization



The epoch of reionization



The epoch of reionization



The Early window before structure formation

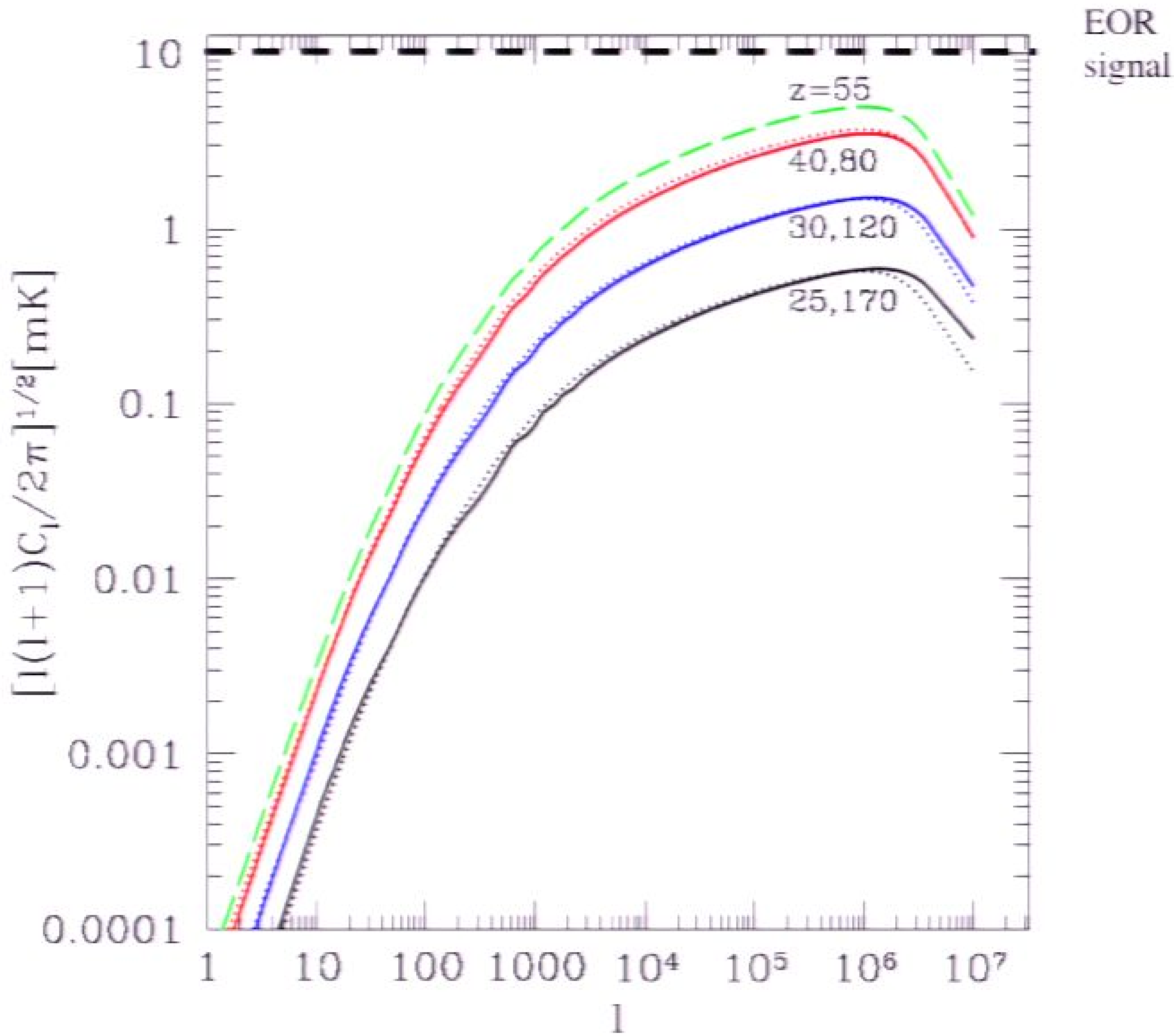


FIG. 2. Angular power spectrum of 21cm anisotropies on the sky at various redshifts. From top to bottom, $z = 55, 40, 80, 30, 120, 25, 170$.

Experimental challenge

CMB:

Background: 3K CMB

Temperature Fluctuations: 30 μK (10^{-5})

E mode polarization: 3 μK (10^{-6})

B mode polarization: 0.1 μK (3 x 10^{-8})

Wavelength: 0.3 cm

Frequency: 100 GHz

21 cm Fluctuations:

Background: 200 K Galaxy

Temperature Fluctuations: 20 mK (10^{-4})

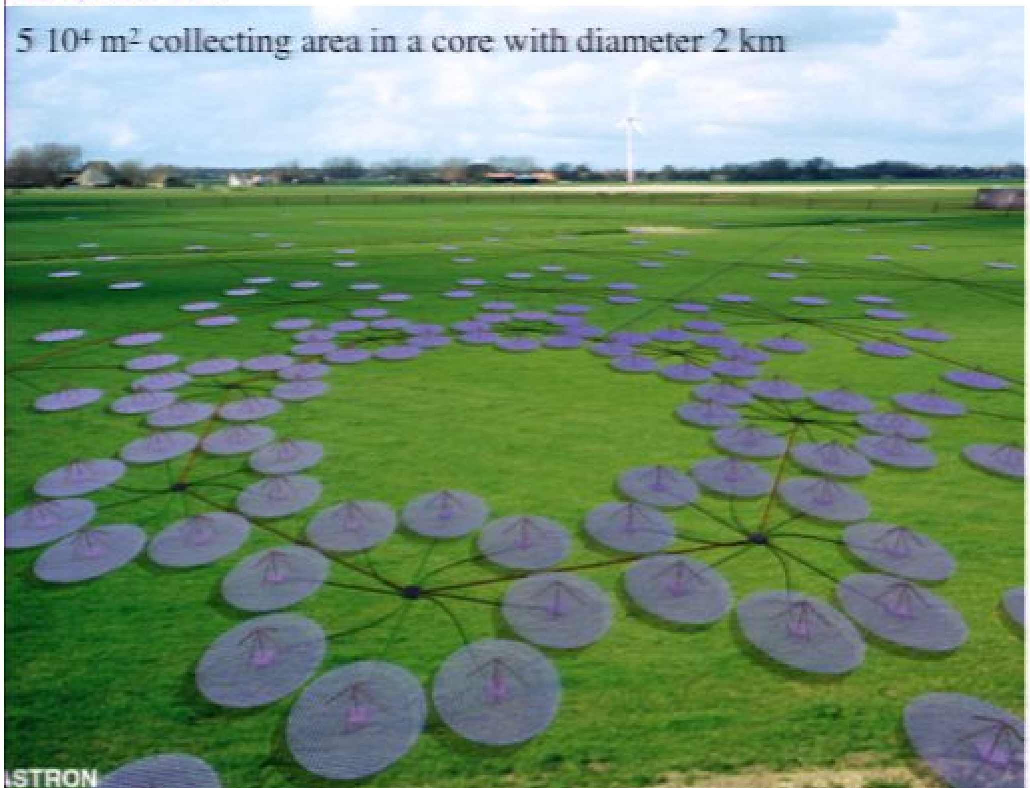
Wavelength: 2 meters

Frequency: 140 MHz

$$\Delta T \propto \frac{\lambda^2 T_{sys}}{A\sqrt{\Delta\nu t_0}}$$

LOFAR

5 10^4 m^2 collecting area in a core with diameter 2 km



21CMA (PAST)

Prototype, Ulastai, West China

Table 1: **Specifications of Baseline PAST instrument.**

Parameter	Goal (at 100 MHz)
Total antennae	1000
Effective Elements	10
Effective area	9000 m^2
Element effective receiver temperature	10 K
Sky brightness temperature	170 K
Imaging field of view	1 sq deg
Angular resolution	3 arc minutes

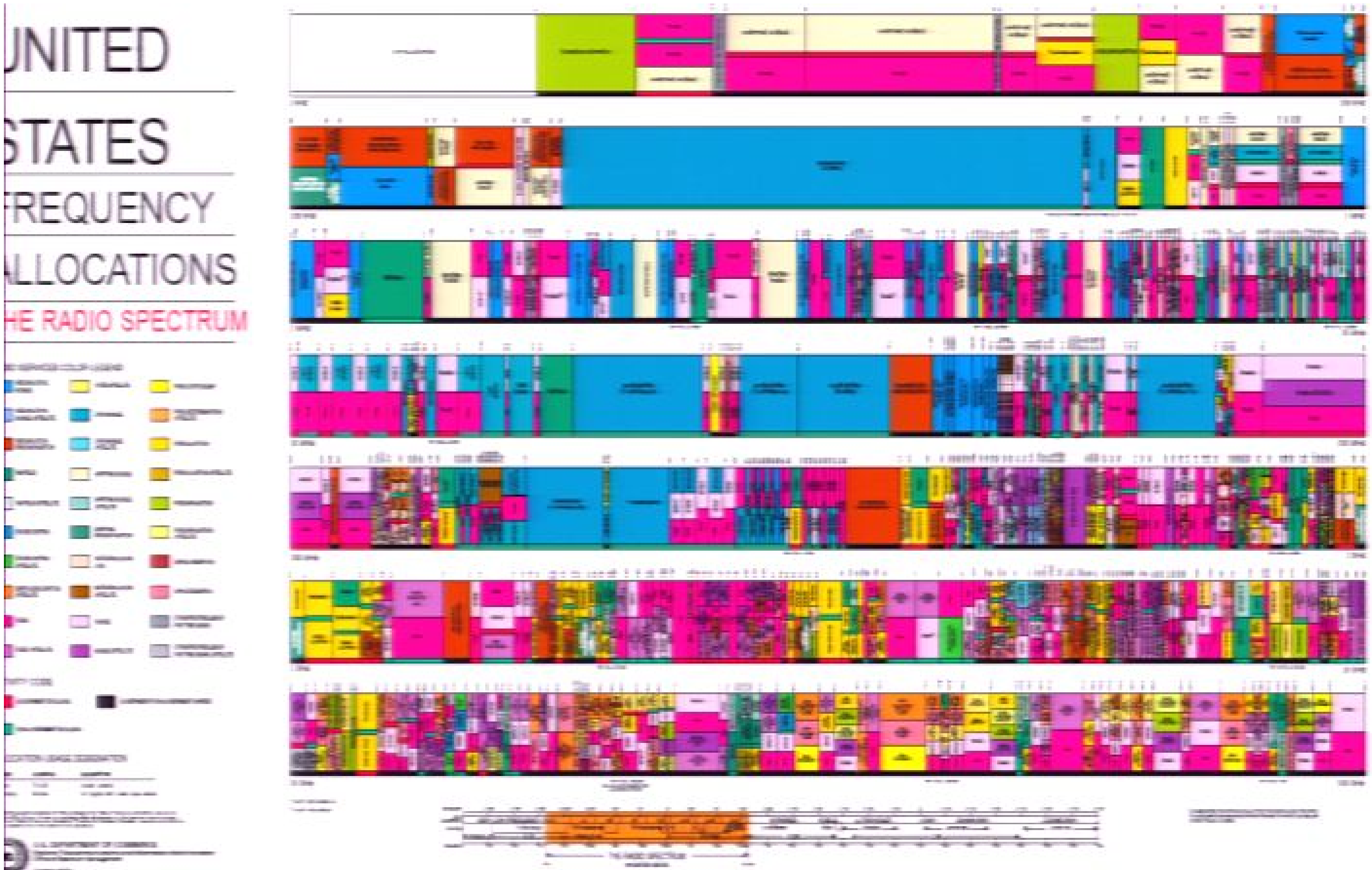
Mileura Wide-field Array Low Frequency Demonstrator (MWA-LFD)

EOR Science Collaboration

MIT: Jacqueline Hewitt, Colin Lonsdale, Miguel Morales
Melbourne: Rachel Webster, Stuart Wyithe, David Barnes
CfA: Avi Loeb, Lincoln Greenhill, Lars Hernquist, Matias Zaldarriaga
Other Institutions: Steve Furlanetto (UCLA), Chris Carilli (NRAO), Frank Briggs (ANU)

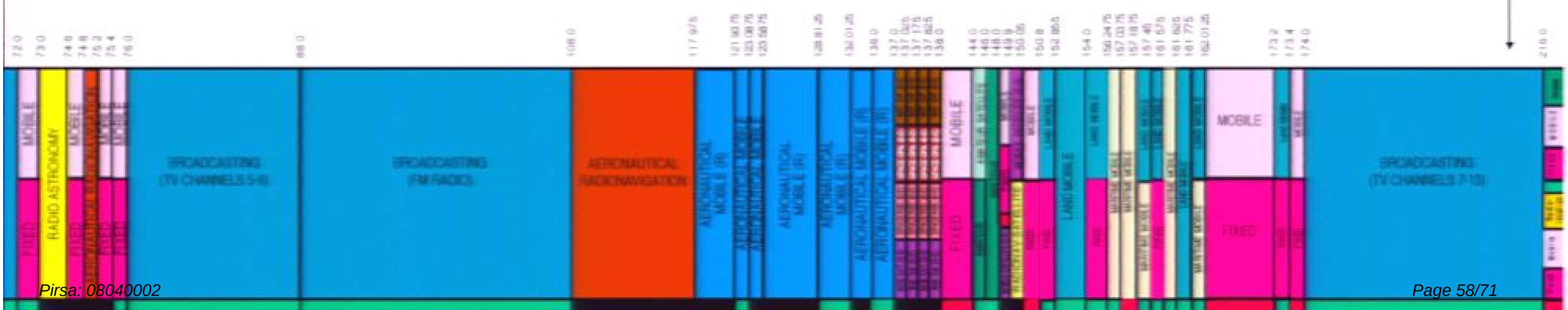
Characteristics of the Array

- 500 16-element antennas in a compact 1.5 km array
- Wide 80–300 MHz frequency range
- Digital receiver & filter chain, 32 MHz at 16 Khz resolution
- Full cross-correlation of all 500 antennas, 20–30° field of view


NITED
STATES
REQUENCY
LLOCATIONS
HE RADIO SPECTRUM

+Z≈2

1+Z≈7


72.0
73.0
74.6
74.8
75.2
75.4
76.0
88.0
108.0
117.975
MOBILE
FIXED
RADIO ASTRONOMY
BROADCASTING
(TV CHANNELS 5-6)
BROADCASTING
(FM RADIO)
AERONAUTICAL
RADIONAVIGATION
AERONAUTICAL
MOBILE (R)
LAND MOBILE
BROADCASTING
(TV CHANNELS 7-13)

Western Australia

Boolardy in the Murchinson area (MWA), 0.01 humans/km^2

Early Deployment

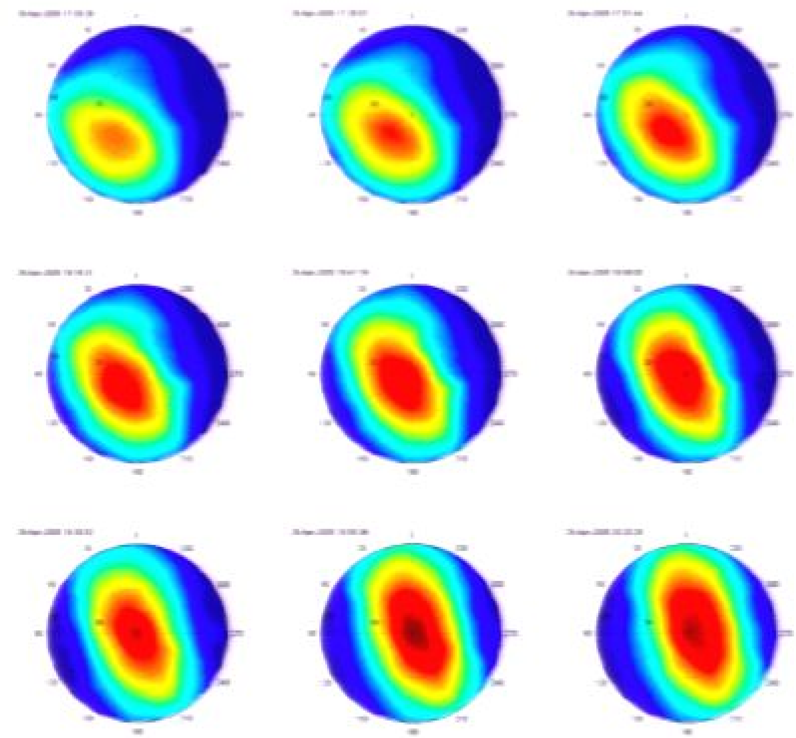


Figure 6. Image sequence showing the galactic center passing overhead at Mileura. The observing frequency is 108 MHz, and the images were made by steering the single-tile beam to 40 grid locations in rapid succession. The zenith is at the center of the images, and the edges area at 30 degrees elevation. The colors cover a brightness range of 4 to 1, and the tile beamwidth is about 34 degrees. The data have not been corrected for the single-dipole power pattern, which peaks at the zenith.

The raw constraining power of 21 cm tomography:

For a 2D survey

$$N_{2D} = l_{max}^2 = 9 \times 10^6 \left(\frac{l_{max}}{3000}\right)^2$$

In the case of 21 cm, there is extra radial information

$$N_{21cm} = 3 \times 10^{16} \left(\frac{l_{max}}{10^6}\right)^3 \left(\frac{\Delta\nu}{\nu}\right) \left(\frac{z}{100}\right)^{-1/2} \propto l_{max}^3$$

Constraints on departures from scale invariance and on primordial non Gaussianity scale as

$$\frac{1}{\sqrt{N_{obs}}}$$

For CMB

$$\frac{1}{\sqrt{N_{obs}}} \sim \frac{1}{l_{max}} \sim 10^{-3}$$

For inflationary models we expect to see (n-1) but not running $(n-1)^2$

$$NG \sim (n-1)\frac{\delta\rho}{\rho}$$ Too small in simple models

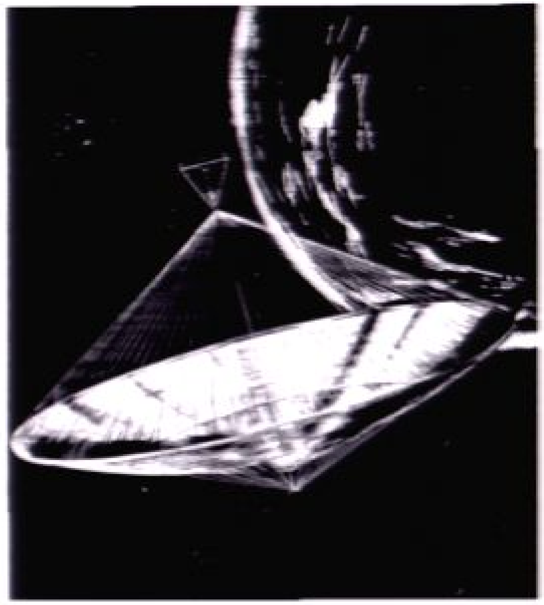
Getting away from RFI and increasing collecting area

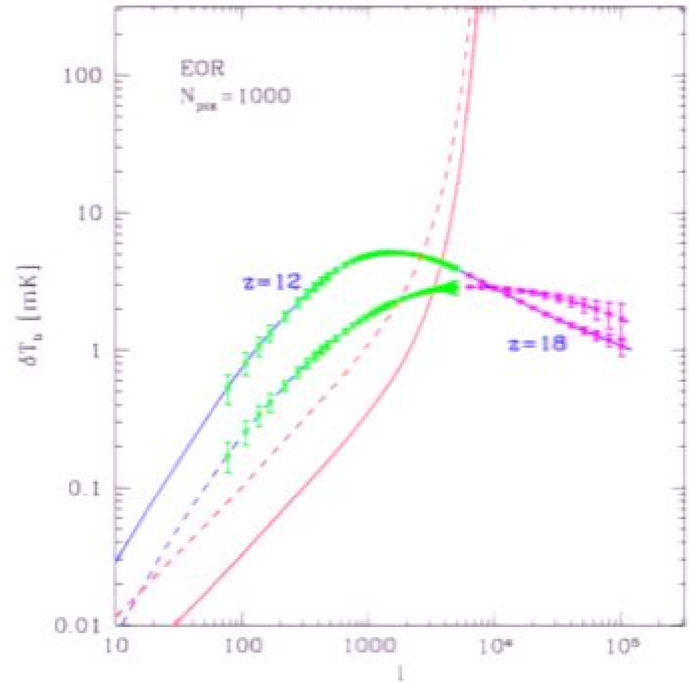
Lunar orbit

Earth Trailing orbit

Wire mesh telescope:
The John M.
Hedgepth Concept
(1965)

6.2 The John M. Hedgepeth Concept





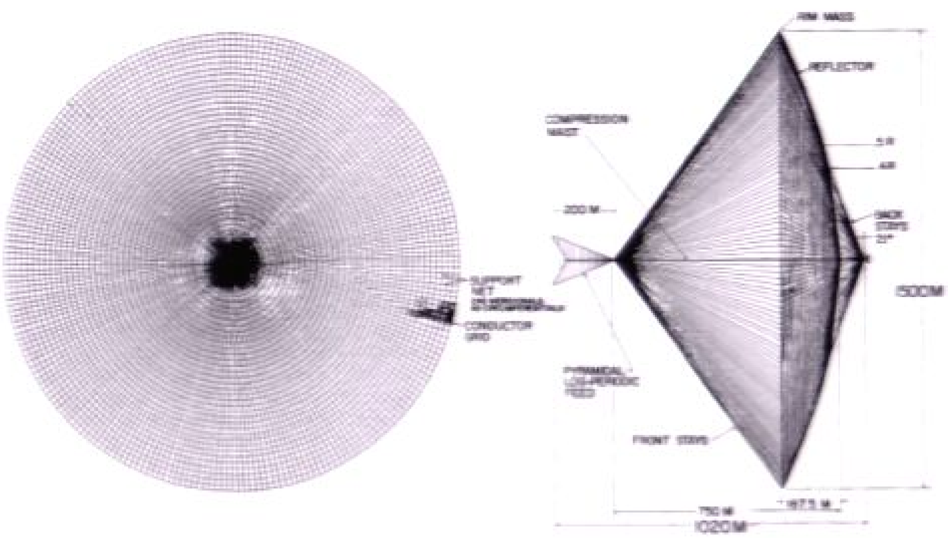
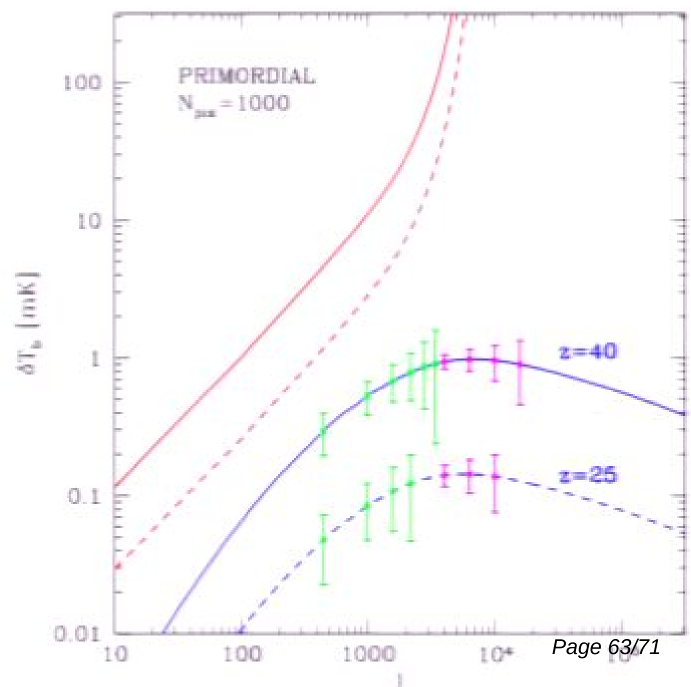


Figure 10. Near Parabolic John M Hedgepeth Concept



Summary:

• Upcoming 21 cm observations have the sensitivity to detect fluctuations in the background which will constrain both cosmological parameters and the physics of reionization, opening a new window for Cosmology.
• In principle this technique might unable us to map the largest fraction of our Hubble volume, resulting in the a huge "number of numbers" measured.
• Will we ever be able to use a substantial fraction of the information that is out there in the 21 cm signal? We will have a much better idea of the answer to this question in a few years when the first observatories come on line.