Title: Observational Probes of Early Universe Cosmology - Lecture 5

Date: Jun 27, 2009 10:00 AM

URL: http://pirsa.org/09060076

Abstract:

An Introduction to Observational Cosmology

Olivier Doré, CITA

Lect 1: Dynamics of the Universe as probed by distance measurements (SNe)
Lect 2: Baryonic Acoustic Oscillations
Lect 3: Dark matter clustering and galaxy surveys
Lect 4: Gravitational lensing
Lect 5: The cosmic microwave background radiation

With material from
Sarah Bridle and Martin White

This lecture:
The Cosmic Microwave Background

1. The origin of the CMB, spectrum, history
2. WMAP satellite and maps
3. The CMB power spectrum, C^{TT}_{ℓ}s
4. Understanding main features, esp 1st peak position
5. Polarization
6. The future

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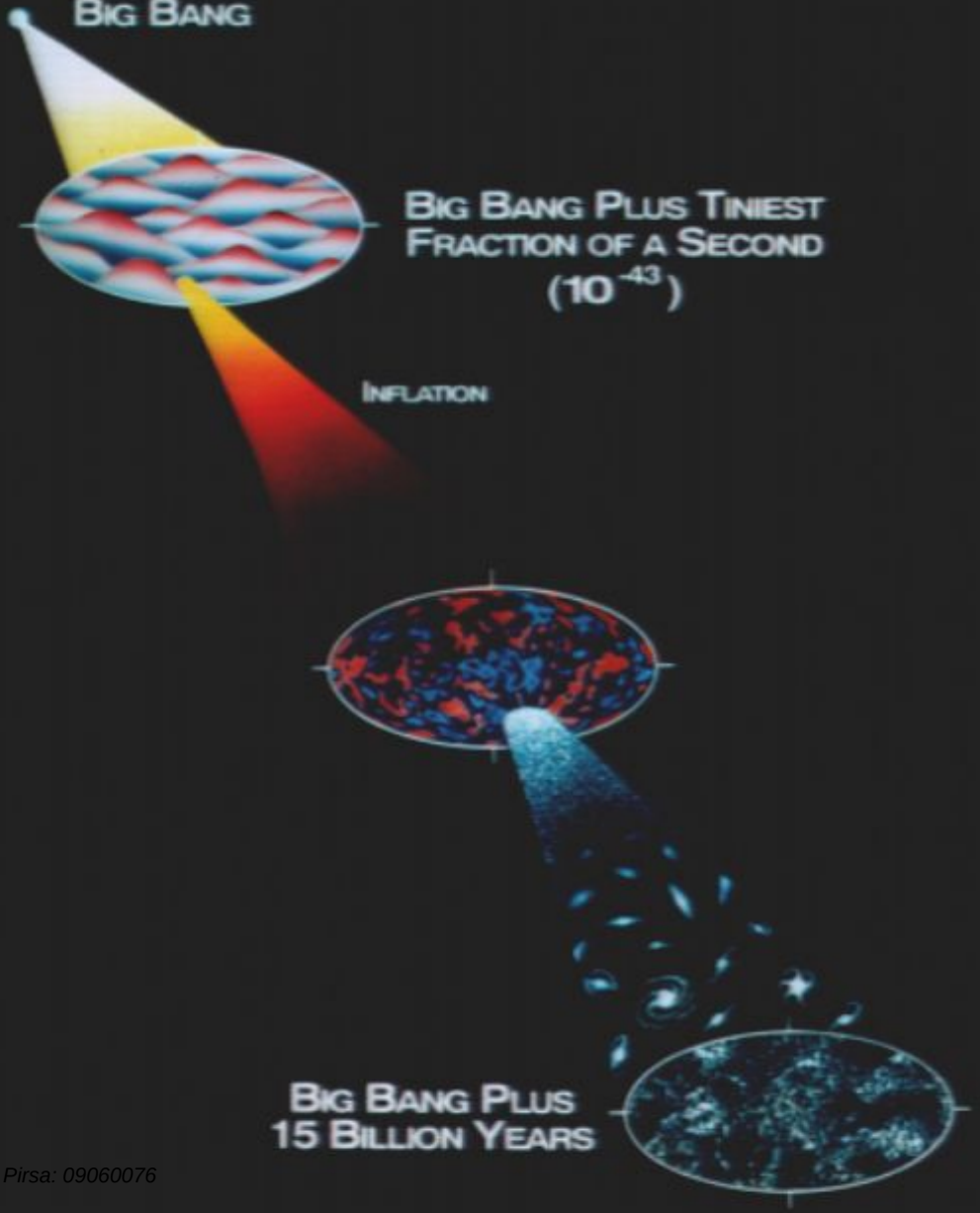
The History of the Universe



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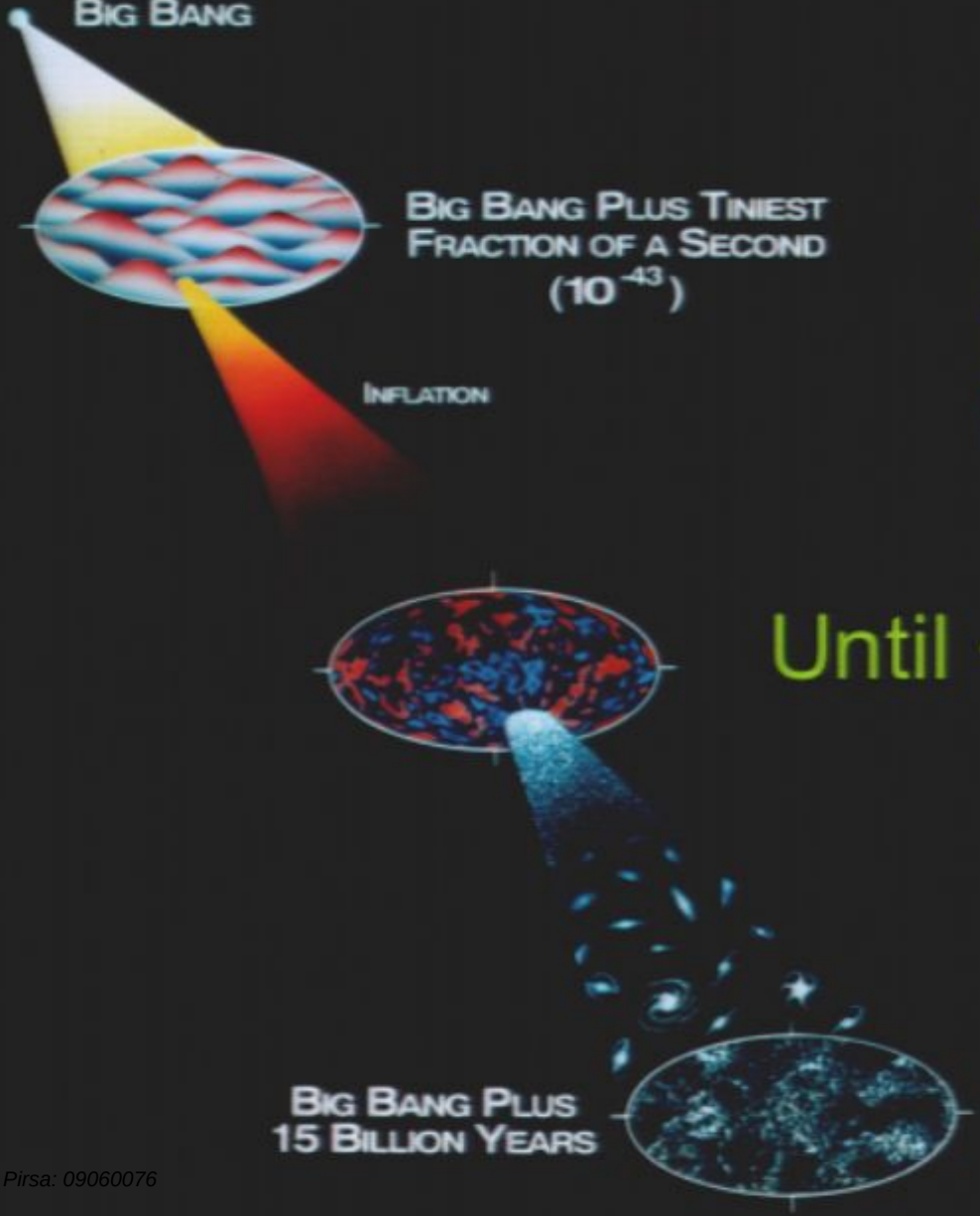


Universe is hot
Electrons are free
Light scatters off electrons

Until ~380,000 years after BB

Universe is cooler
e^- and p^+ form hydrogen
Light travels freely

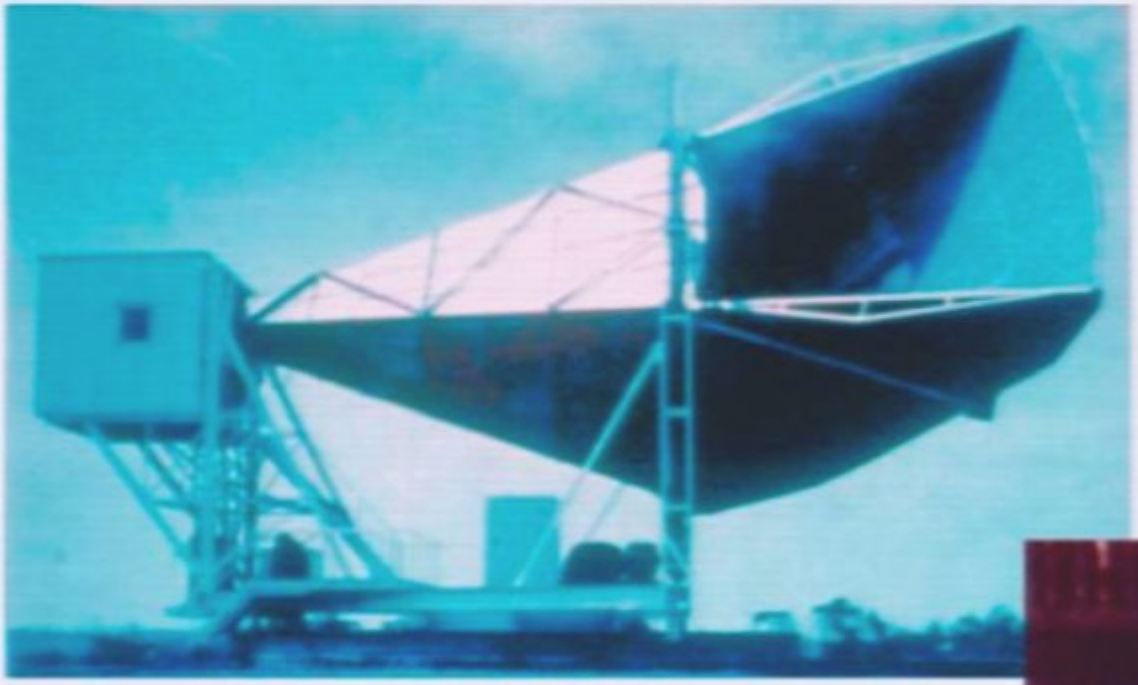
Why Microwave?

Why Microwave?

- Universe was ~ 3000° K at 380,000 yr
- Full of visible light (~1μm)

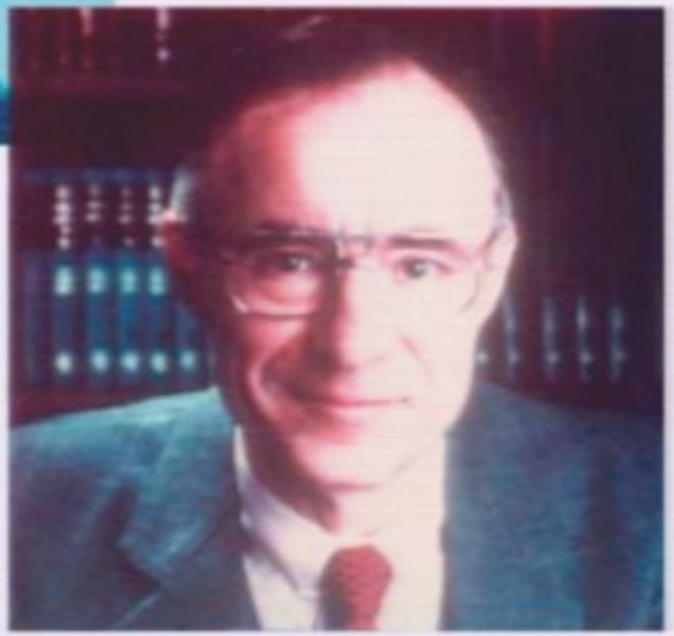
Universe is expanding

Discovery of Cosmic Background



Microwave Receiver

Robert Wilson



Arno Penzias

Graphic from WMAP website

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Why Microwave?

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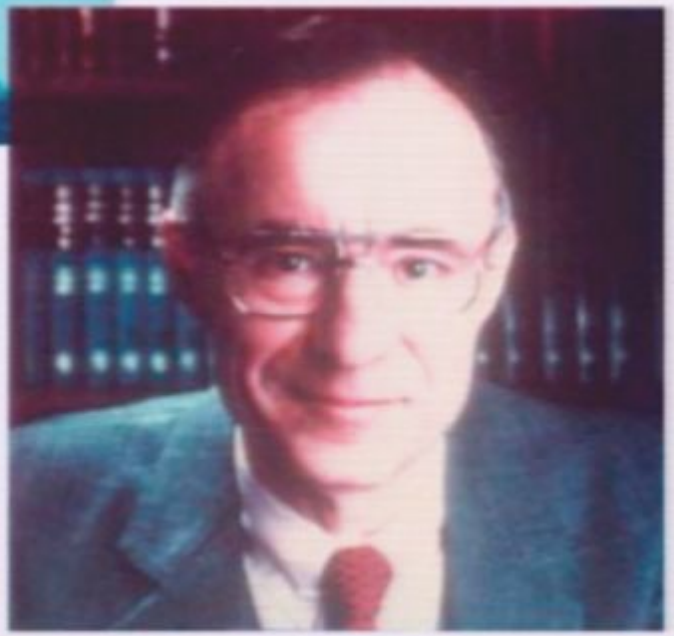
Universe is expanding

- Causes light to change wavelength
- Visible light becomes microwaves (~1cm)

Discovery of Cosmic Background

Microwave Receiver



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Graphic from WMAP website

- 400 photons per cubic cm !

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Graphic by Wayne Hu, http://background.uchicago.edu/~whu/beginners/introduction.html

The History of CMB observations

1965

Penzias and Wilson

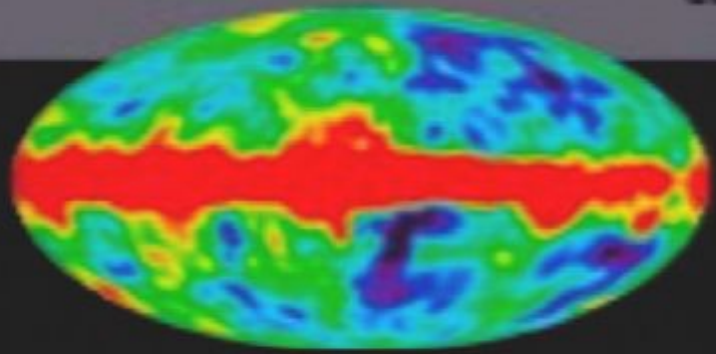
1965

Discovery

1992

COBE

1992



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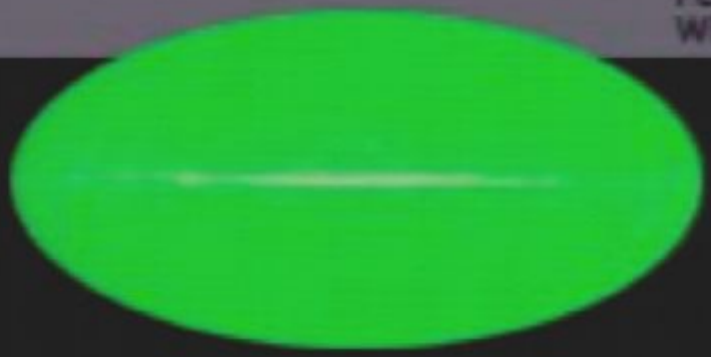

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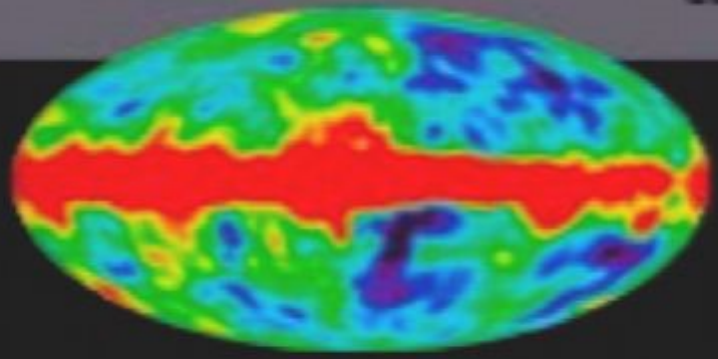
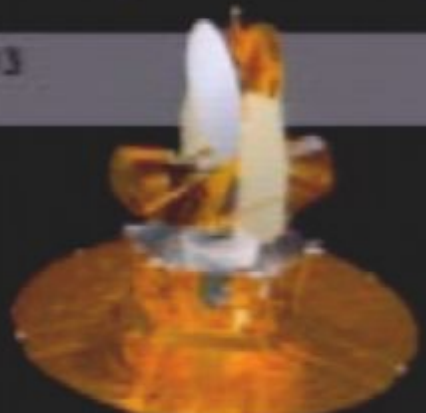


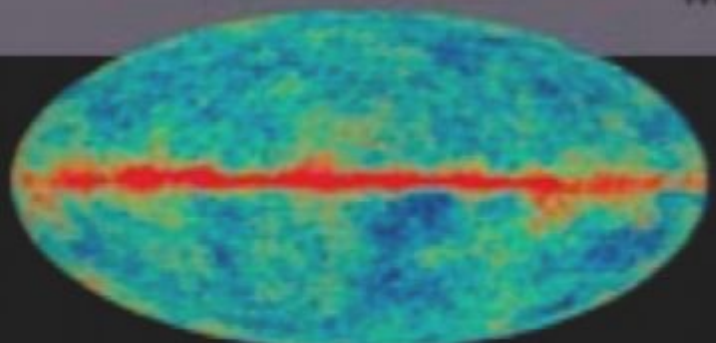
COBE

2003

WMAP



2003



WMAP

Graphic from WMAP website

The frequency spectrum

The frequency spectrum

- Universe in equilibrium -> Black body
- Observe perfect black body at 2.73K

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- Can relate present day no. photons, protons, 13.6eV to get $T_{recombimation}$.
  - From T_{CMB} today, get $z_{recombination}$

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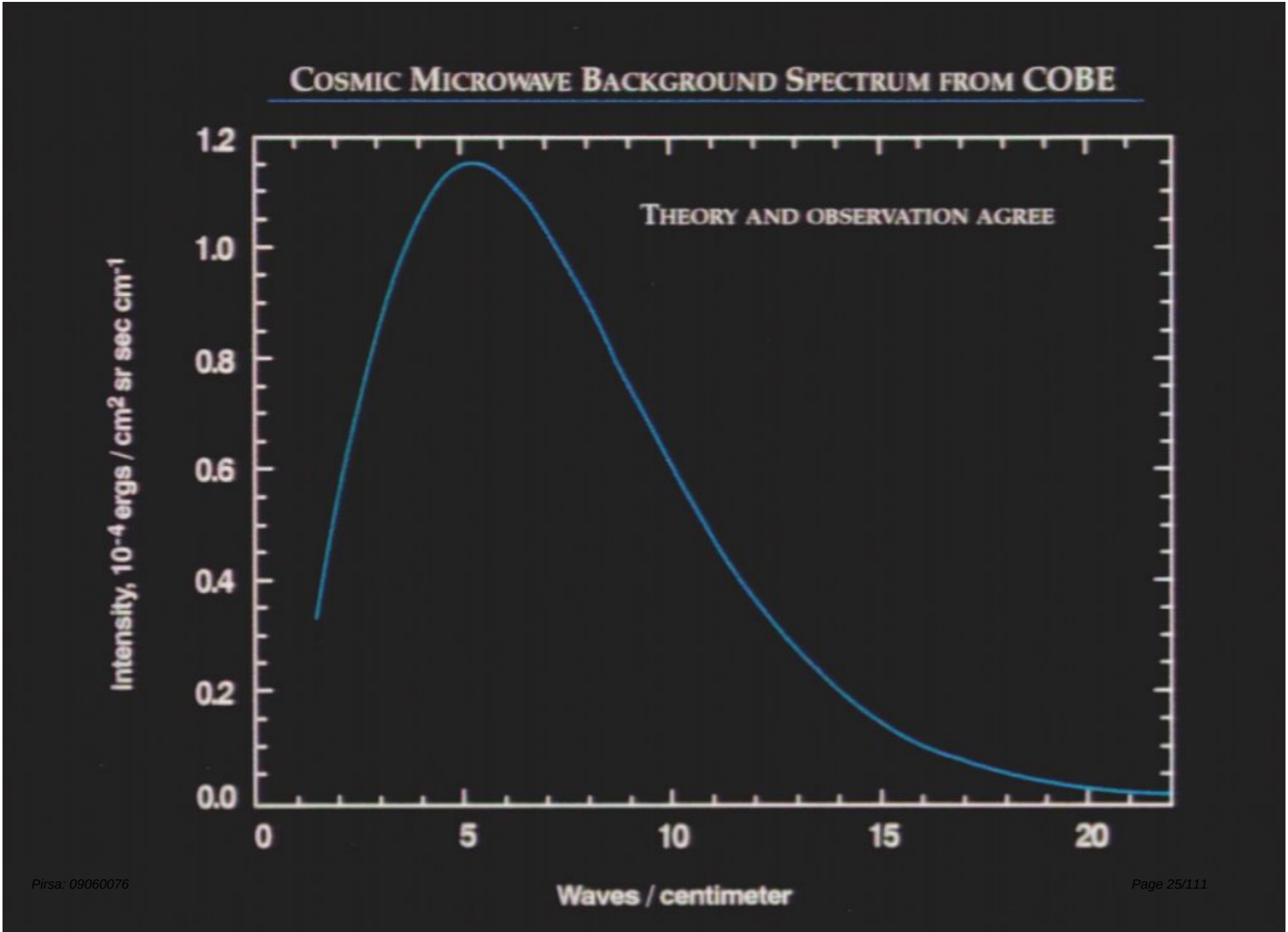
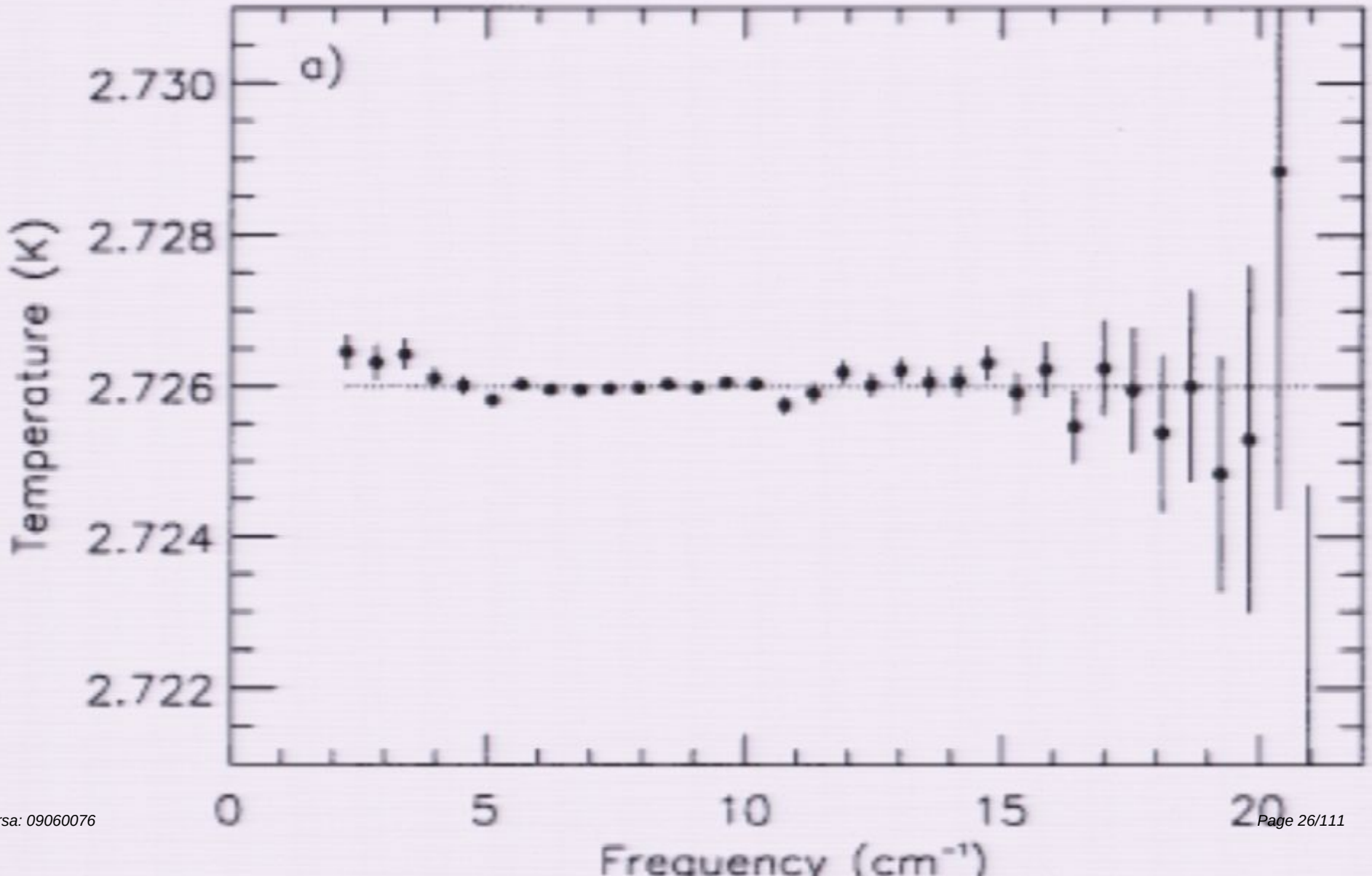

COSMIC MICROWAVE BACKGROUND SPECTRUM FROM COBE
THEORY AND OBSERVATION AGREE
Intensity, 10-4 ergs / cm2 sr sec cm-1
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
Waves / centimeter

COBE residuals (Mather et al 1994)



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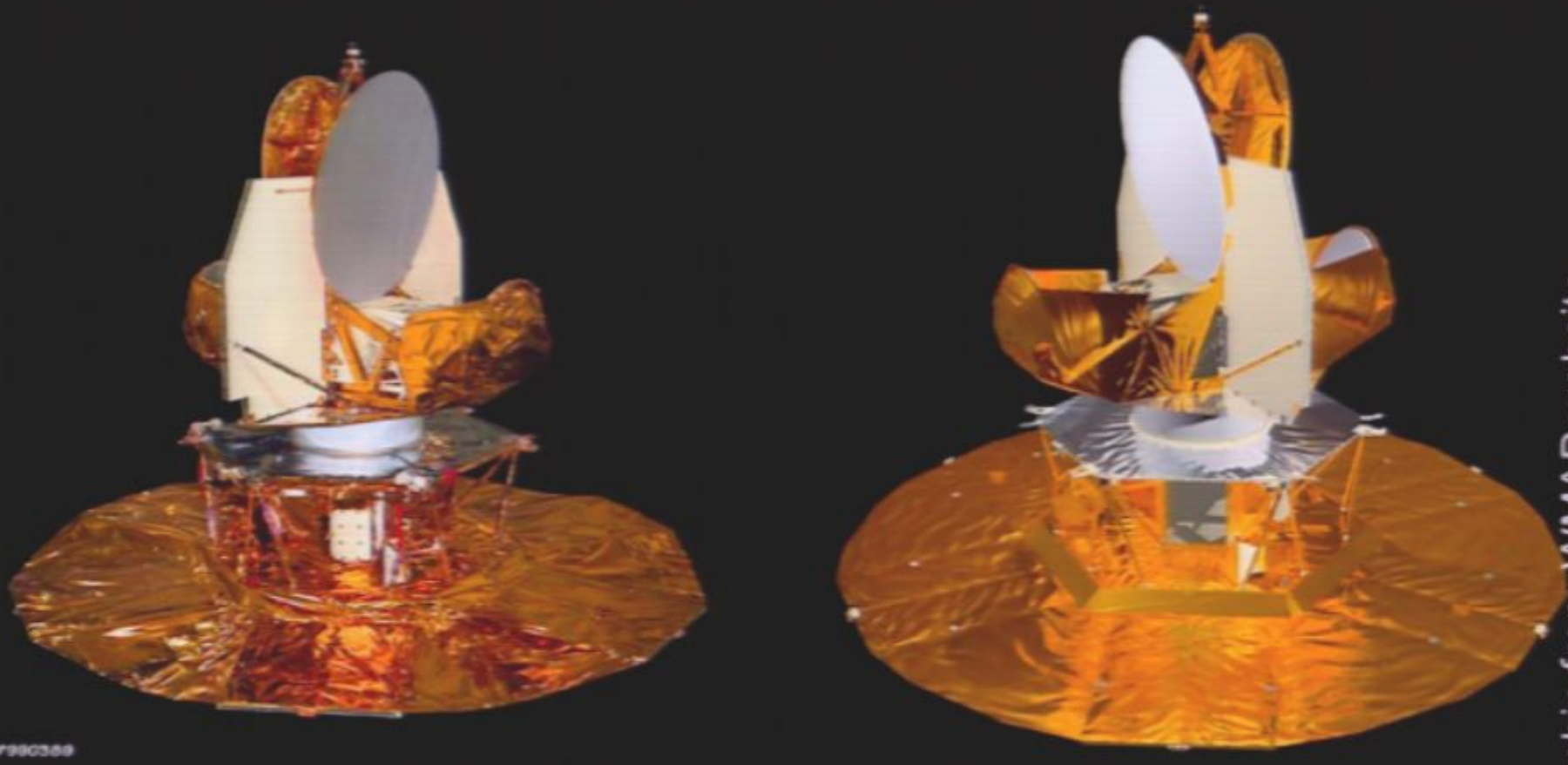
The WMAP Satellite



Graphic from WMAP website

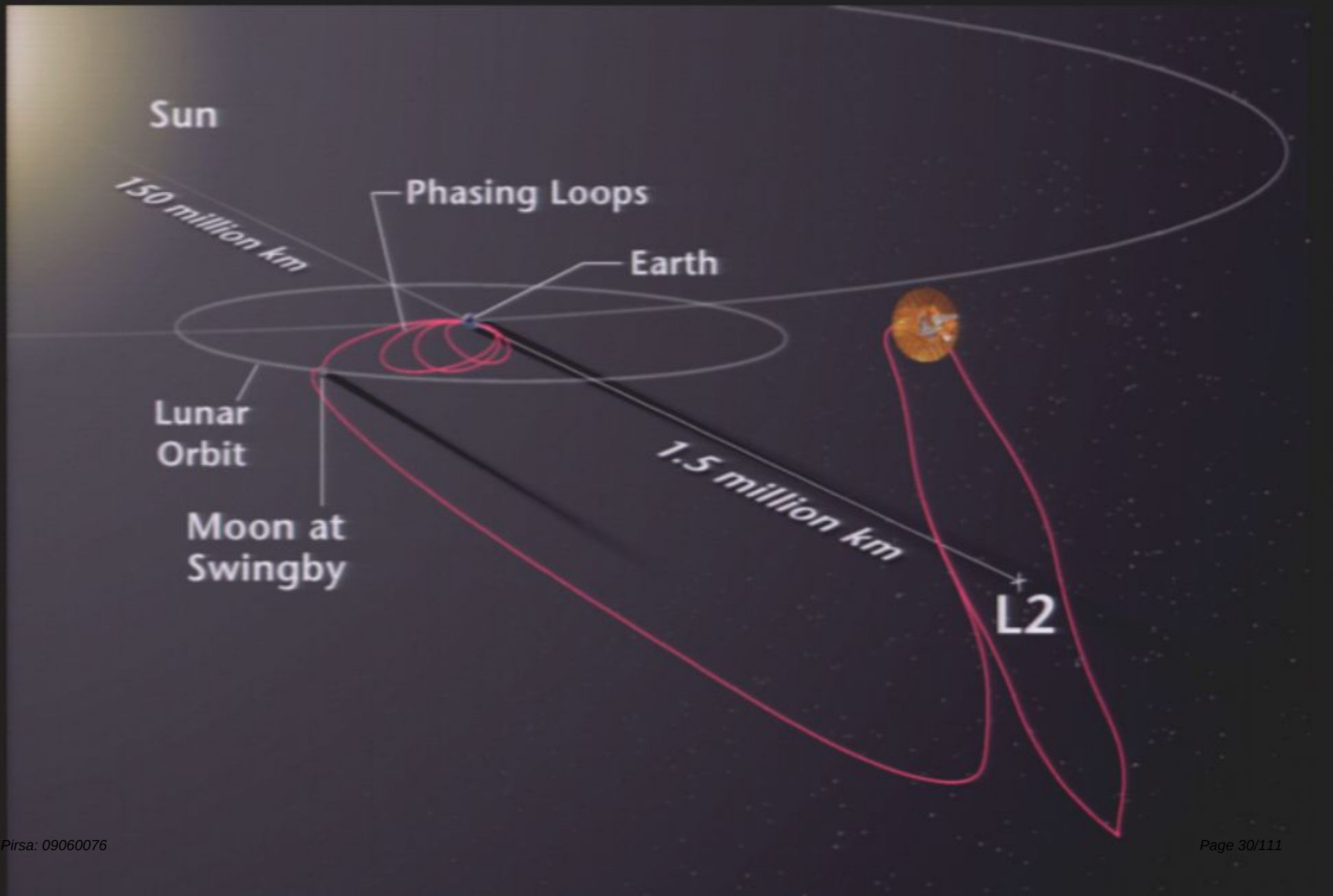
WMAP=Wilkinson Microwave Anisotropy Probe

WMAP Launch

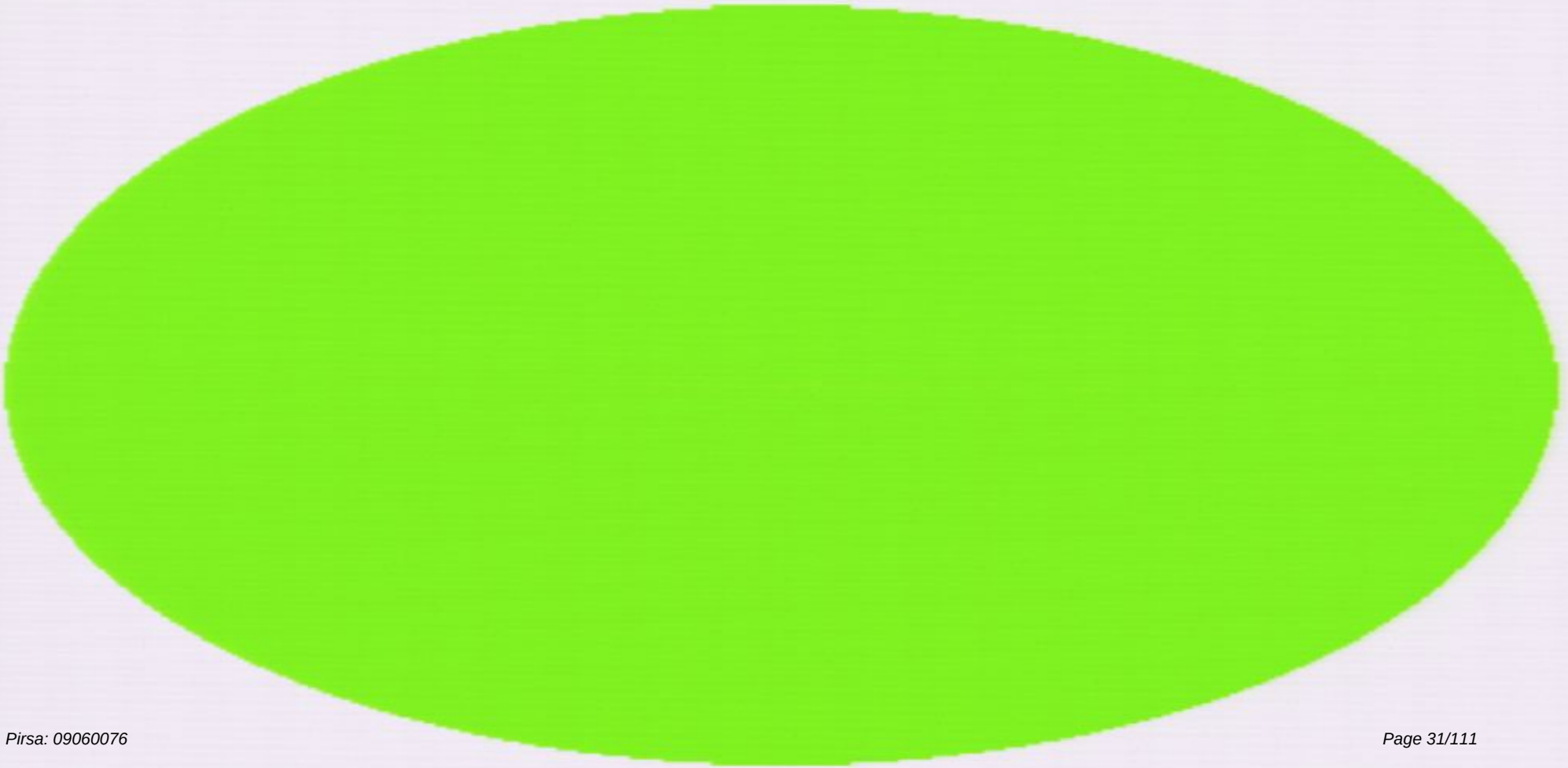
June 30, 2001 at 3:47 EDT

Delta II Model 7425-10
Delta Launch Number 286
Star-48 third stage motor
Cape Canaveral Air Force Station
Pad SLC-17B

Trajectory to L2



What WMAP saw



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The Isotropy of the CMB

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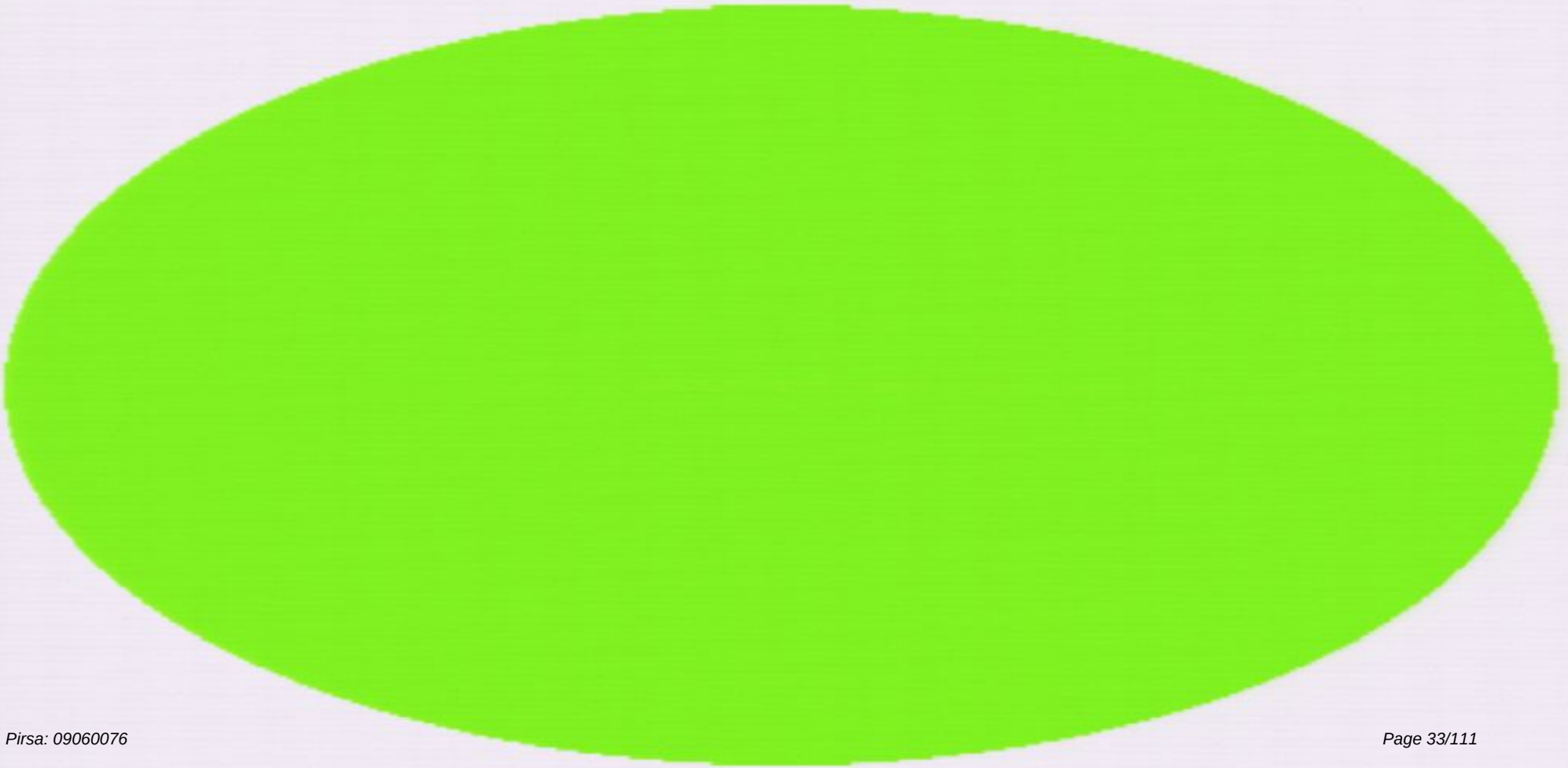


Graphic from WMAP website

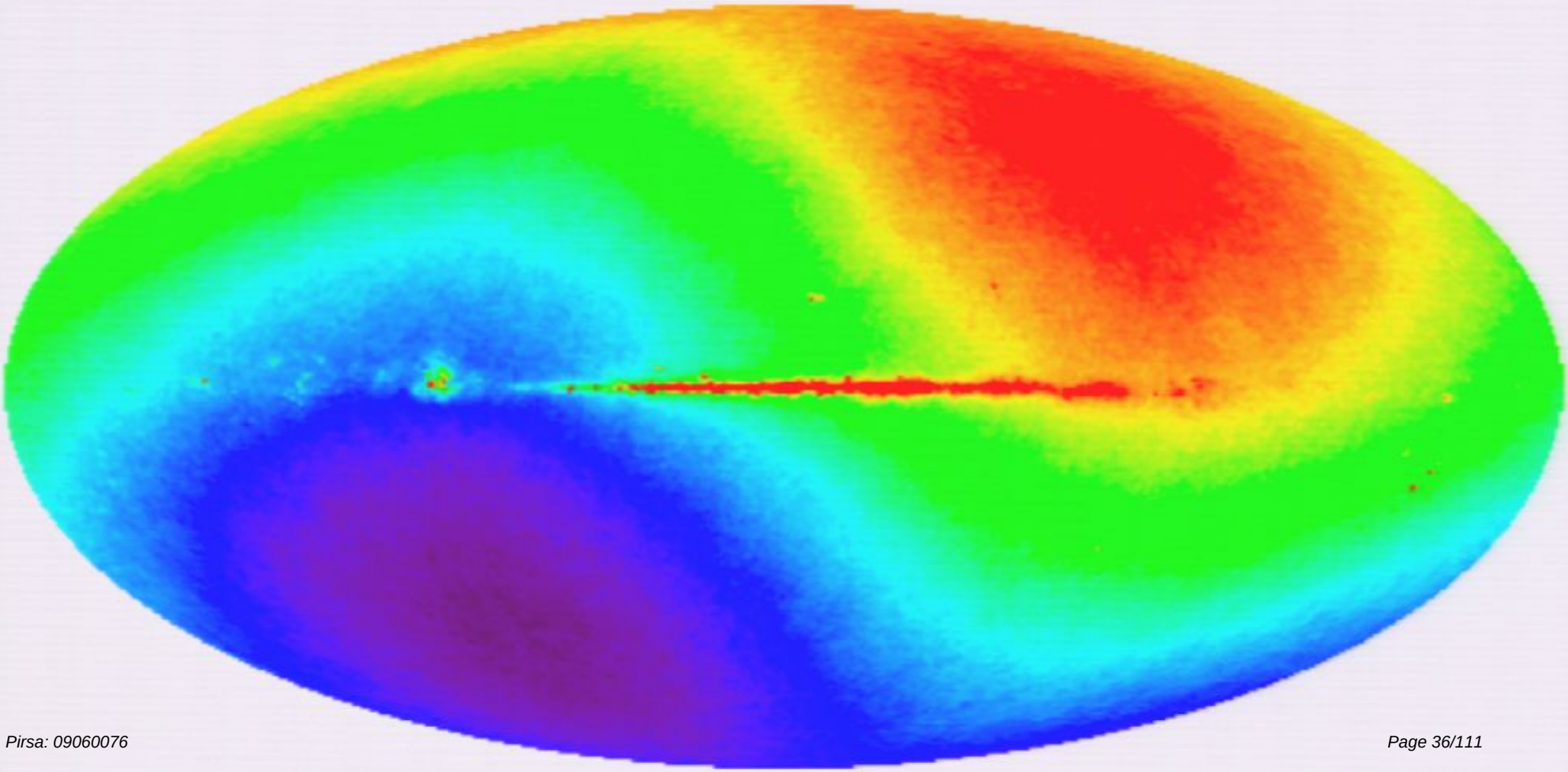
The Isotropy of the CMB

The Isotropy of the CMB

- CMB = snapshot of z~1000 universe
  - z~1000 universe was homogeneous
- Leads to 'Horizon problem'
  - Horizon size ~ c x time since Big-Bang
  - Horizon at z~1000 is ~ 1° on sky
  - Sky at 0° and 180° not yet 'causally connected'
- 'Inflation' invoked to solve
  - Rapid expansion expands horizon scale to greater than observable universe size

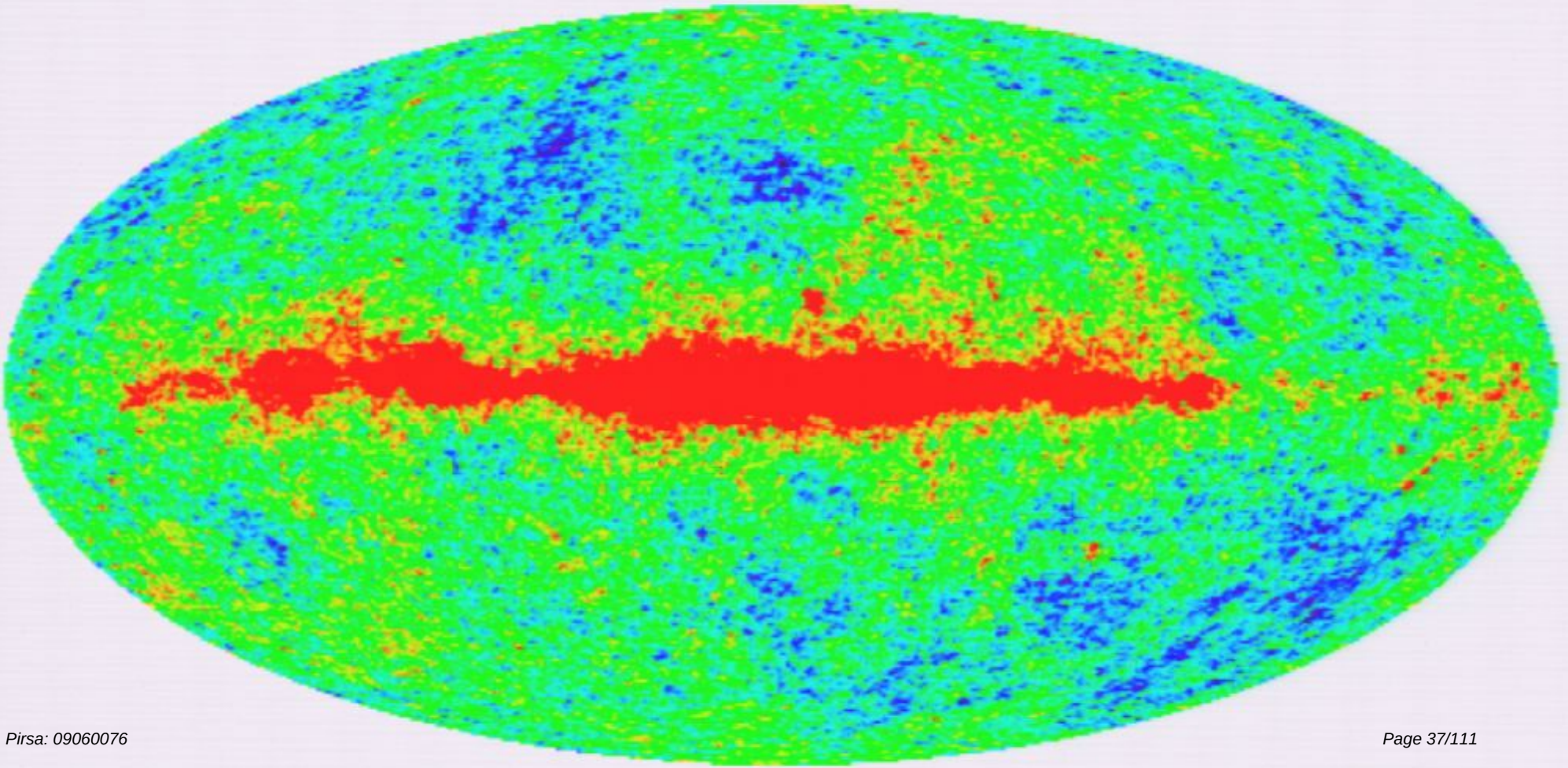
Zooming the colour scale…

1 in 1000



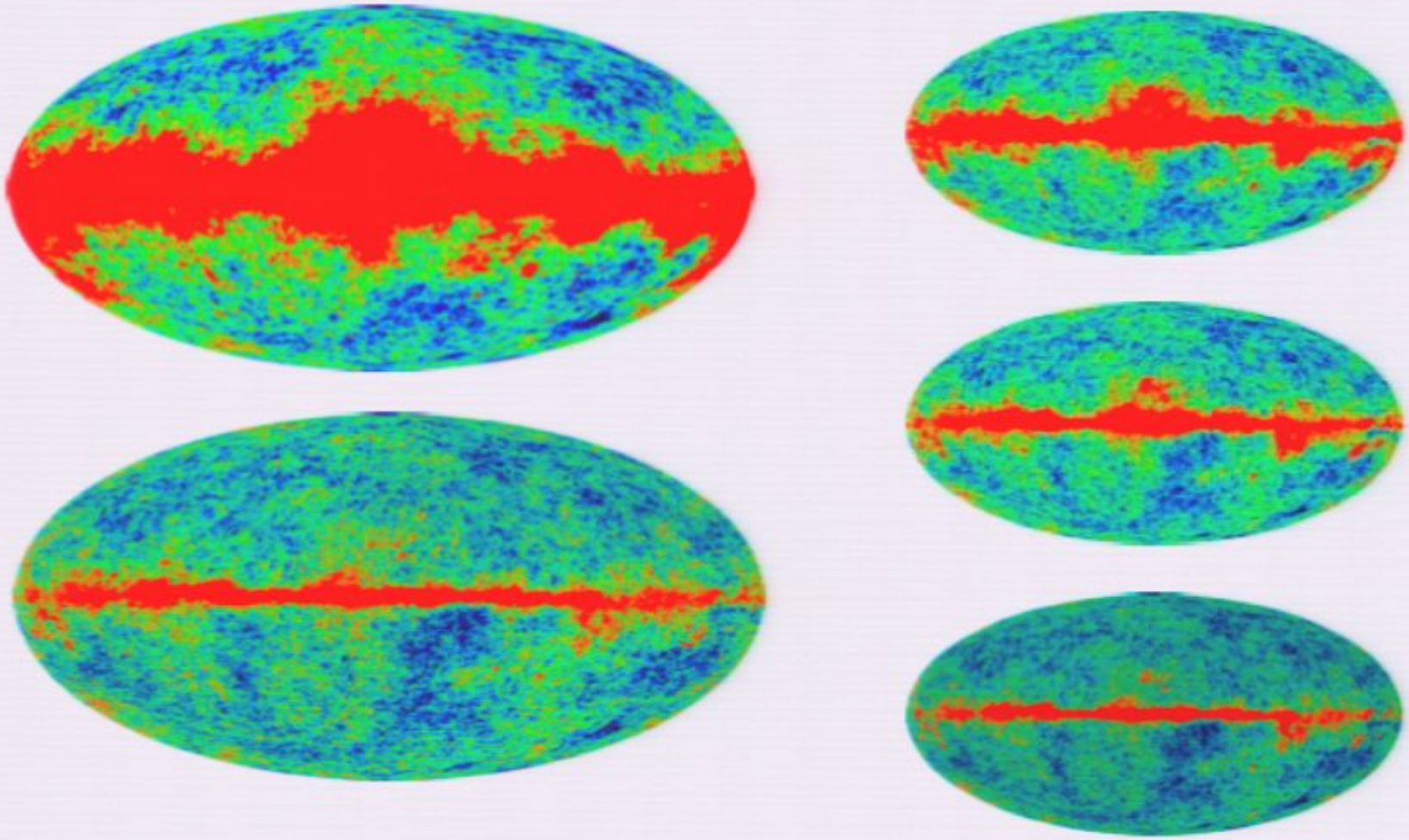
Graphic from WMAP website

Removing the effect of our motion through the galaxy



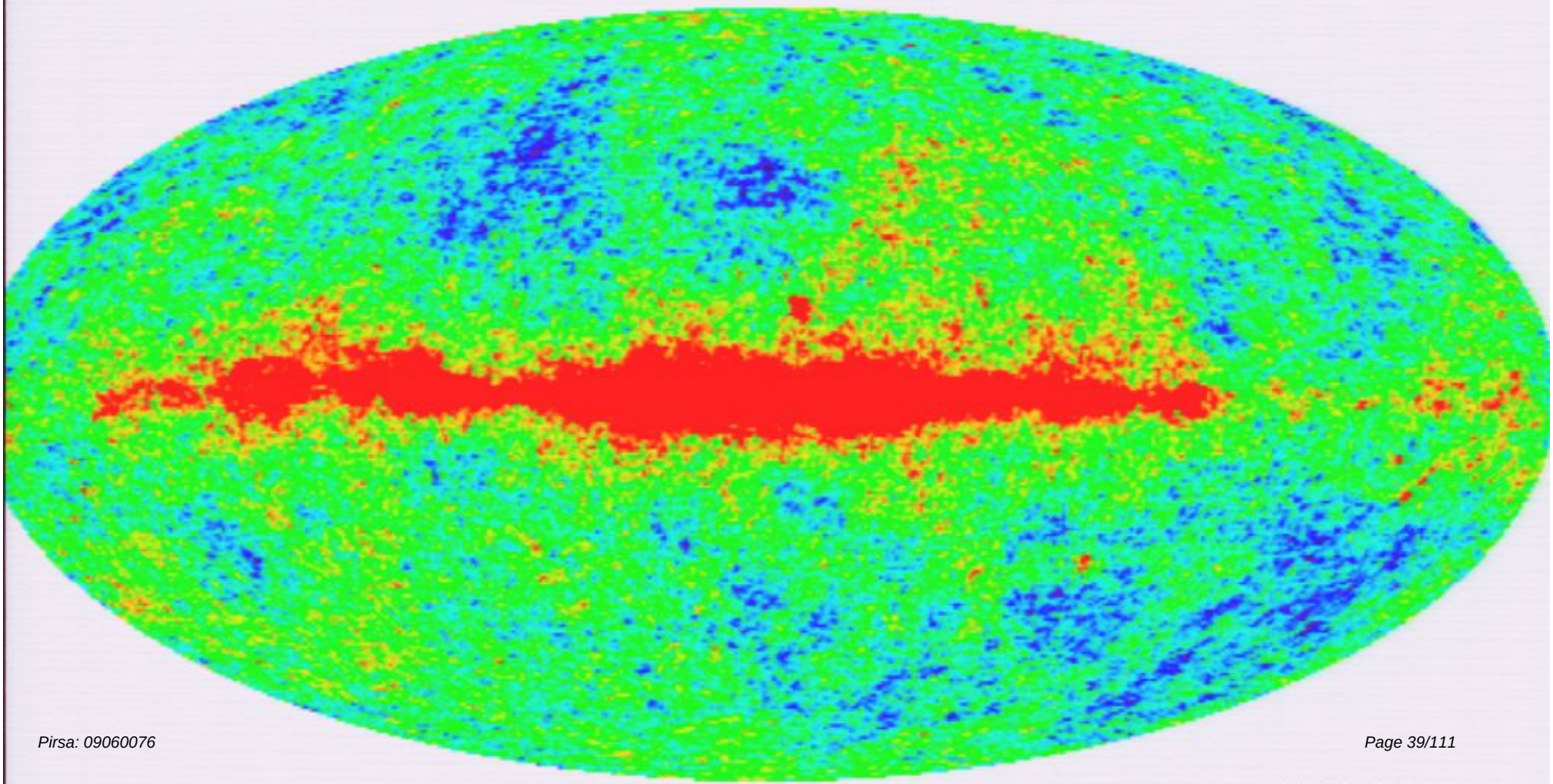
Graphic from WMAP website

Observations in 5 frequency bands
23 GHz to 90 GHz



Graphic from WMAP website

Dust in our galaxy is the most prominent feature



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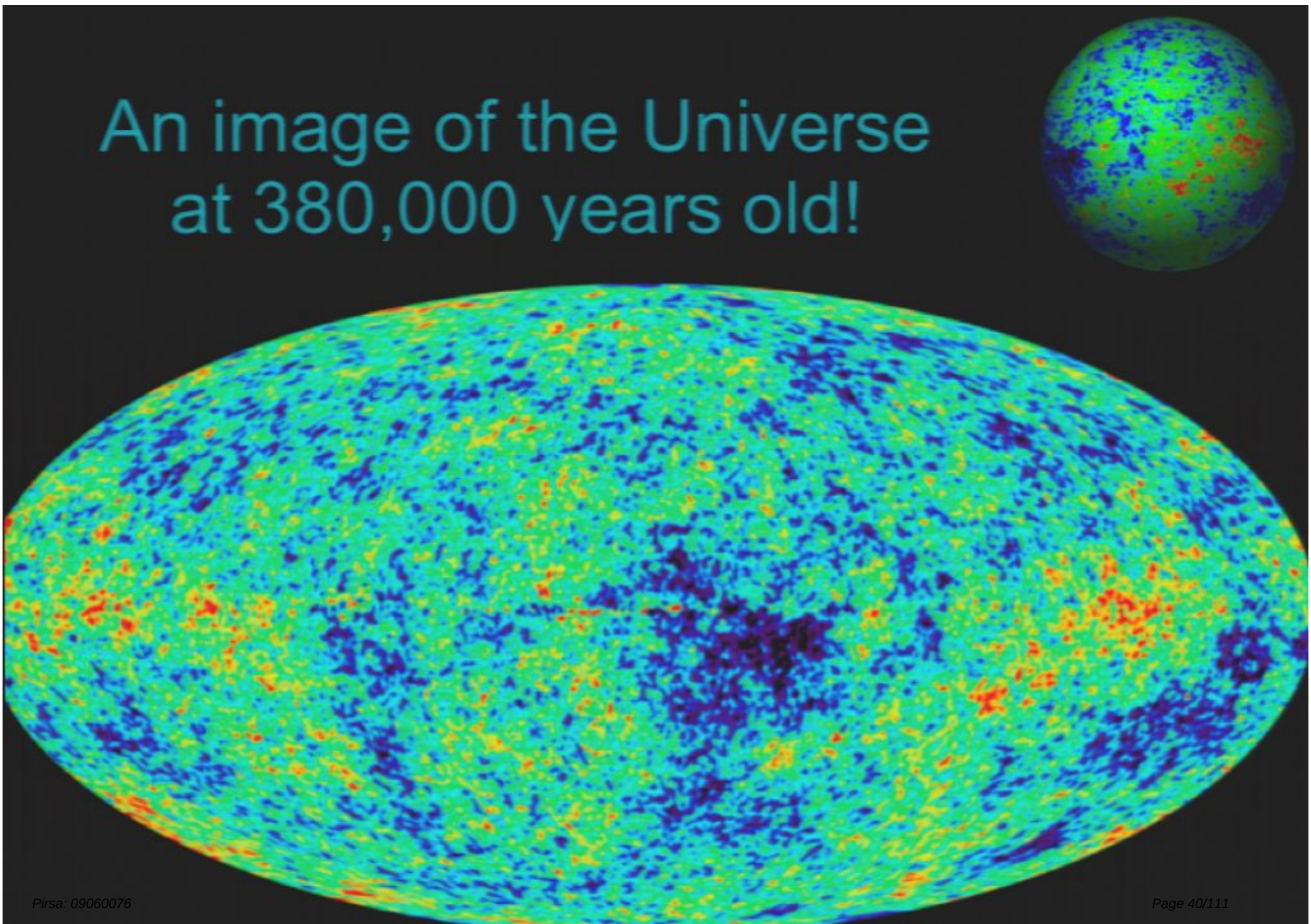
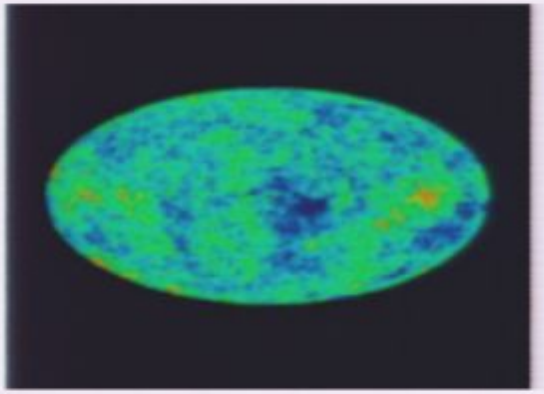
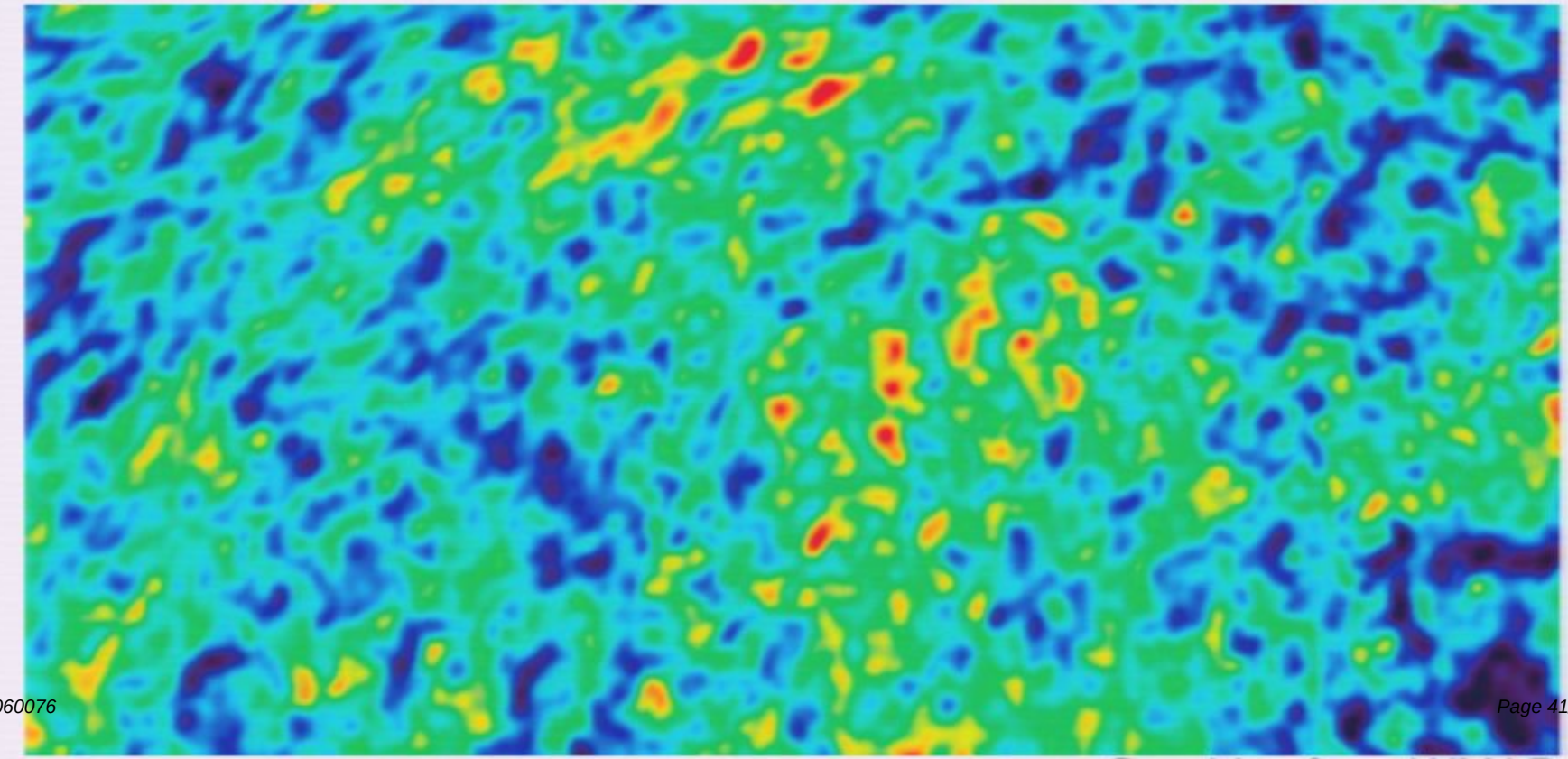
An image of the Universe at 380,000 years old!



Graphics from WMAP website

A characteristic scale exists of ~ 1 degree





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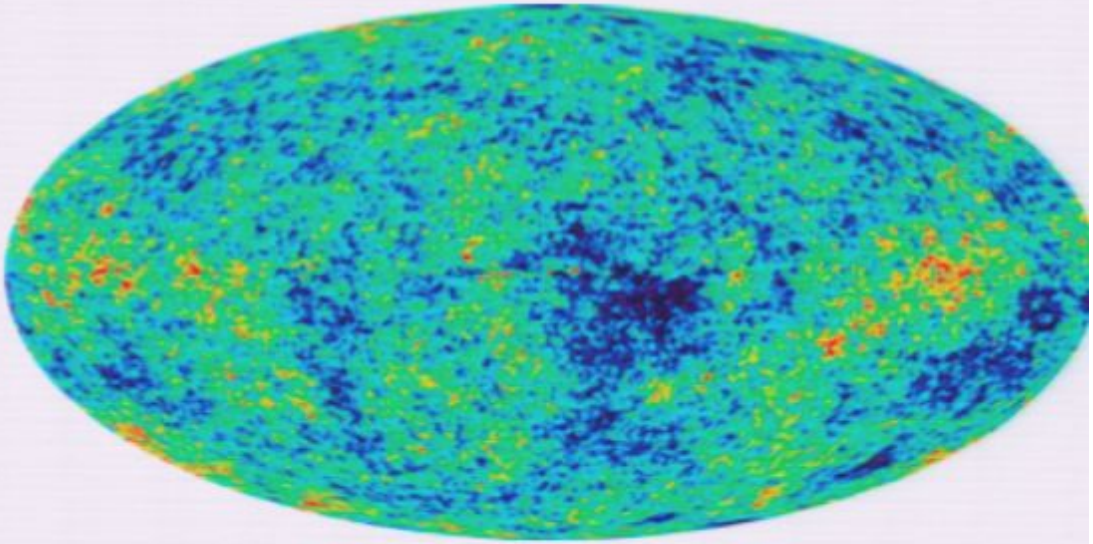
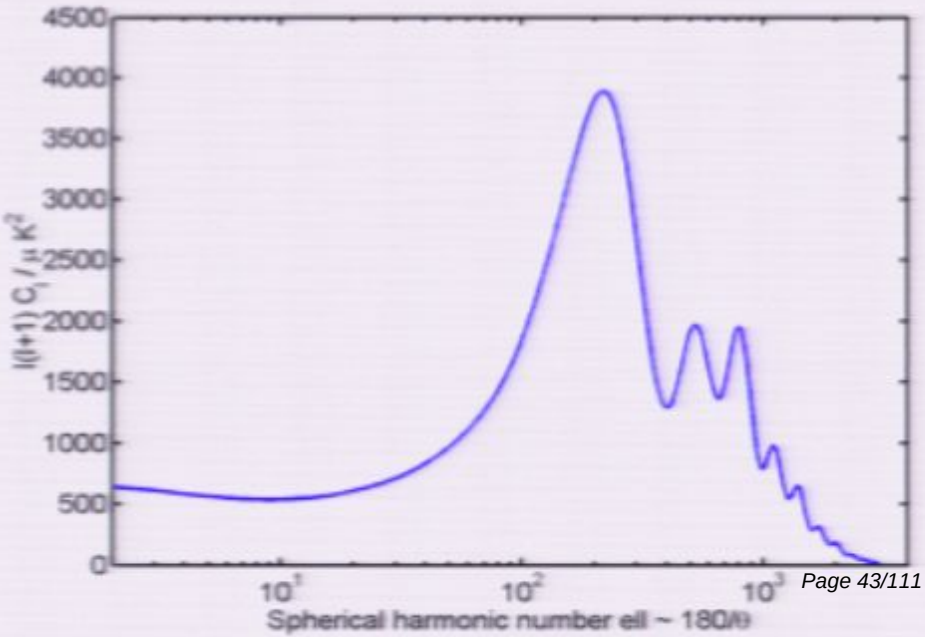
Statistical properties





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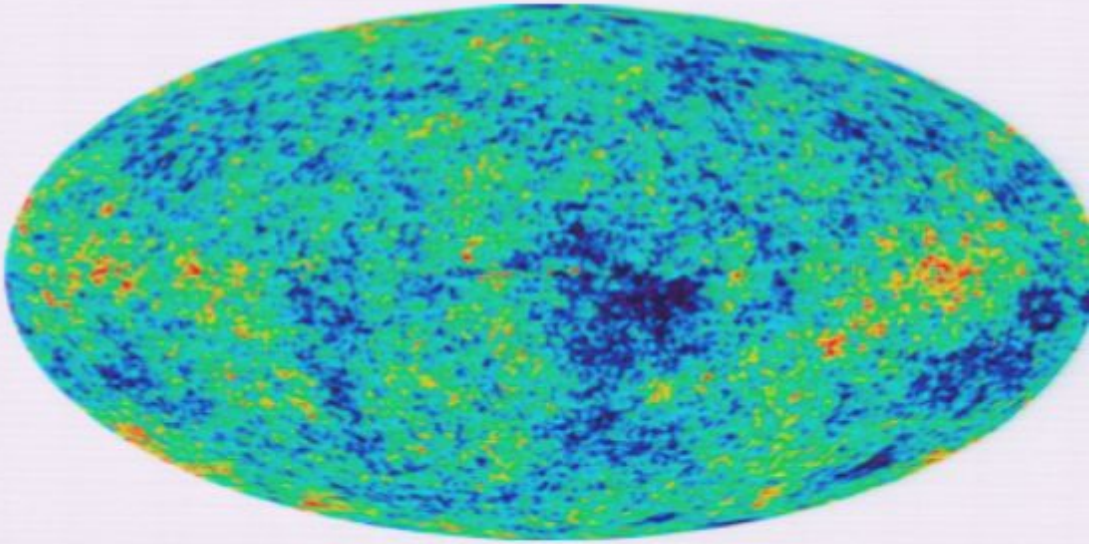
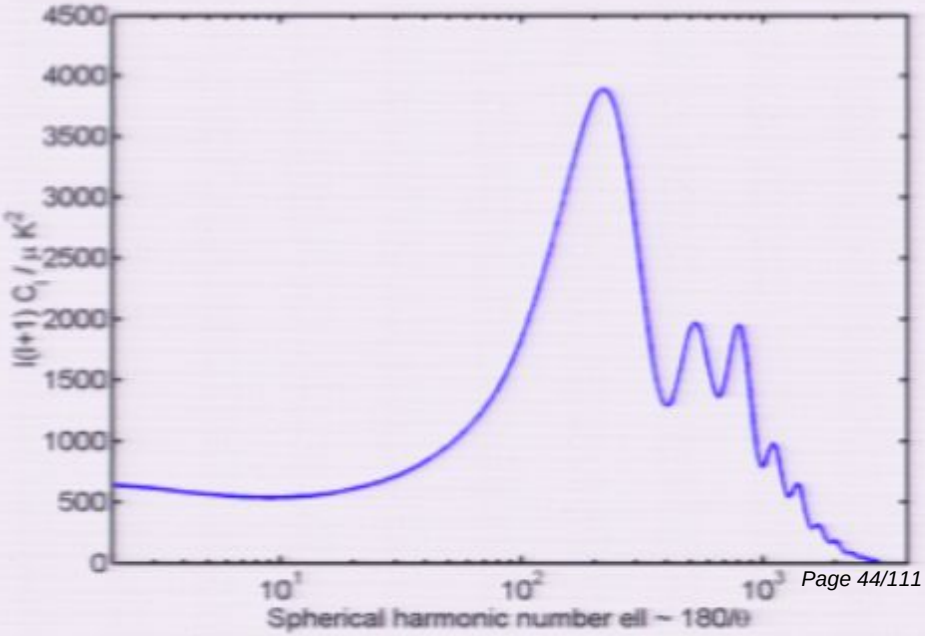


- Spherical harmonic transform
- ~Fourier transform



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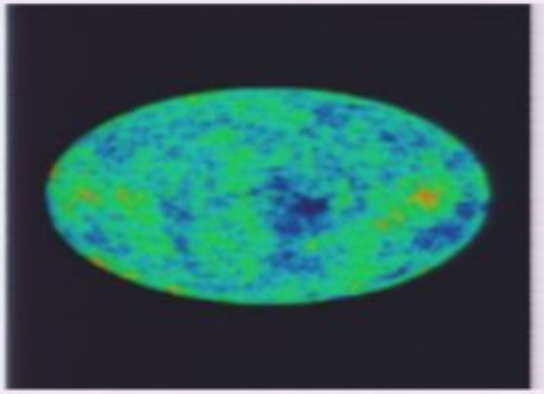

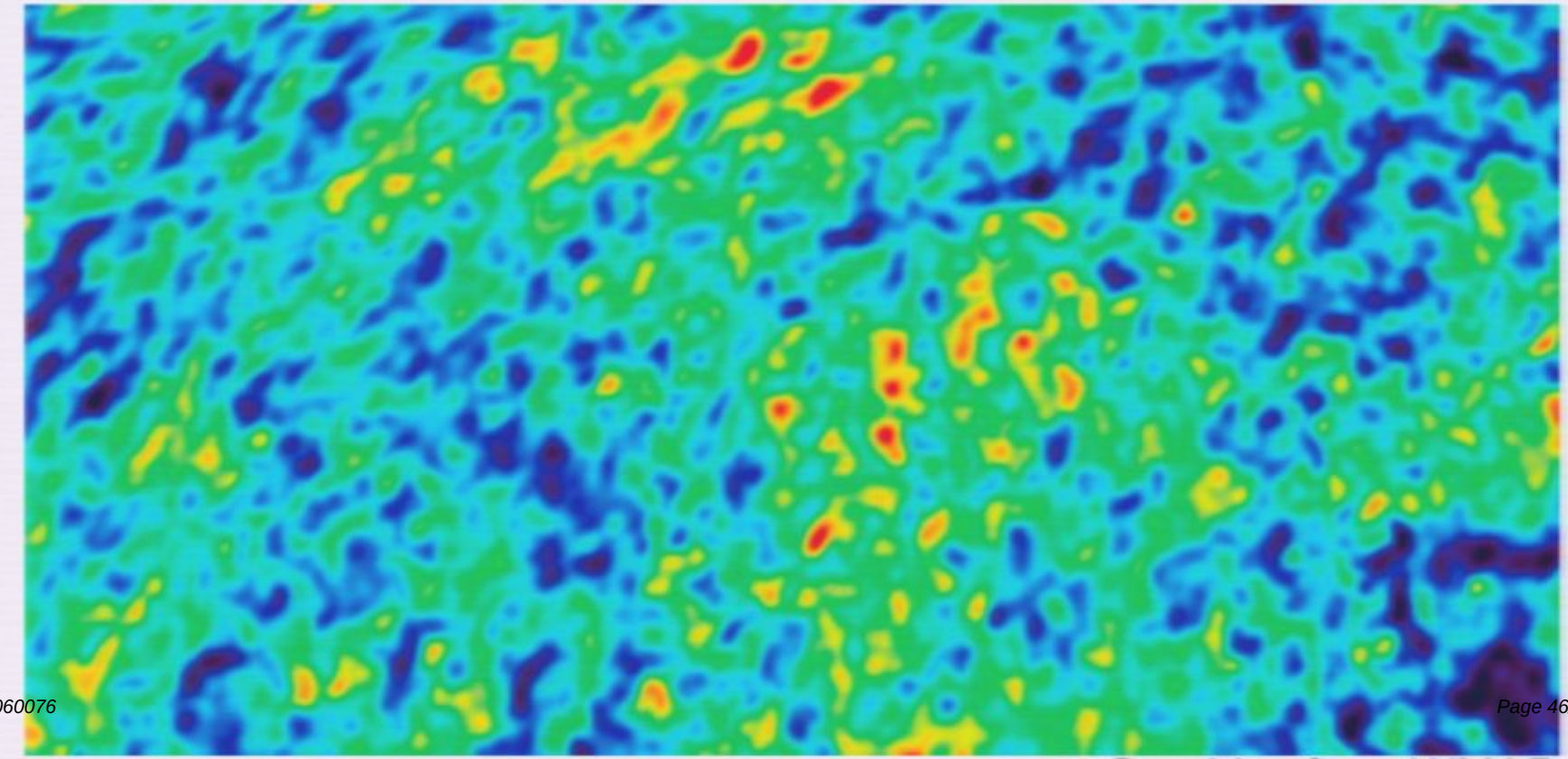

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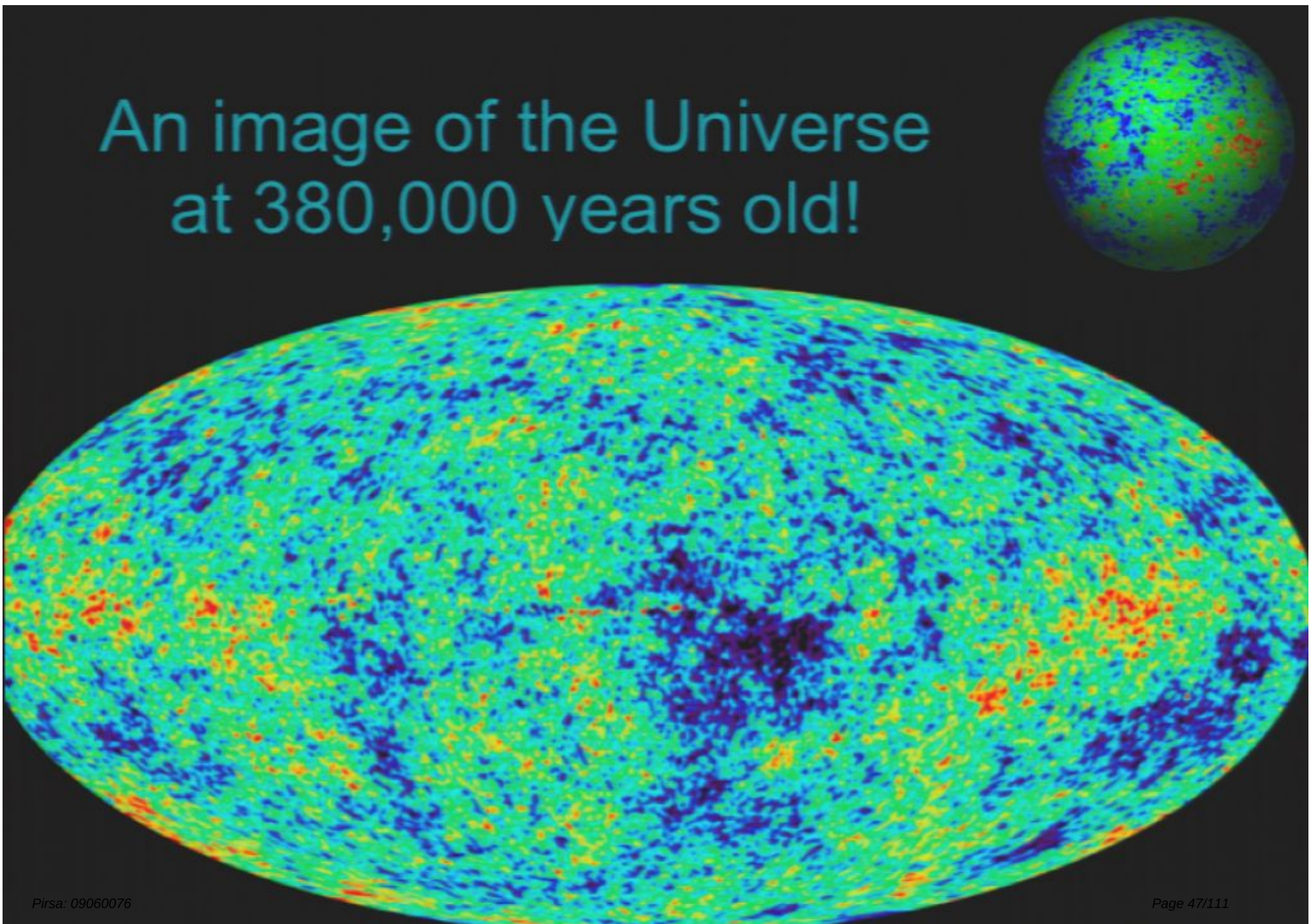

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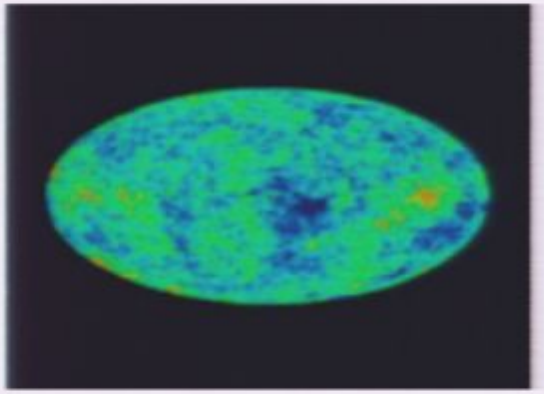

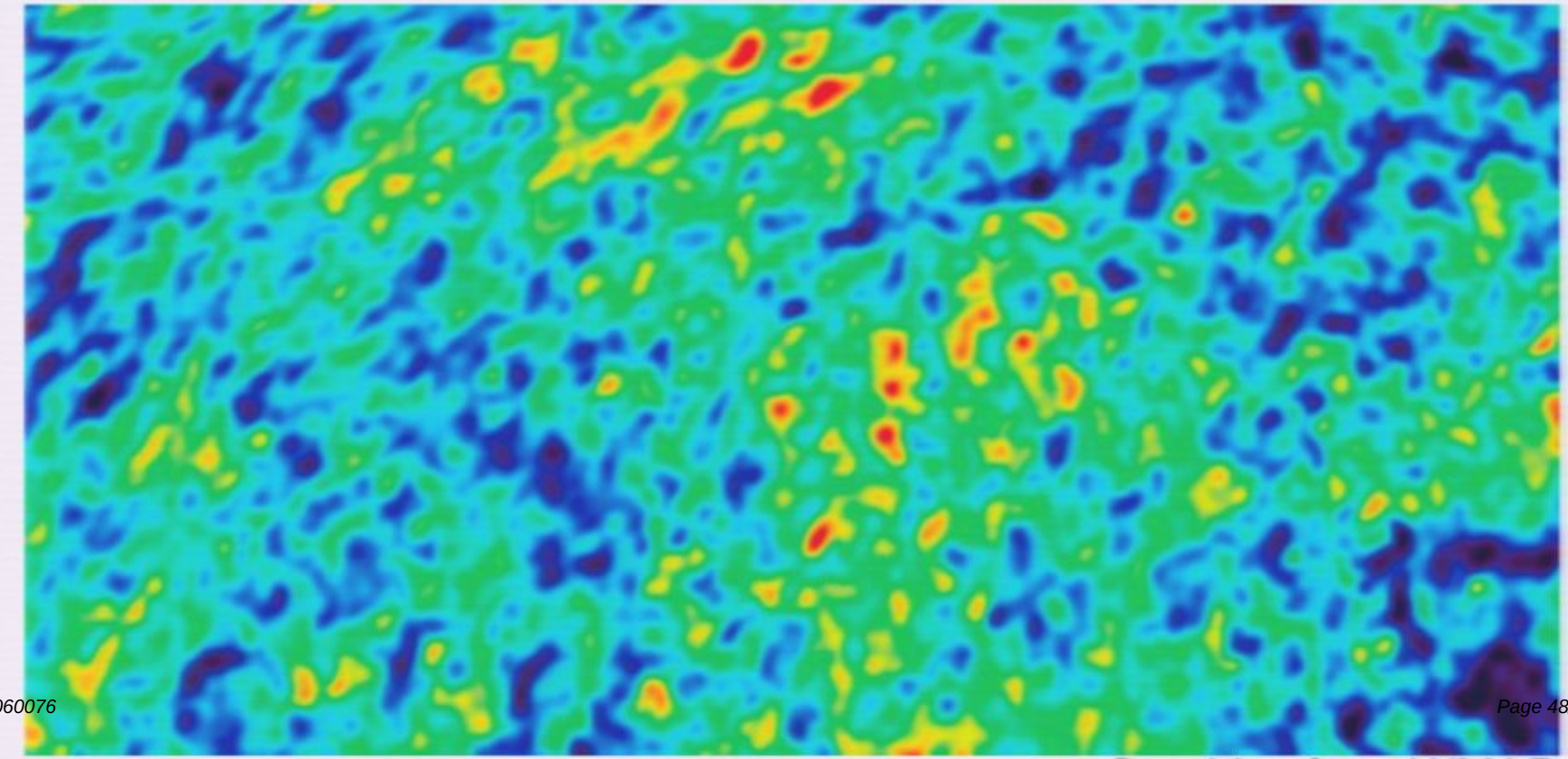

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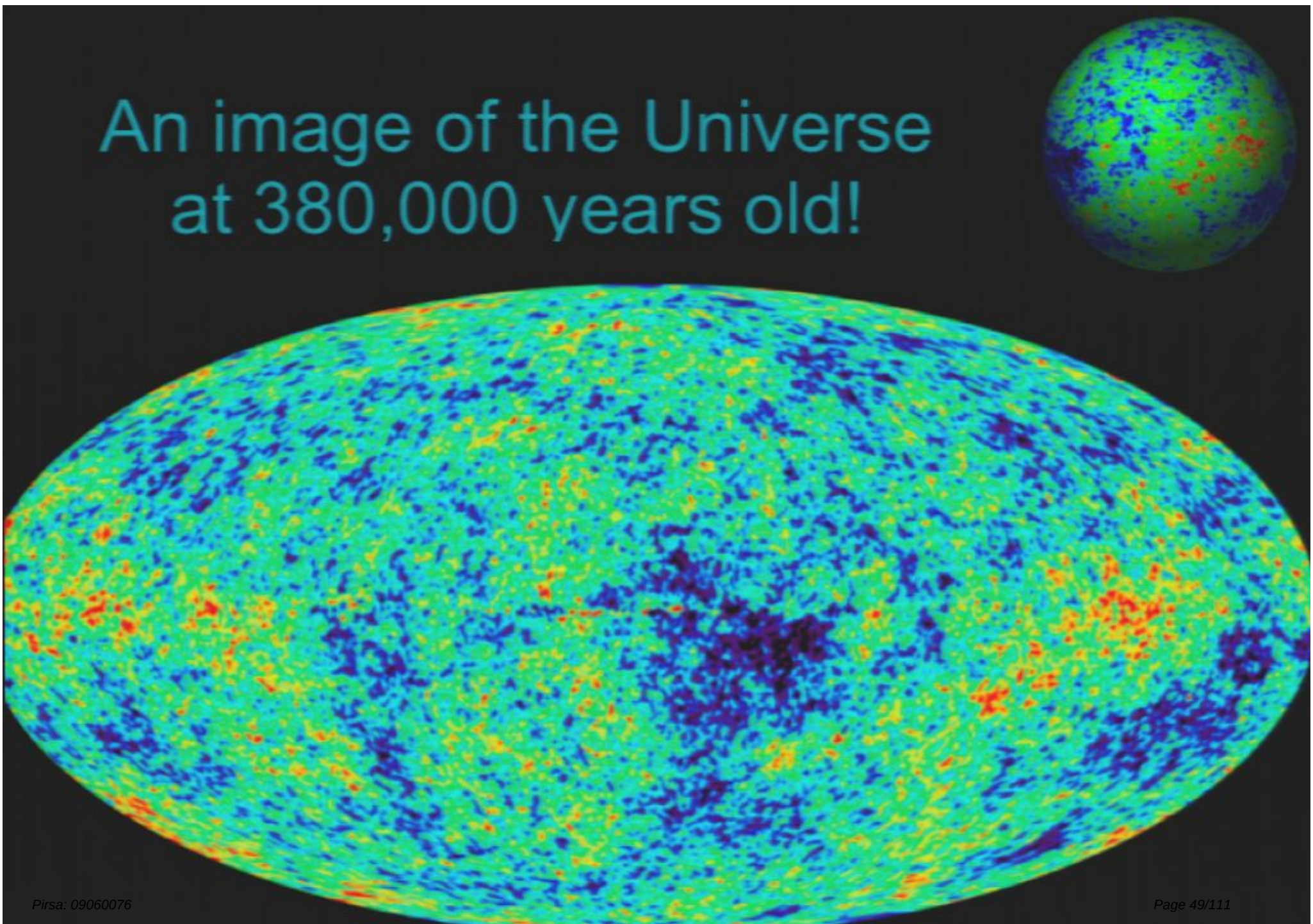

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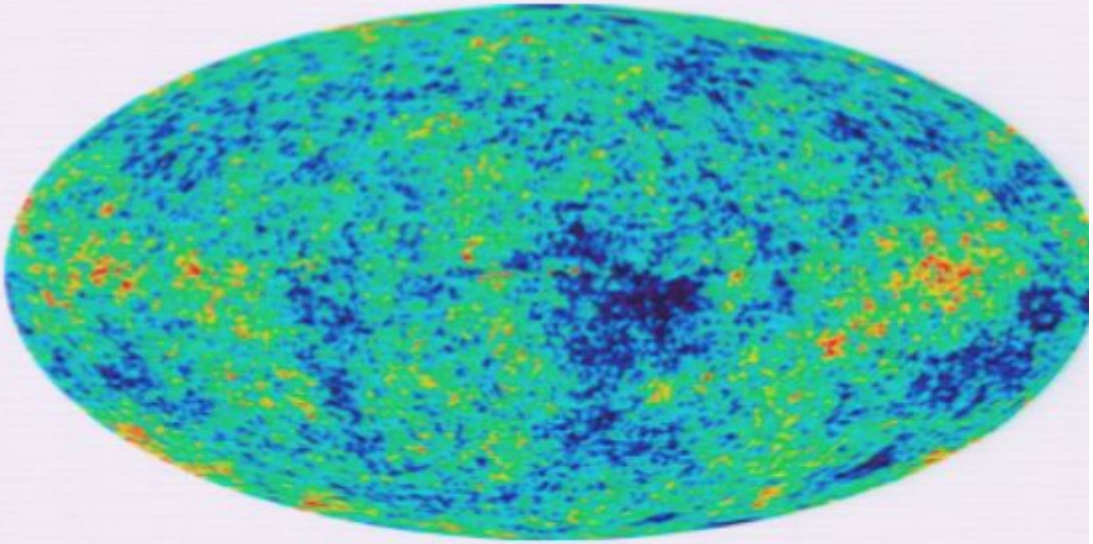

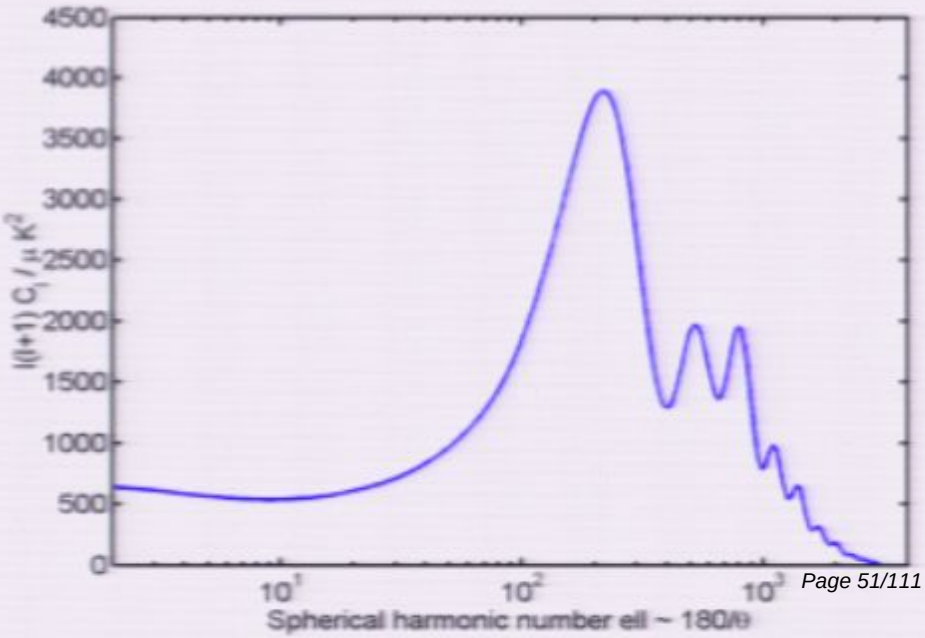

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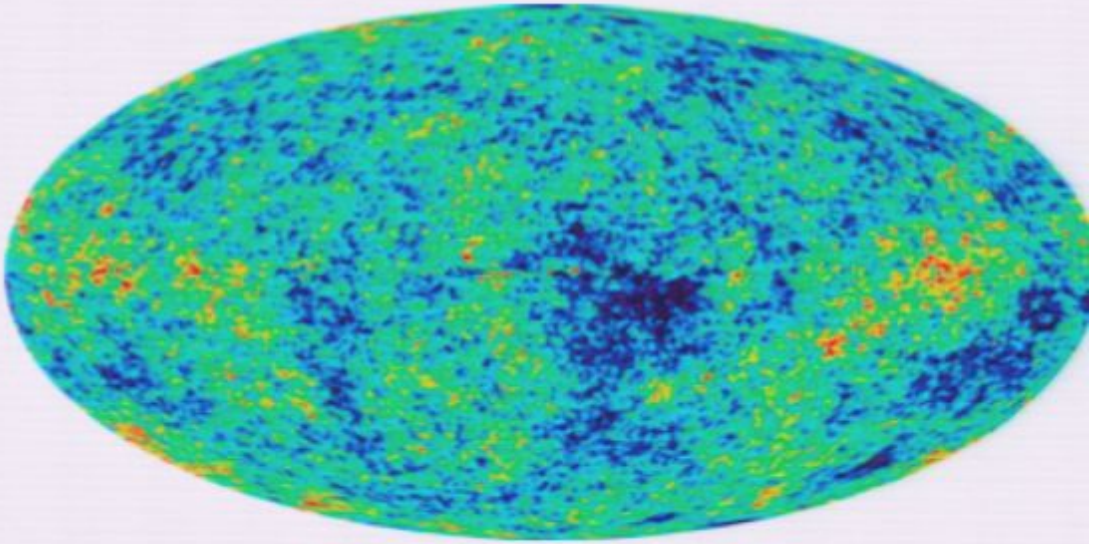
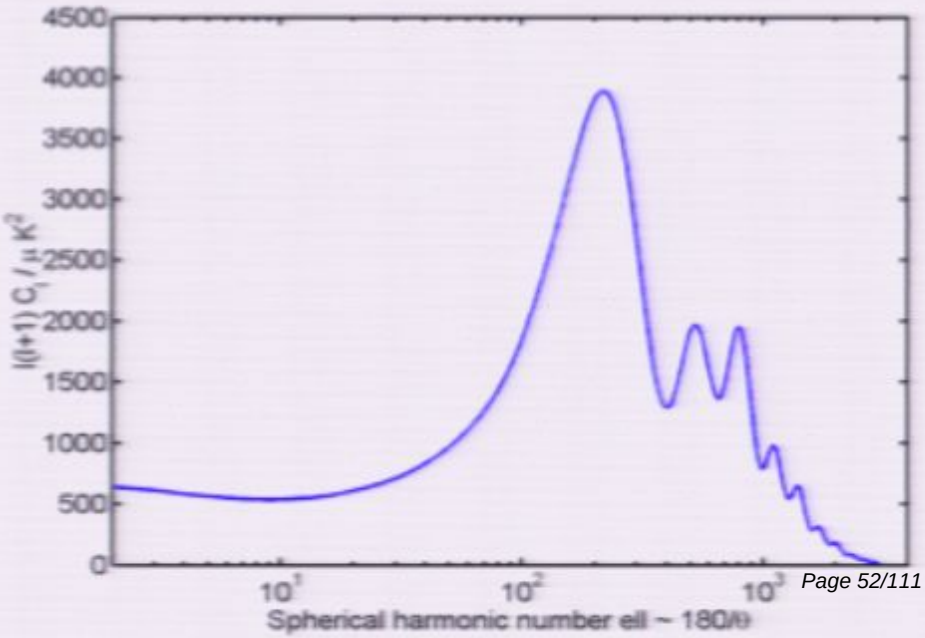


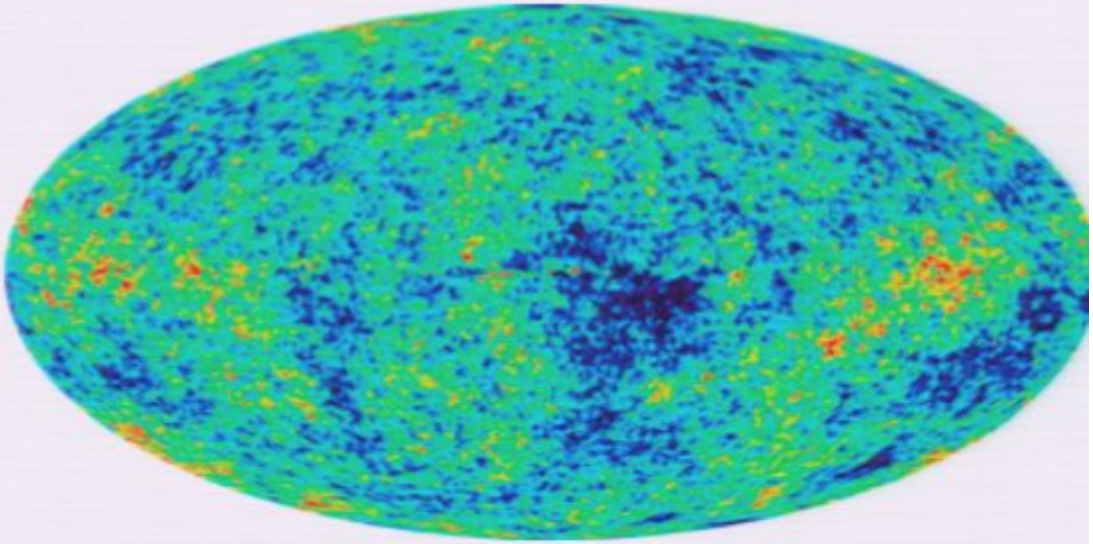
- Spherical harmonic transform

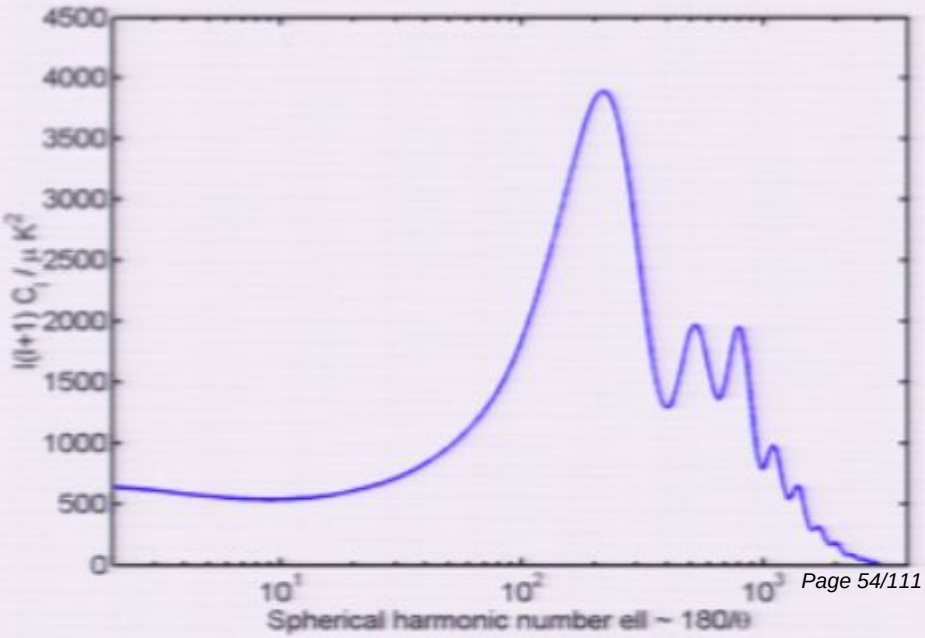


What are the C_ℓs?

- Qualitatively: ~power in each Fourier mode
- Quantitatively:

Statistical properties





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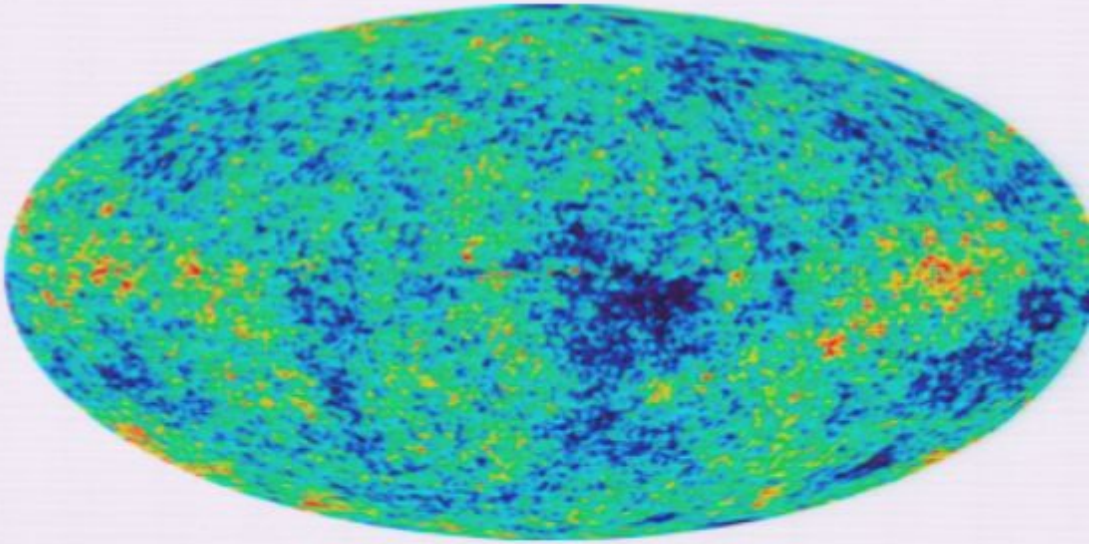

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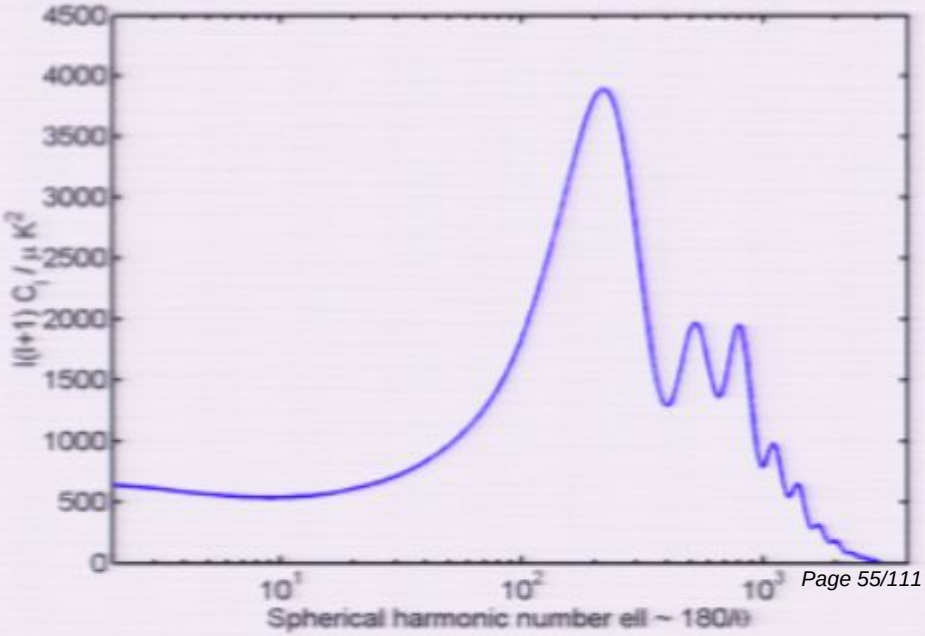

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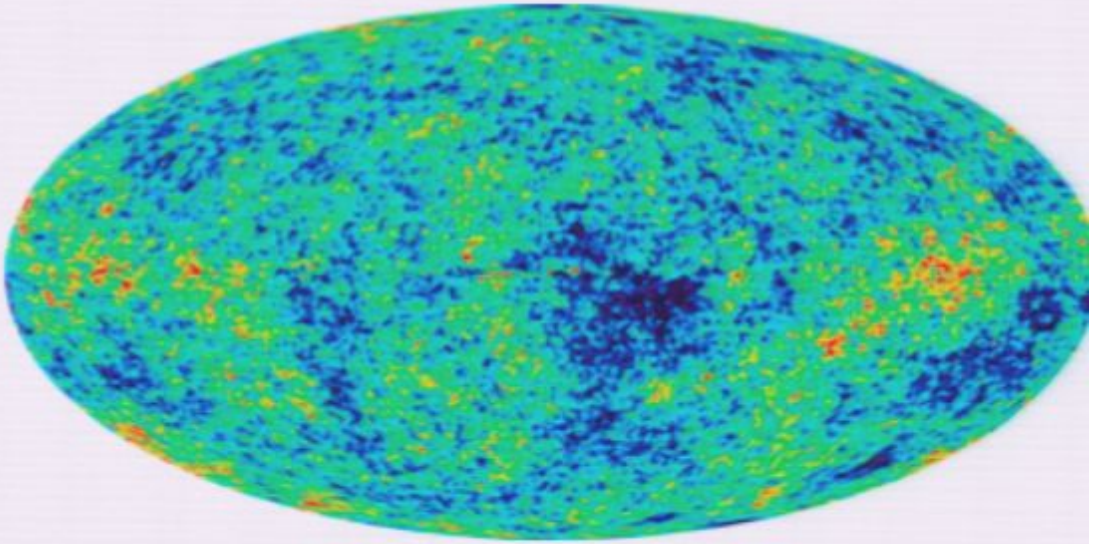
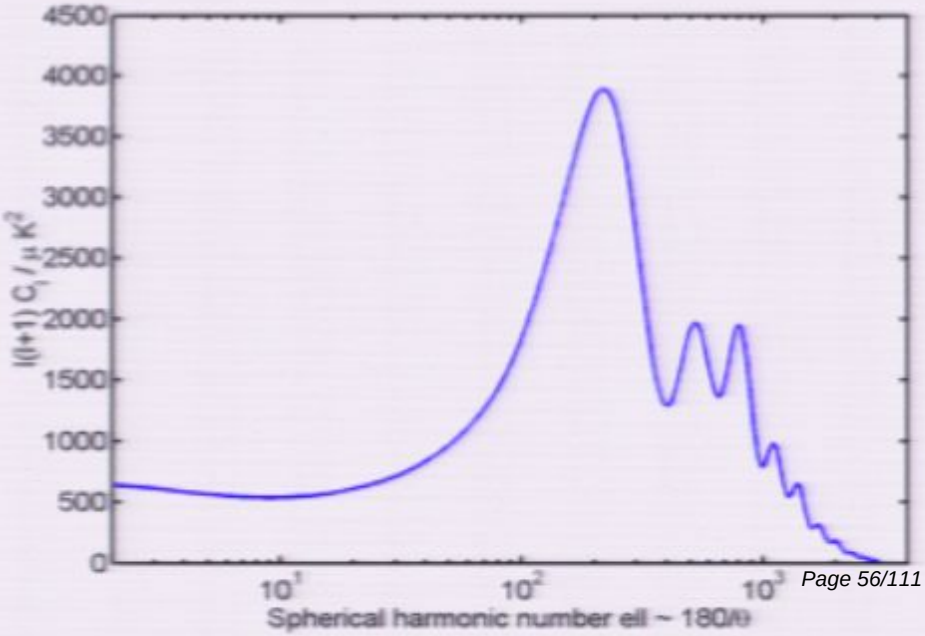


- Spherical harmonic transform
- ~Fourier transform
- Quantifies clumpiness on different scales



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$$T_{\rm CMB} = 2.726 K$$

$$\Delta T(\theta, \phi) = T(\theta, \phi) - T_{\rm CMB}$$

What are the C_ℓs?

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$$T_{\rm CMB} = 2.726 K$$

$$\Delta T(\theta,\phi) = T(\theta,\phi) - T_{\rm CMB}$$

$$a_{\ell m} = \int \frac{\Delta T(\theta,\phi)}{\rm T_{CMB}} Y_{\ell m}(\theta,\phi)\ {\rm d}\Omega$$

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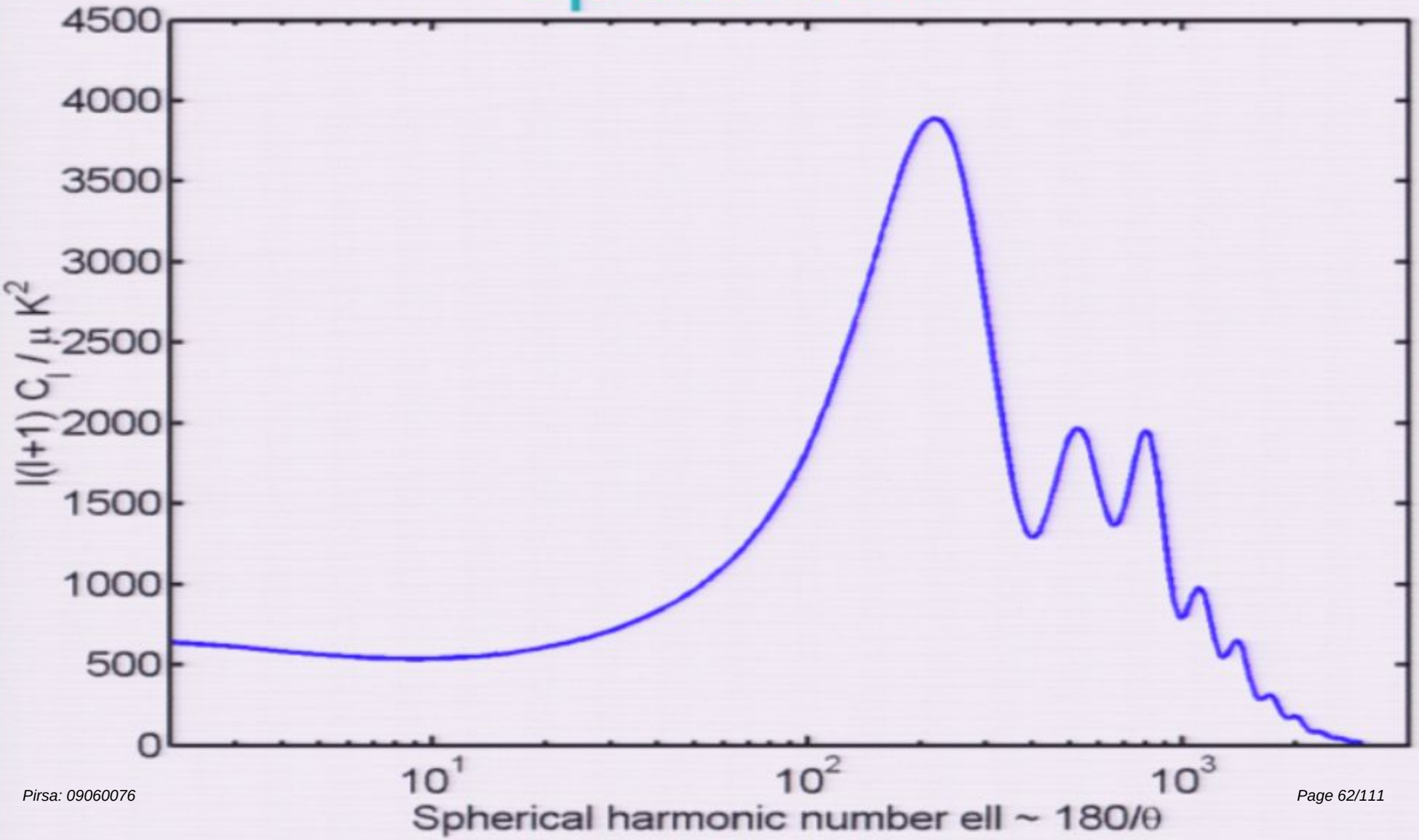
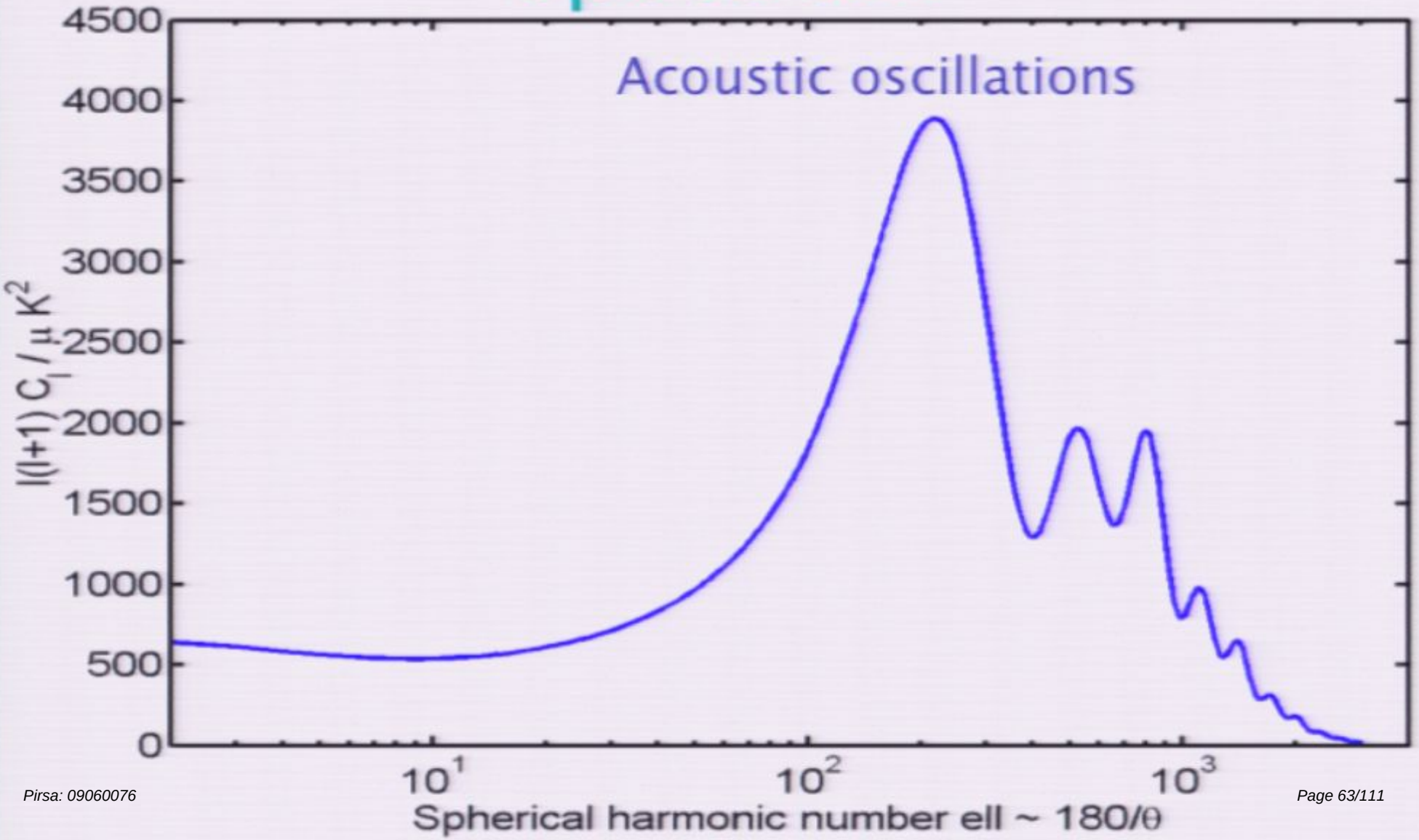
$$C_\ell = \langle |a_{\ell m}|^2 \rangle$$

3 regimes of CMB power spectrum



3 regimes of CMB power spectrum



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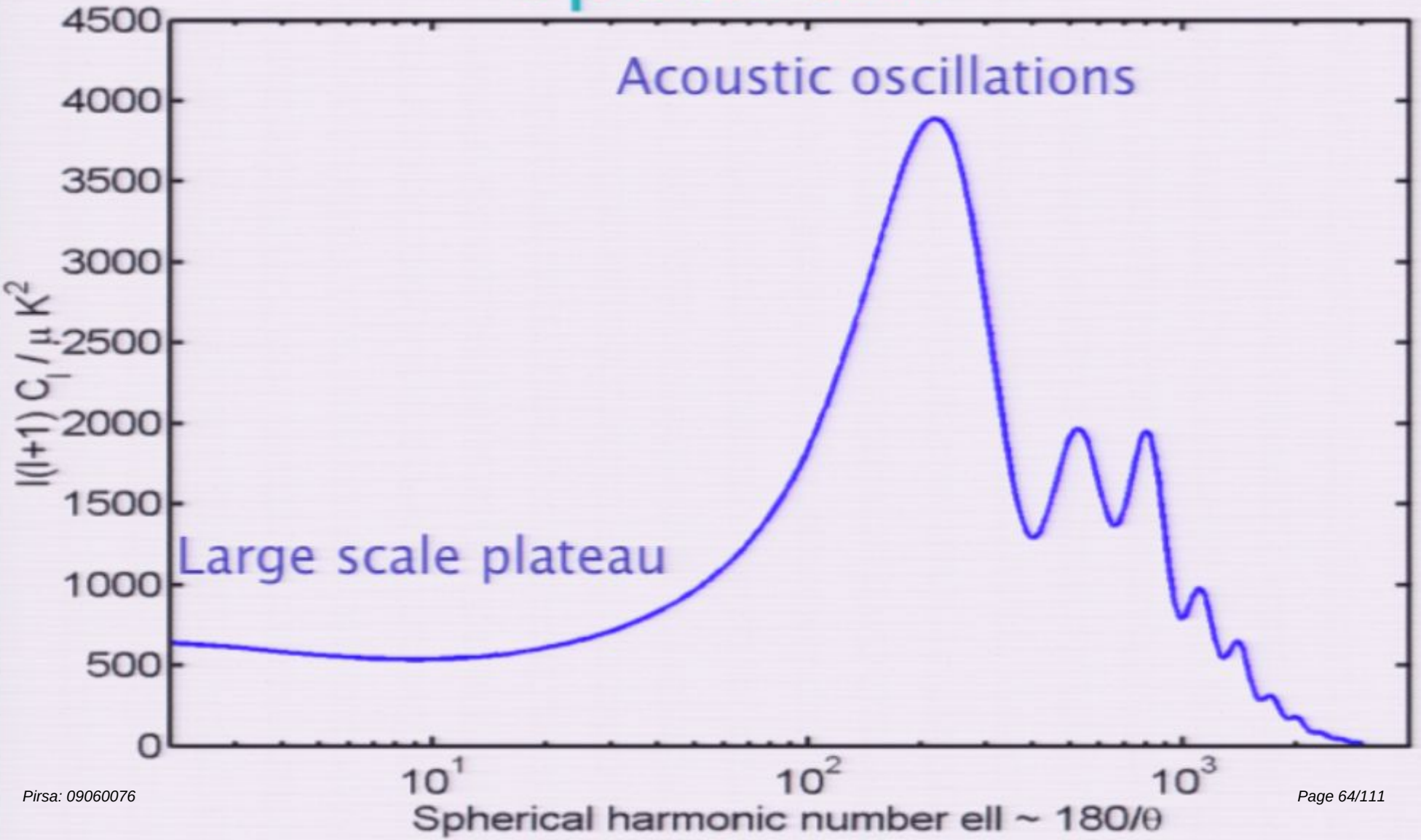
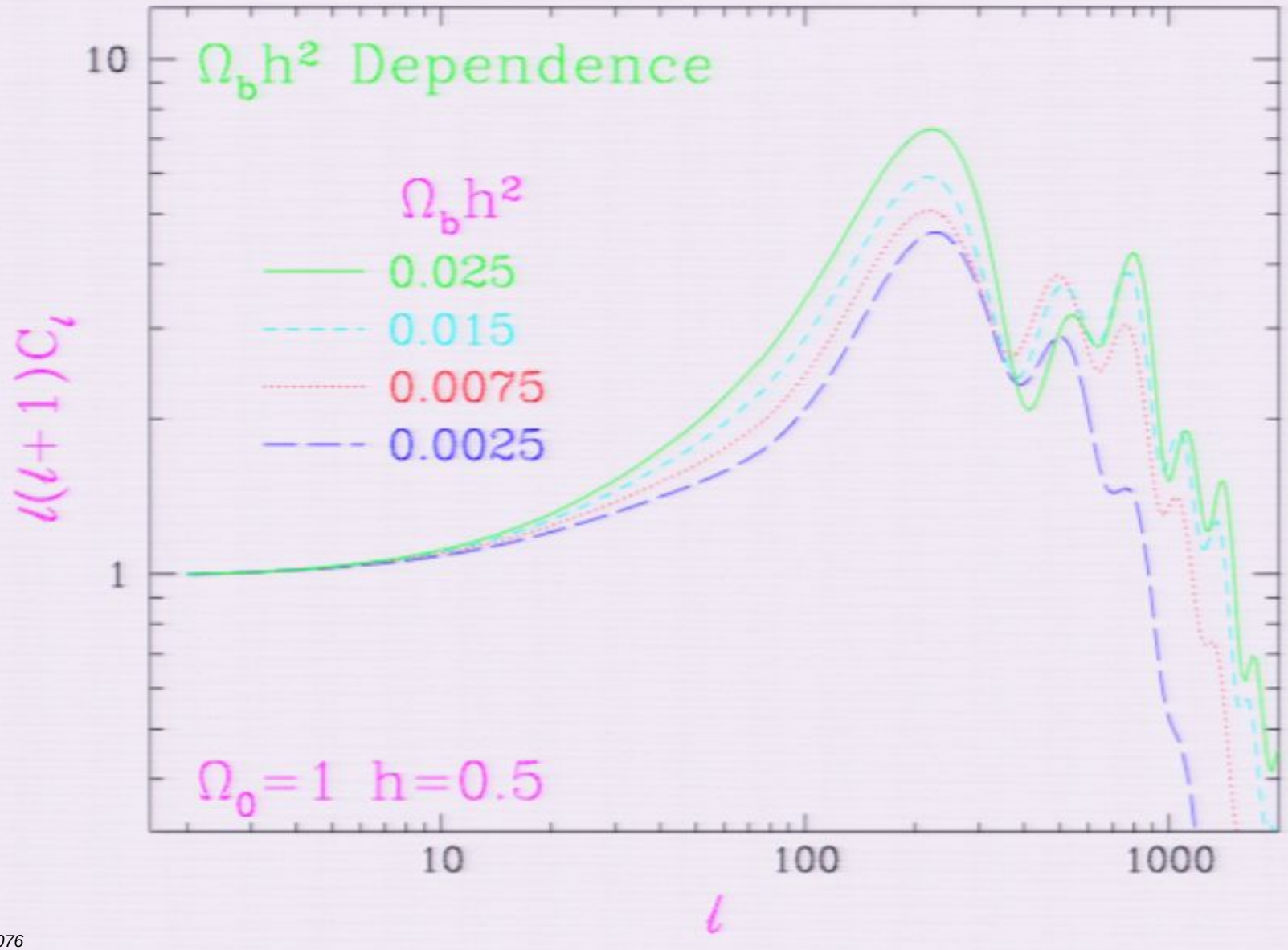


Cosmological Parameters

- Universe content: Ω_b, Ω_{DM}, f_ν, Ω_Λ, $w(z)$
- Universe dynamics: H_0
- Clumpiness: σ_8, $n_s(k)$
- Primoridial gravity waves: A_t, n_t
- When the first stars formed: z_{re}
- Other: WDM, isocurvature, non-Gaussianity...

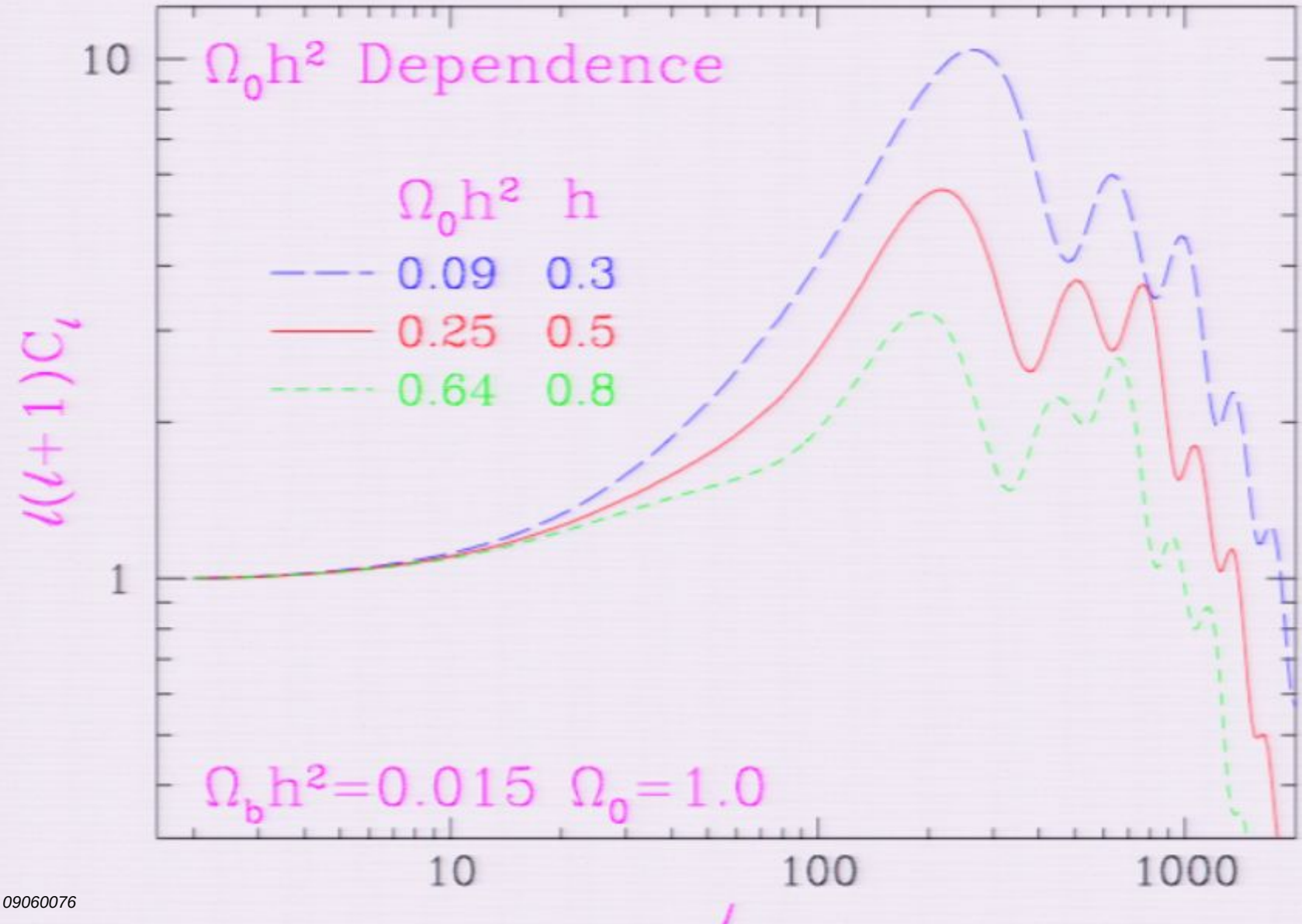
Each parameter has an effect on the CMB

Increasing Baryon Density



Graphic by Wayne Hu, http://background.uchicago.edu/~whu/beginners/introduction.html

Decreasing Matter Density



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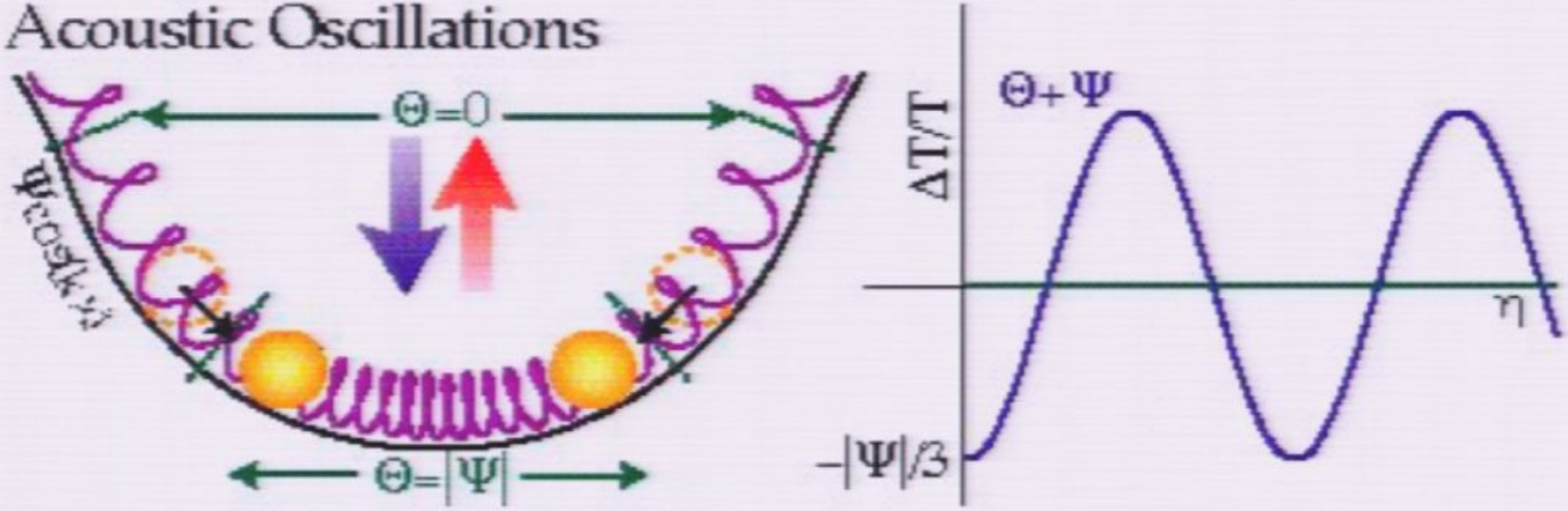
Understand main feature: position of 1st peak

- Bouncing fluid causes peak structure
- Curvature of Universe -> peak locations

Bouncing fluid

- Photon-baryon fluid oscillates in dark matter potential wells



- Large scales oscillate slowest

Graphic by Wayne Hu, http://background.uchicago.edu/~whu/beginners/introduction.html

The first acoustic peak

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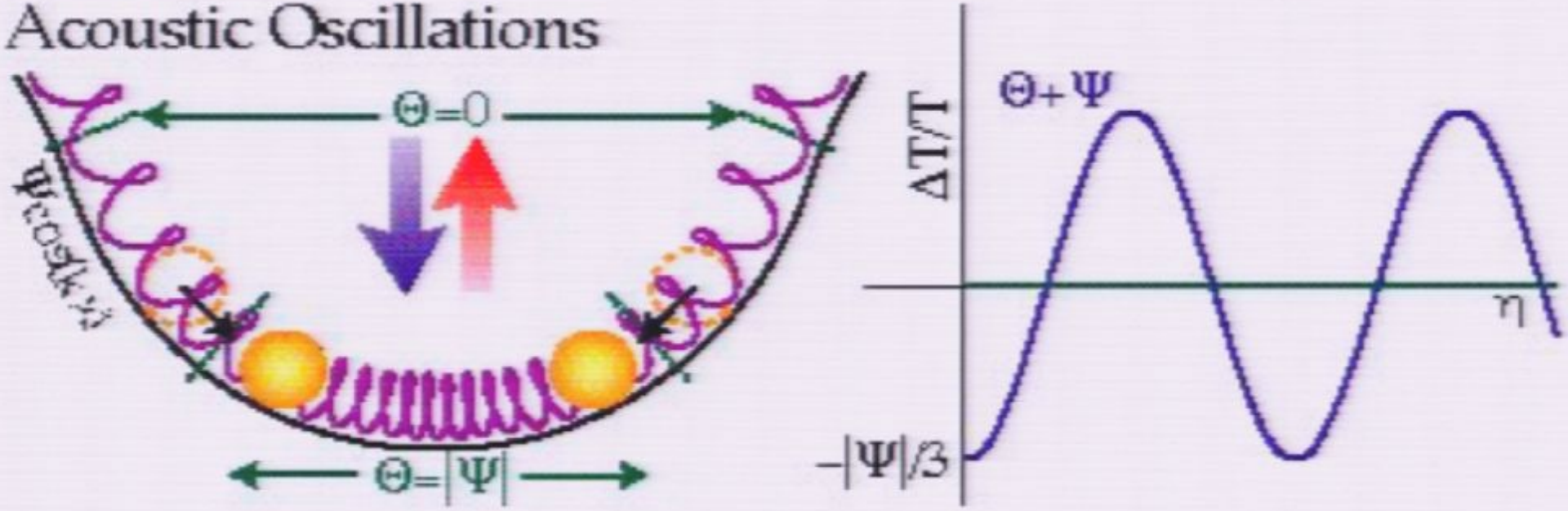

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The first acoustic peak

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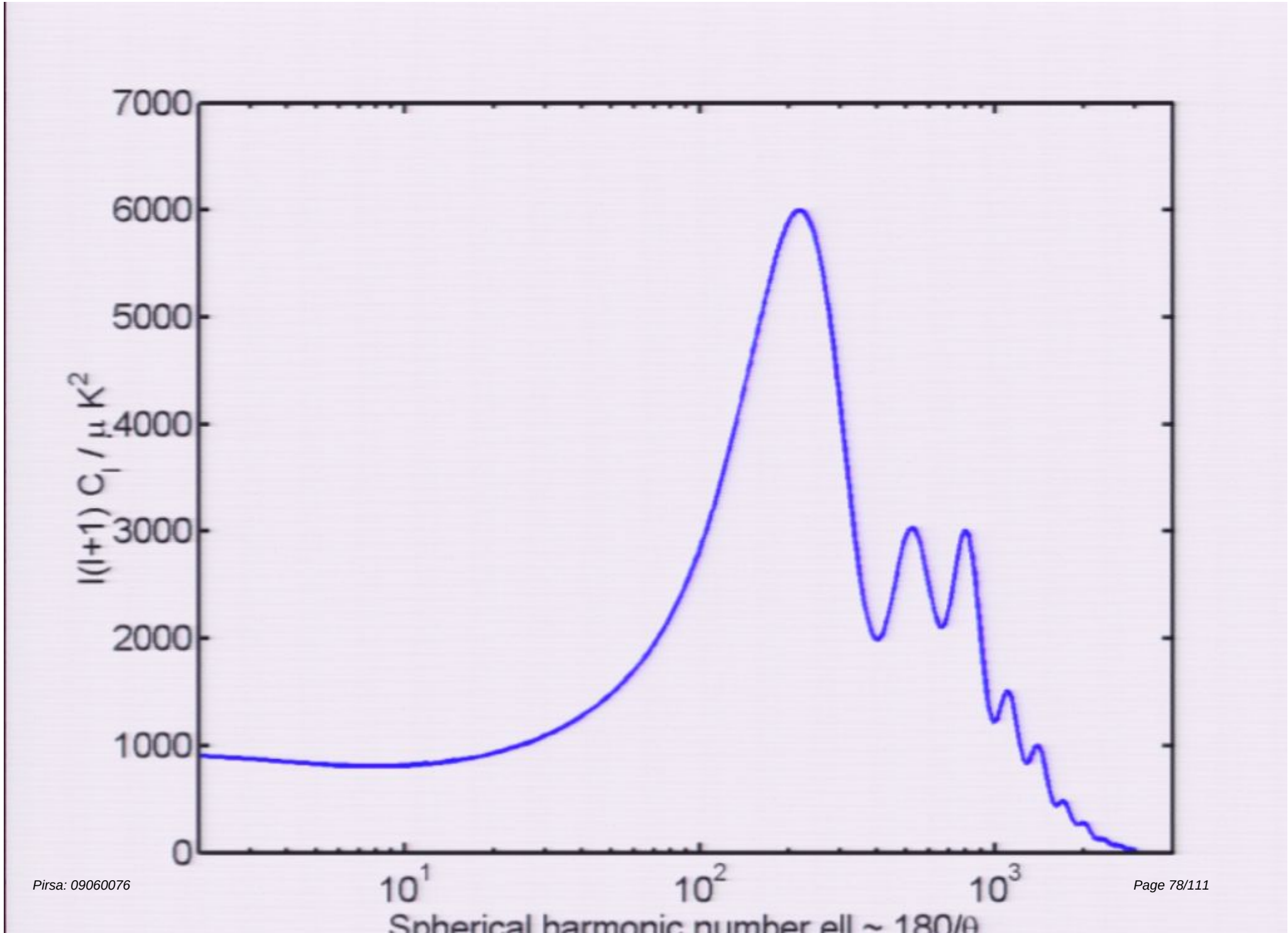
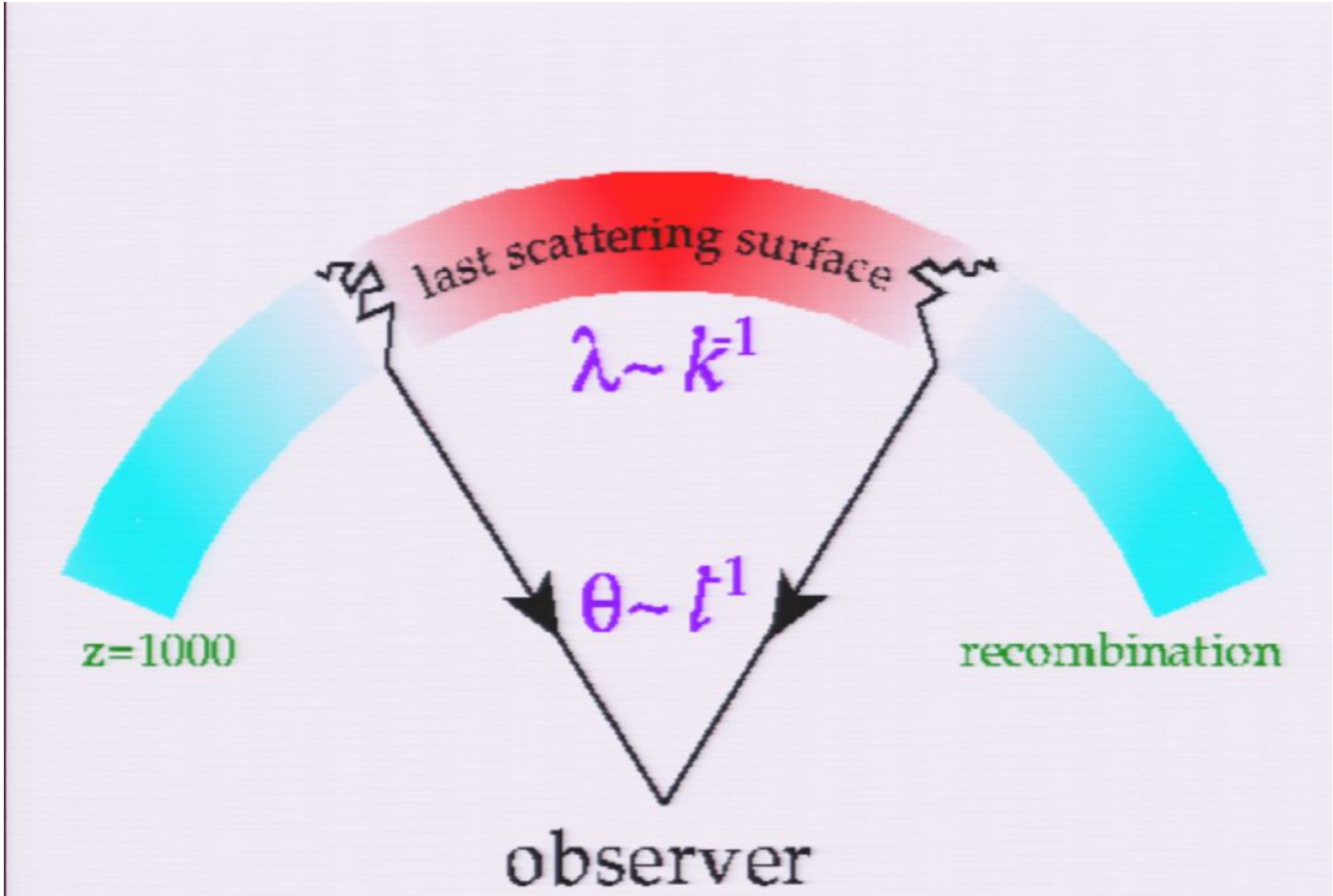
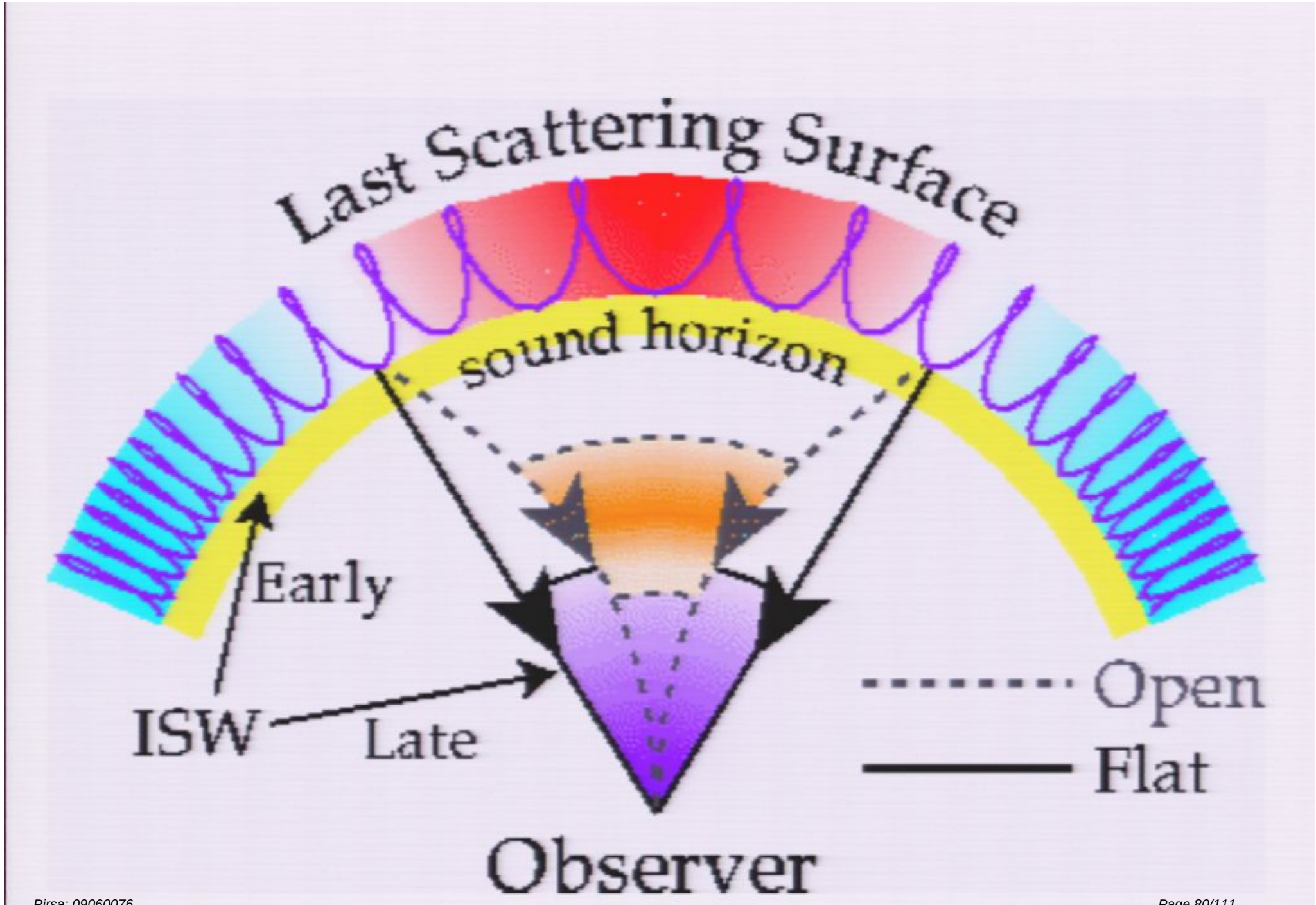
  - it is at maximum T => hot-spot
- Scale = collapse speed x time allowed
  - ~ sound speed x age of universe at z~1000
  - ~ 200 ($\Omega_m h^2$) Mpc comoving

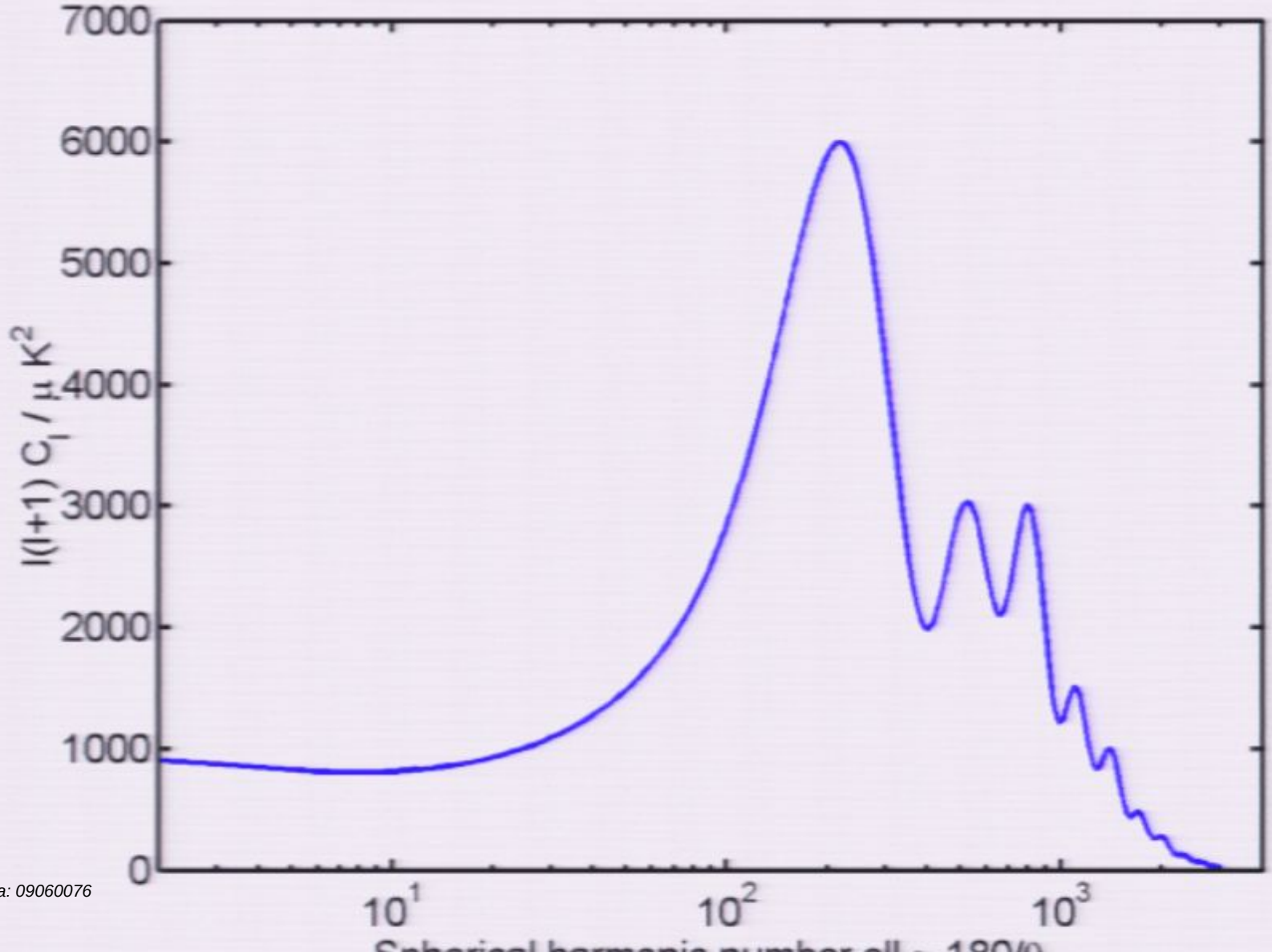

7000
6000
5000
4000
3000
2000
1000
0
l(l+1) C_l / μ K^2
10^1
10^2
10^3
Spherical harmonic number ell ~ 180/θ


last scattering surface
$\lambda \sim k^{-1}$
$\theta \sim \ell^{-1}$
z=1000
recombination
observer

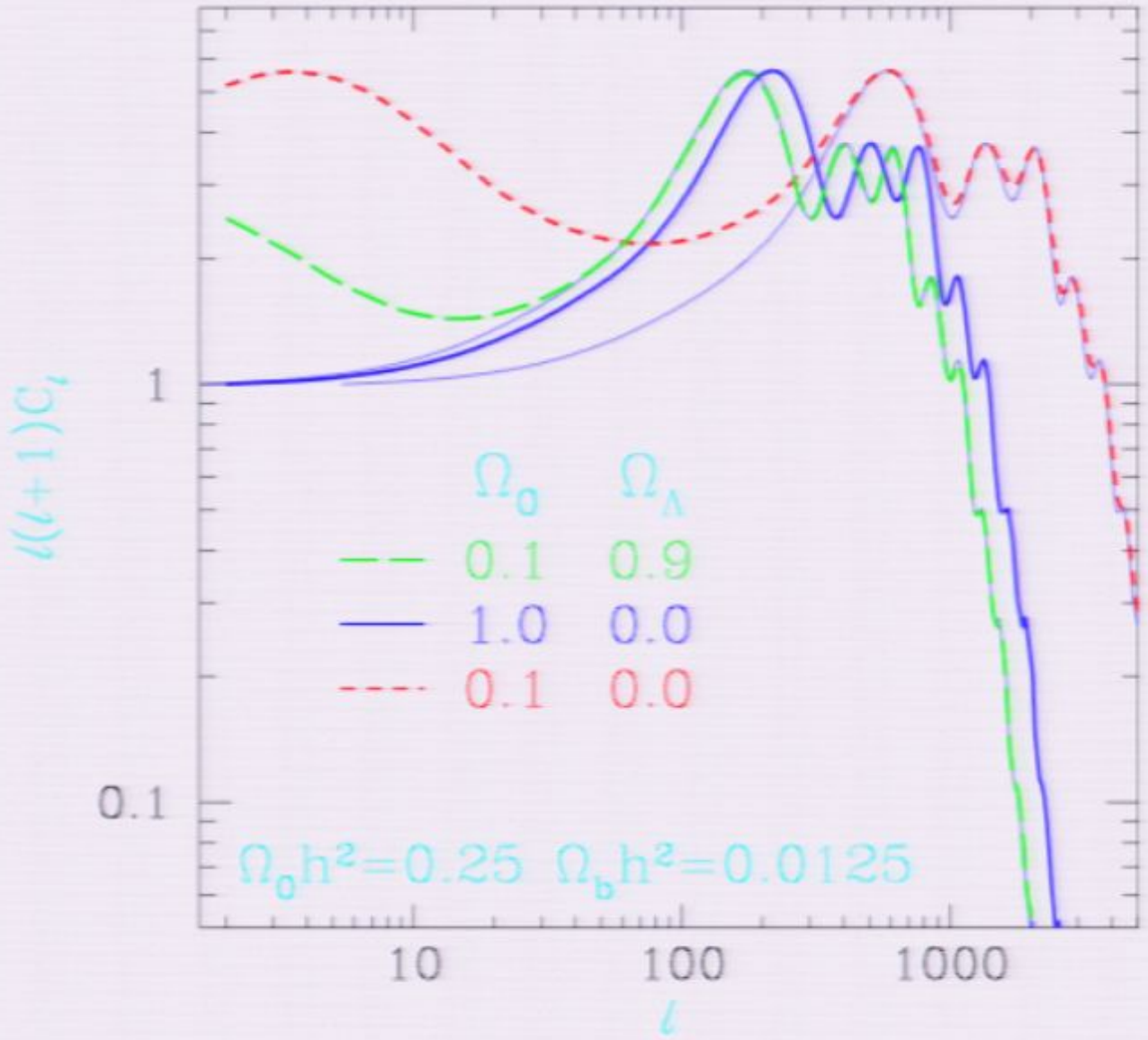


Graphic from WMAP website

Which way will the peak move?



Flat → Open
Peak shifts to the right



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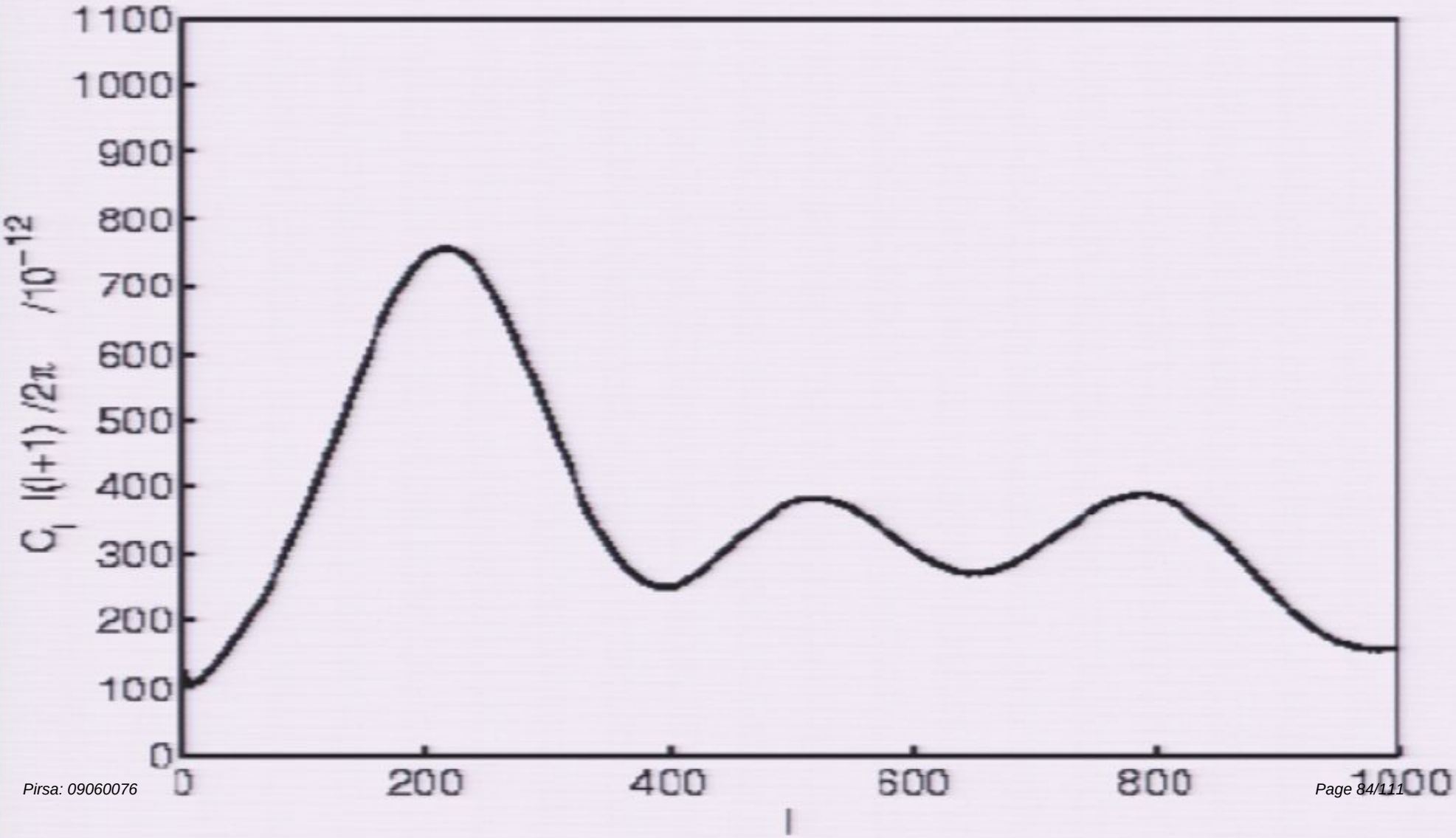
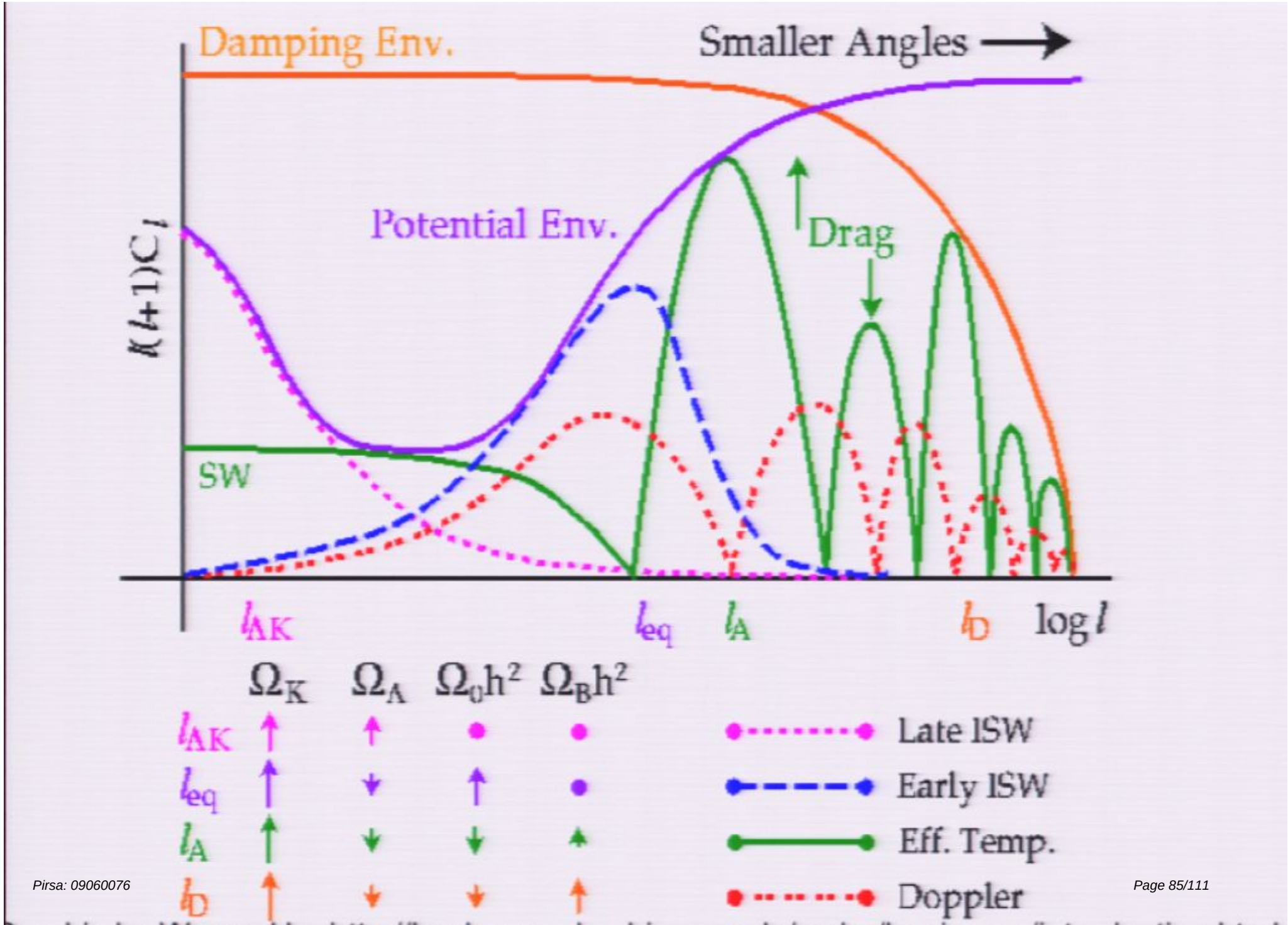
Secondary peaks

- Plot is ~ FT of (T(θ) –mean(T))
- Second peak = collapse, expand to max
- Third peak = collapse, expand, collapse
- etc..
- Expect peaks to be equally spaced in l

Plot on linear axes



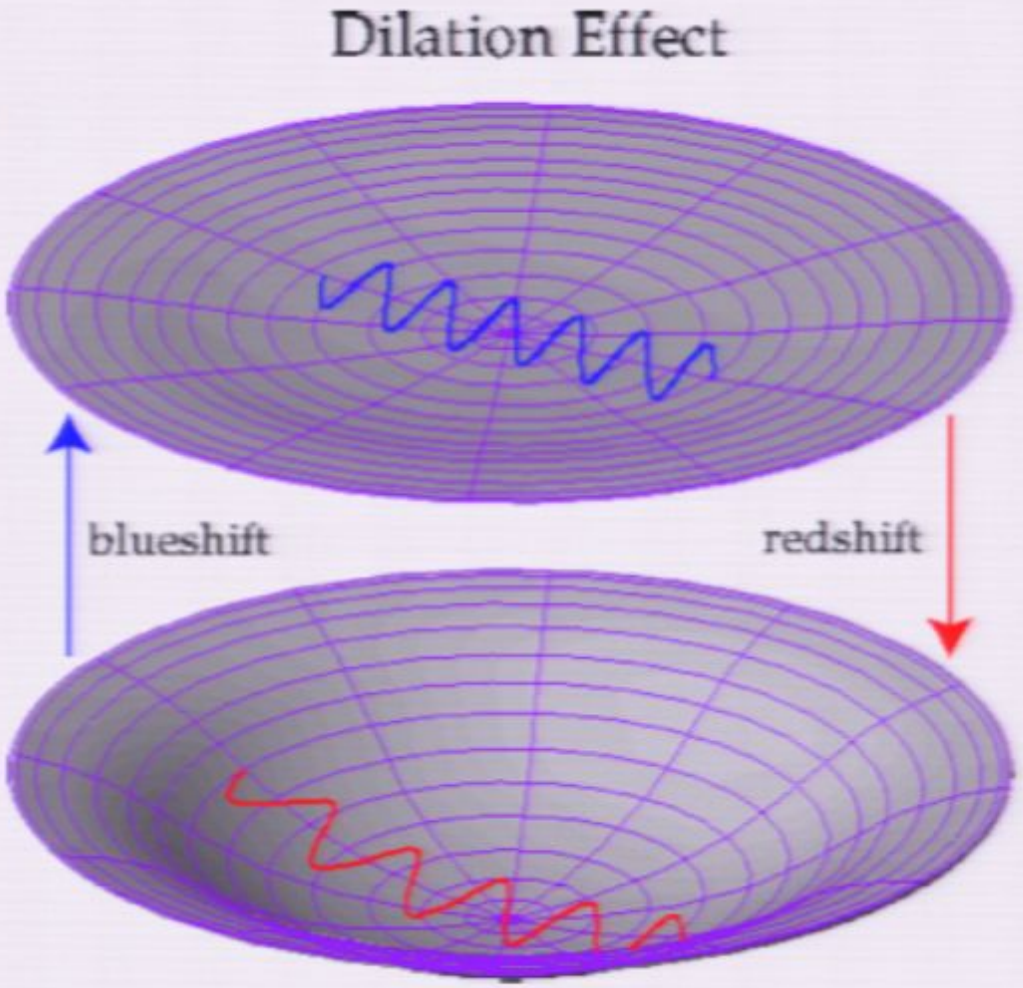

Damping Env.
Smaller Angles
Potential Env.
Drag
SW
$l(l+1)C_l$
l_{AK}
l_{eq}
l_A
l_D
log l
Ω_K Ω_A Ω_0h^2 Ω_Bh^2
l_{AK} ↑ ↑ ● ●
l_{eq} ↑ ↓ ↑ ●
l_A ↑ ↓ ↓ ↑
l_D ↑ ↓ ↓ ↑
Late ISW
Early ISW
Eff. Temp.
Doppler

Largest scales: the Sachs-Wolfe effect

- Gravitational potential wells due to DM
  - Follows large scale matter power spectrum
- Photons climb out of potential wells
  - gravitational redshift: cold -> deep well
  - $\Delta \nu / \nu \sim \Delta T / T \sim \Delta \Phi / c^2$
- Full GR
  - factor 2/3 ~ deep wells, t is smaller -> hotter
  - $\Delta T / T = 1/3 \, \Delta \Phi / c^2$

ISW

- Integrated Sachs-Wolfe effect
- Due to photons travelling through collapsing structures
- Boosts power at low ℓ in C^{TT}_{ℓ}



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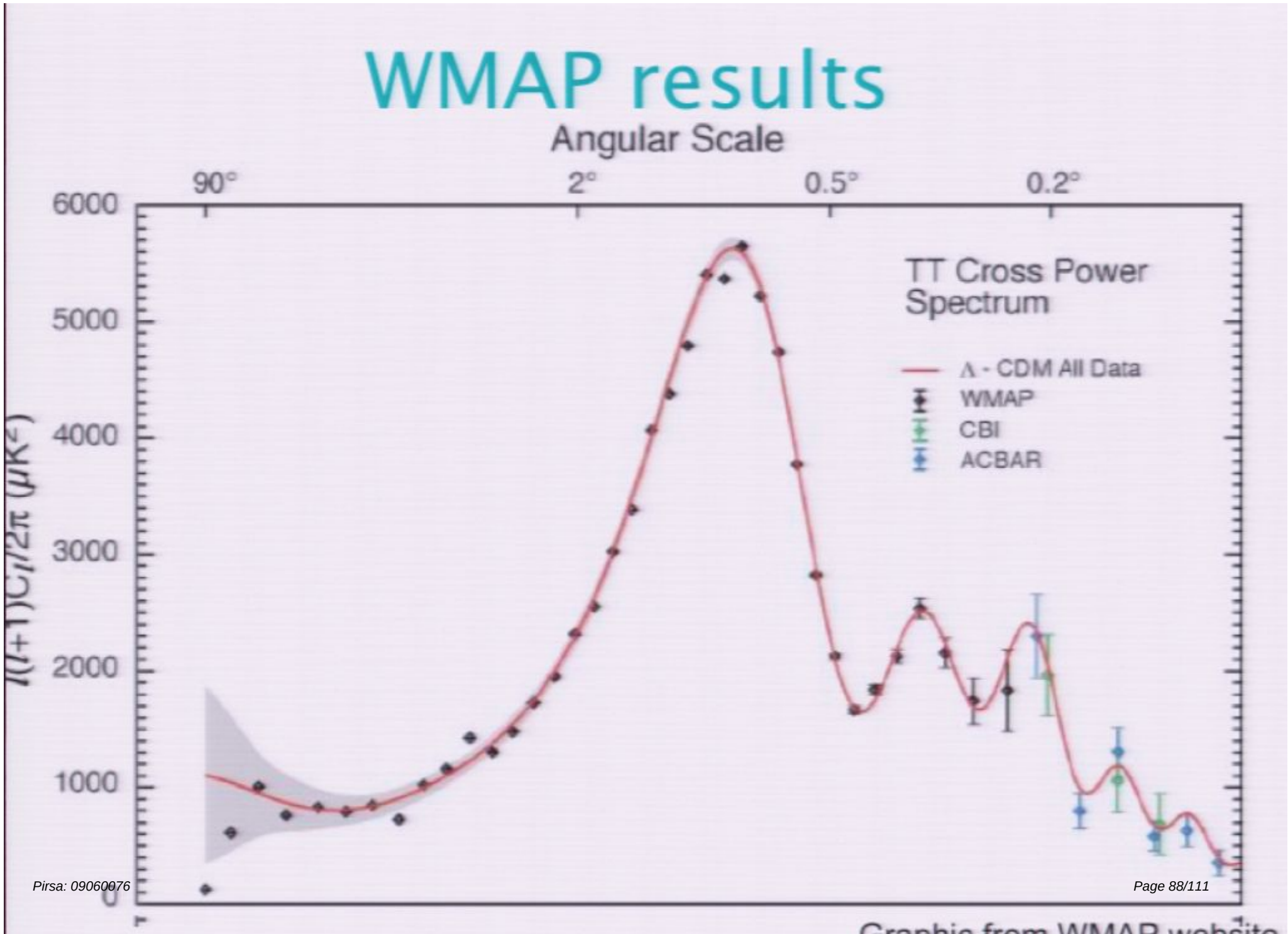
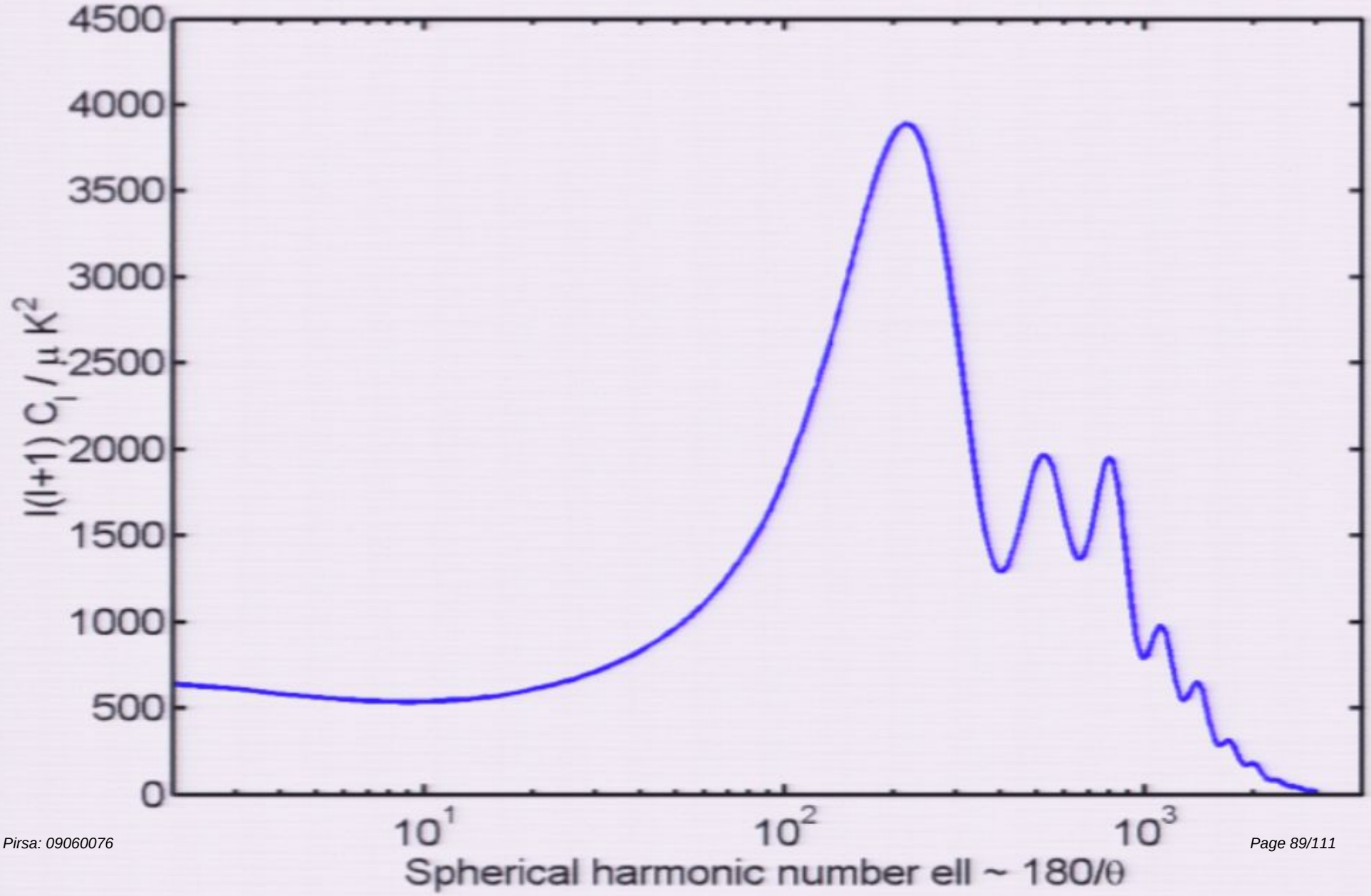
WMAP results



Graphic from WMAP website

CMB cheat sheet



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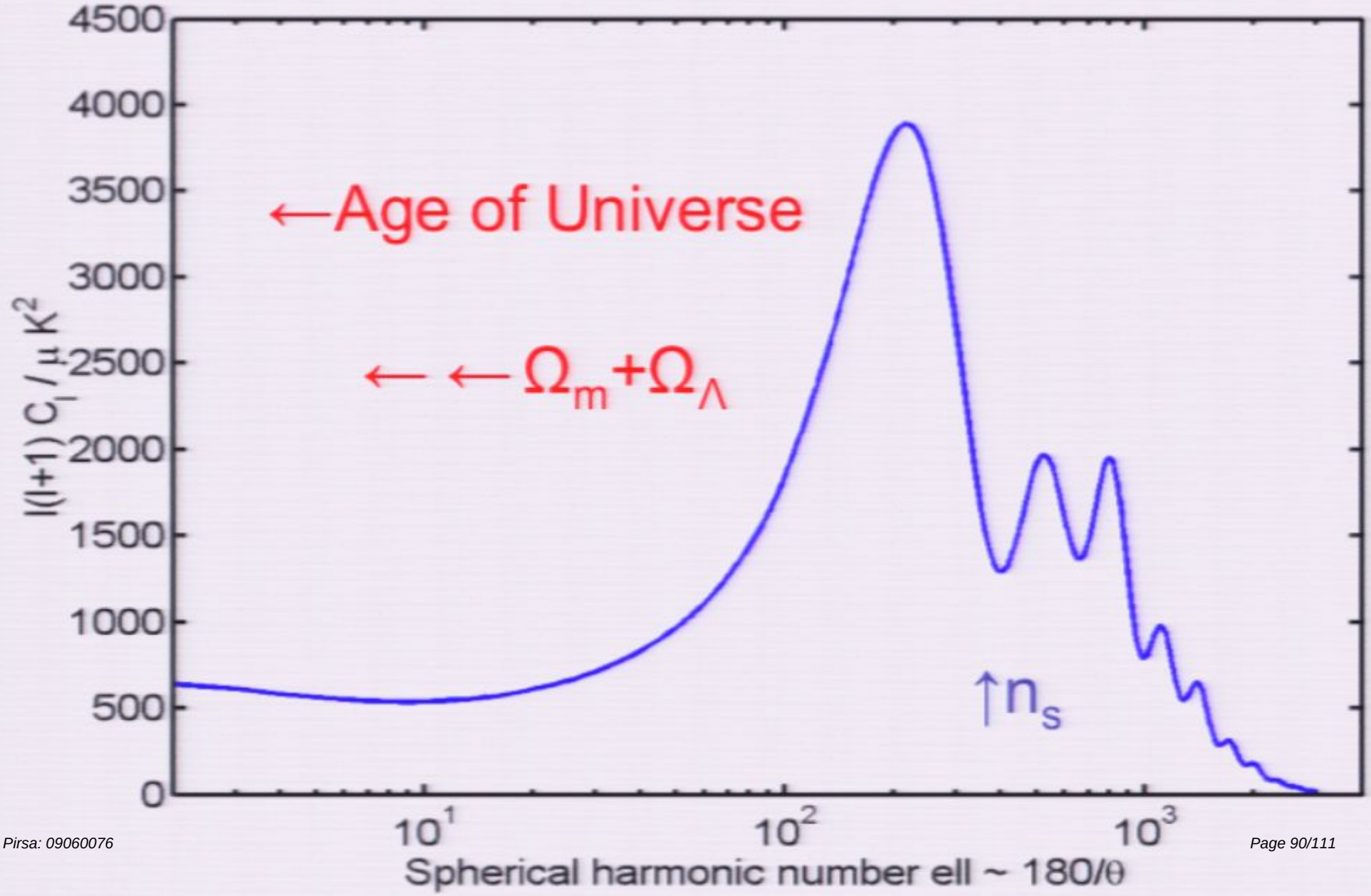

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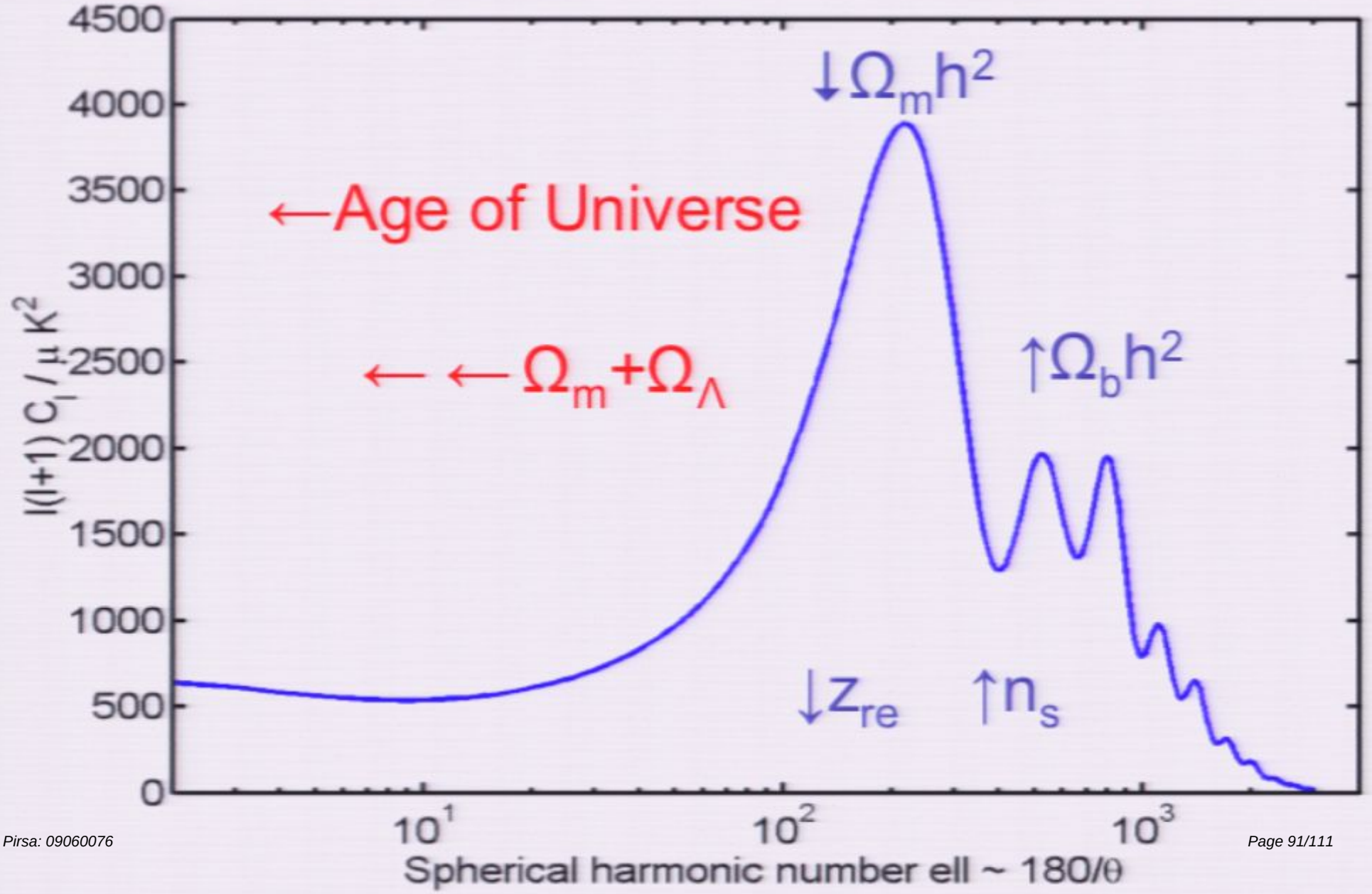

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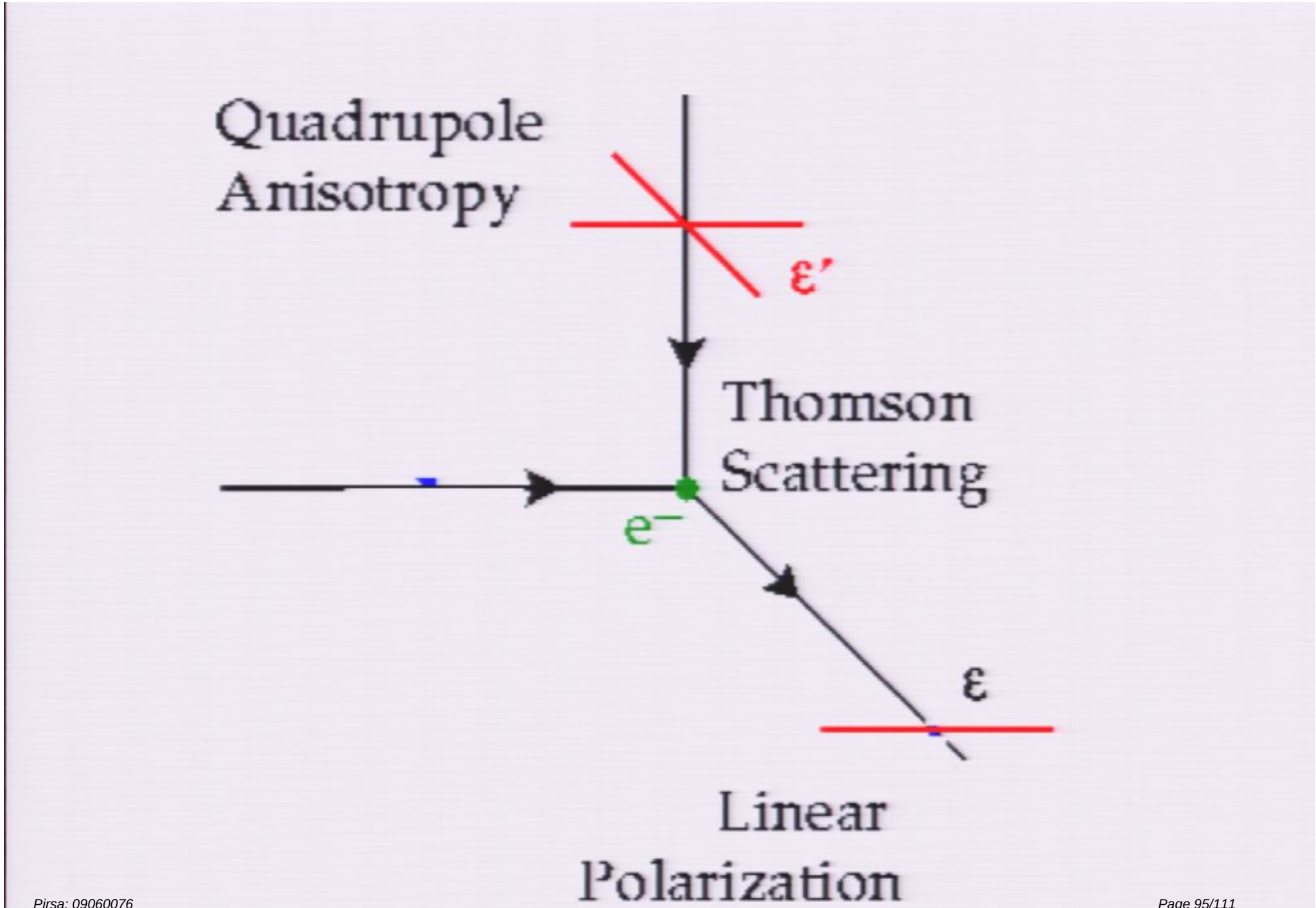
CMB polarization

CMB polarization

- Measure polarization angle and mag. at each point on the sky
- Decompose this into 2 maps: E and B
  - E is like contour lines on a map
  - B is like water going down a plughole
- Can correlate with non-polarized signal
  - possible power spectra: TT, TE, TB, EE, EB, BB
  - Expect TB and EB to be zero due to parity



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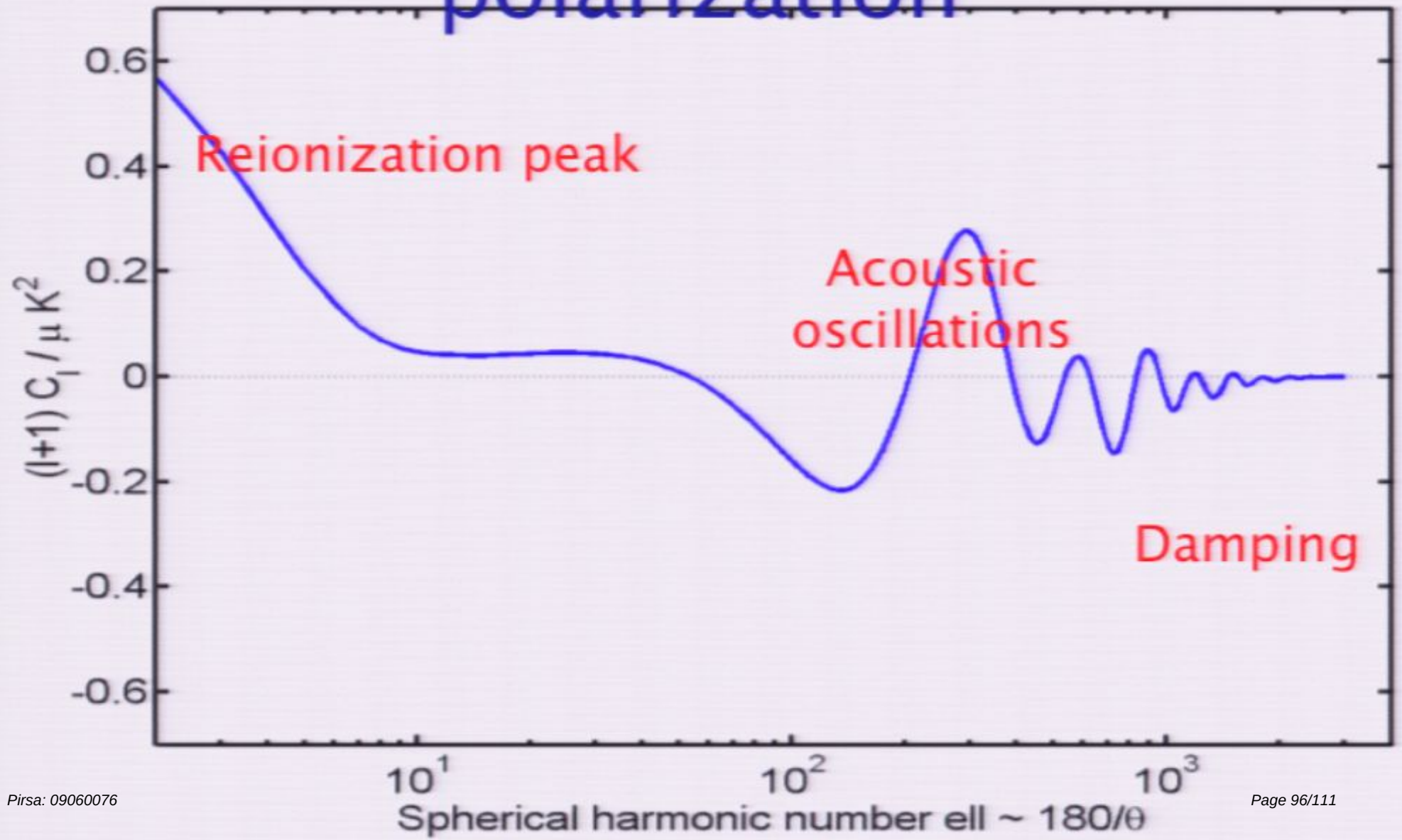
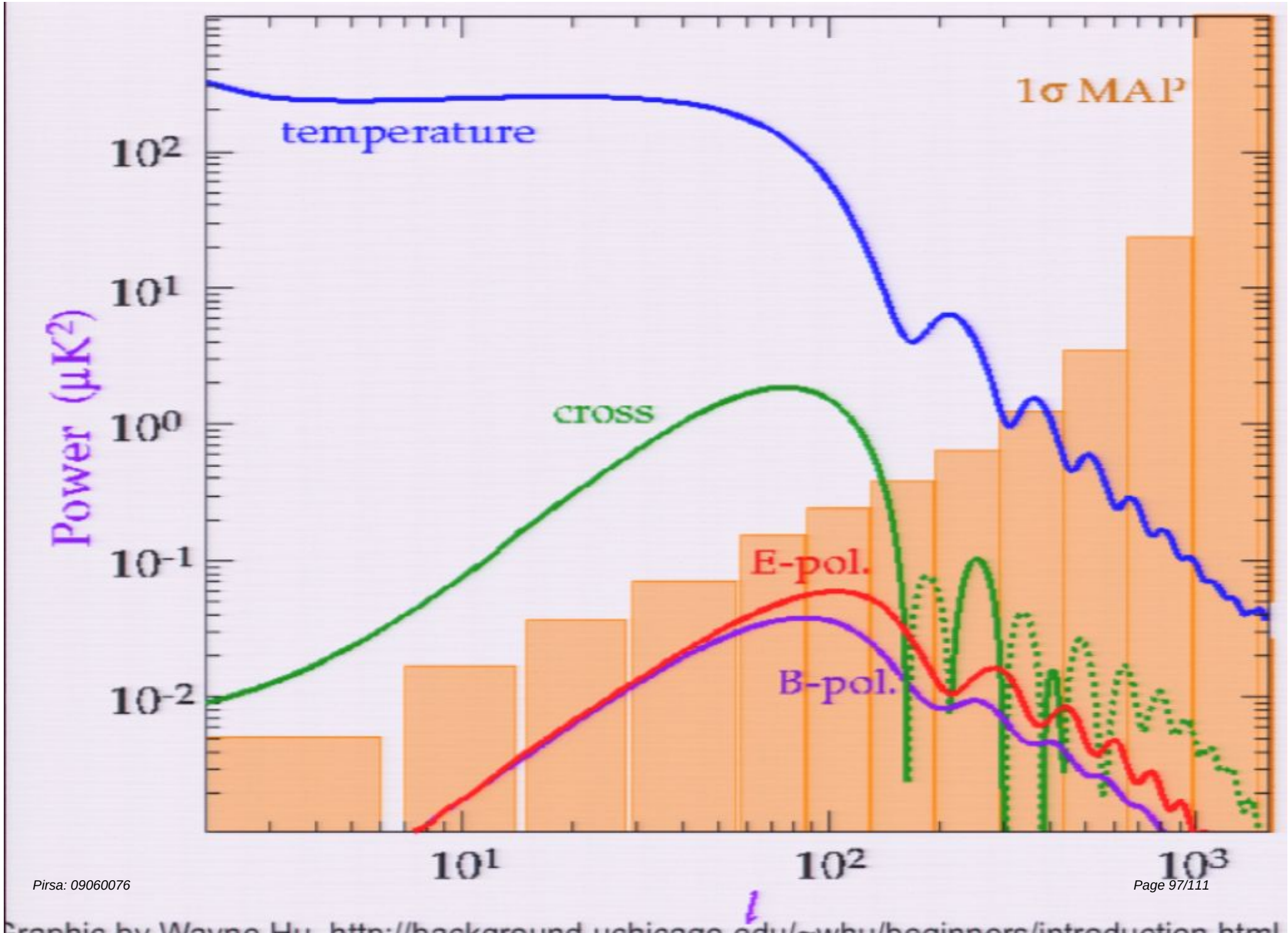
3 regimes of CMB TE polarization





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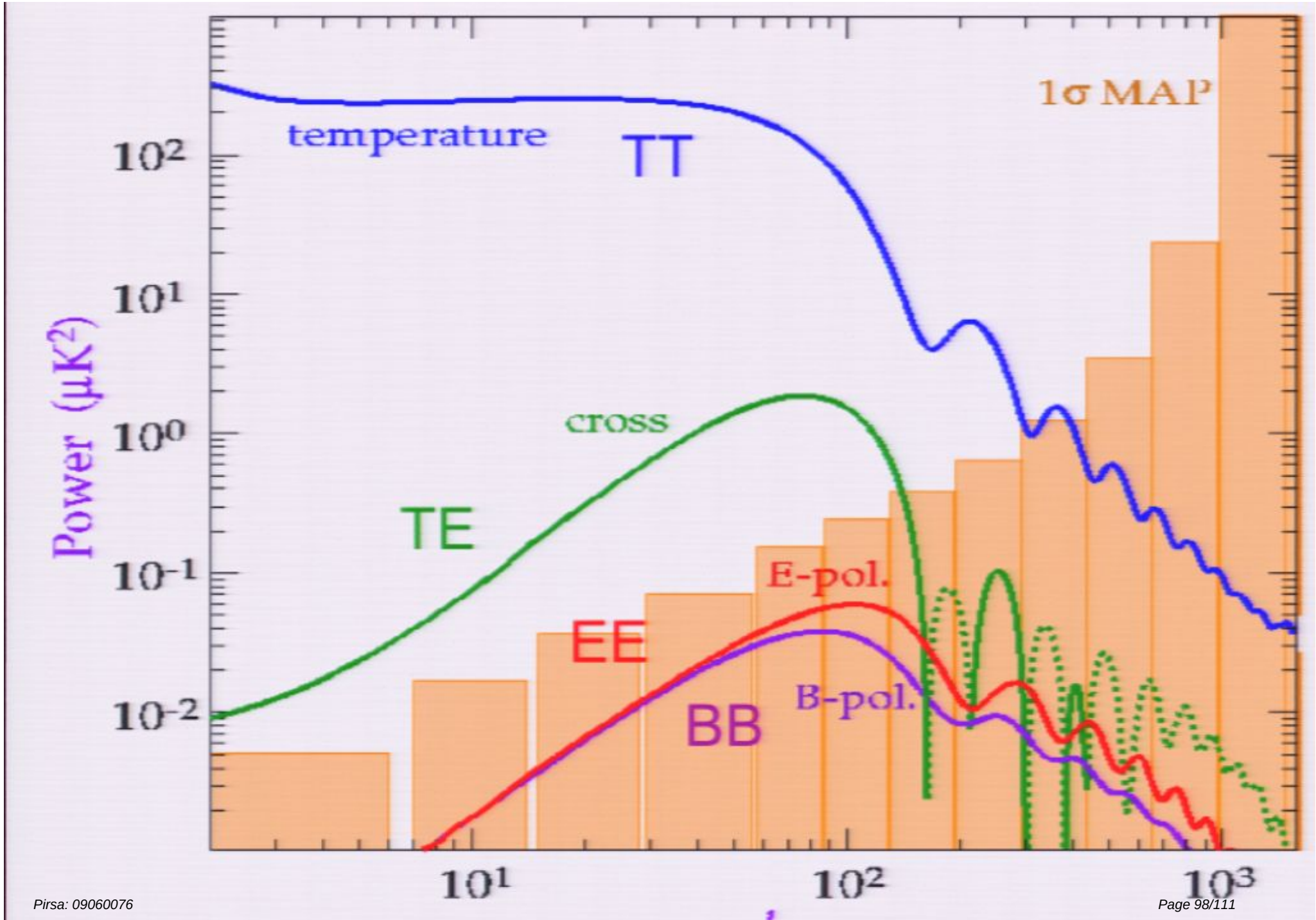

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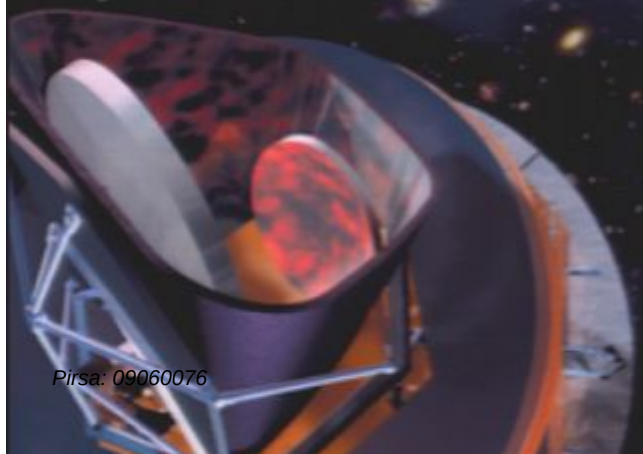
esa

PLANCK

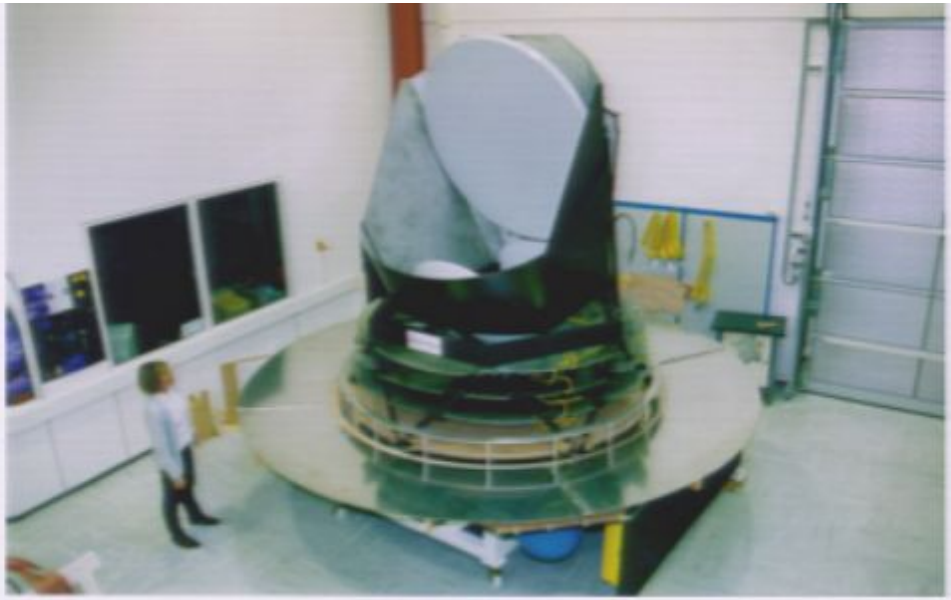
Looking back to the dawn of time
Un regard vers l'aube du temps

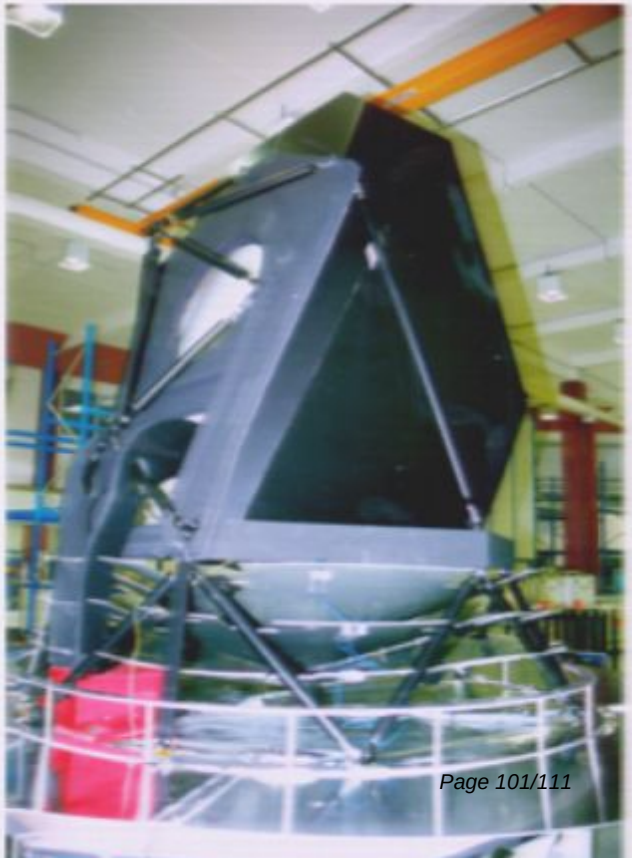


esa

PLANCK

From Planck website





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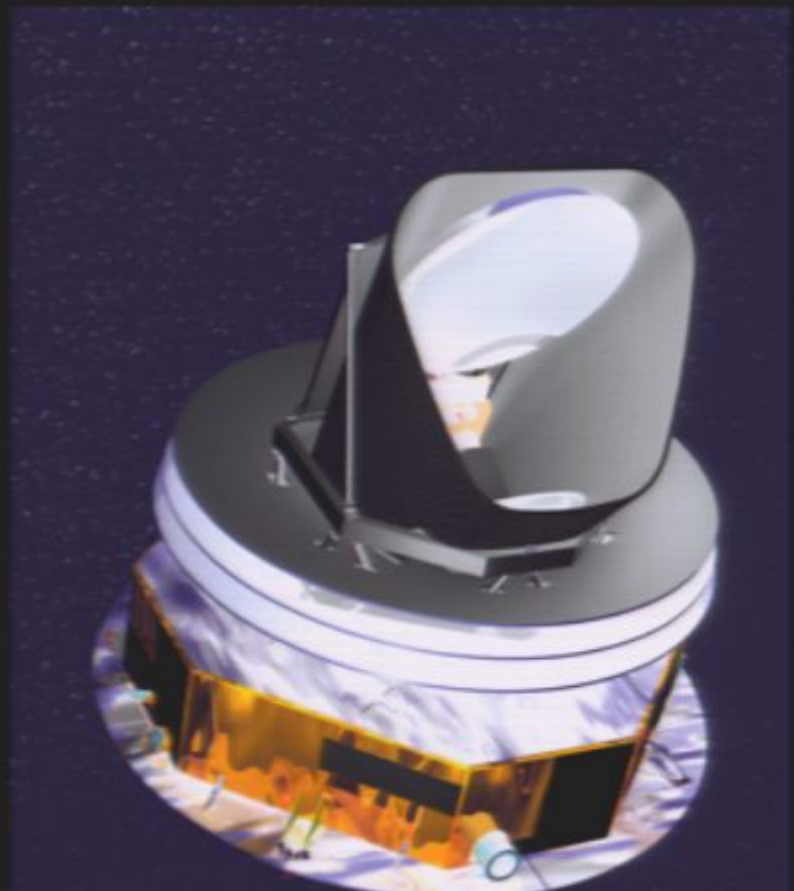
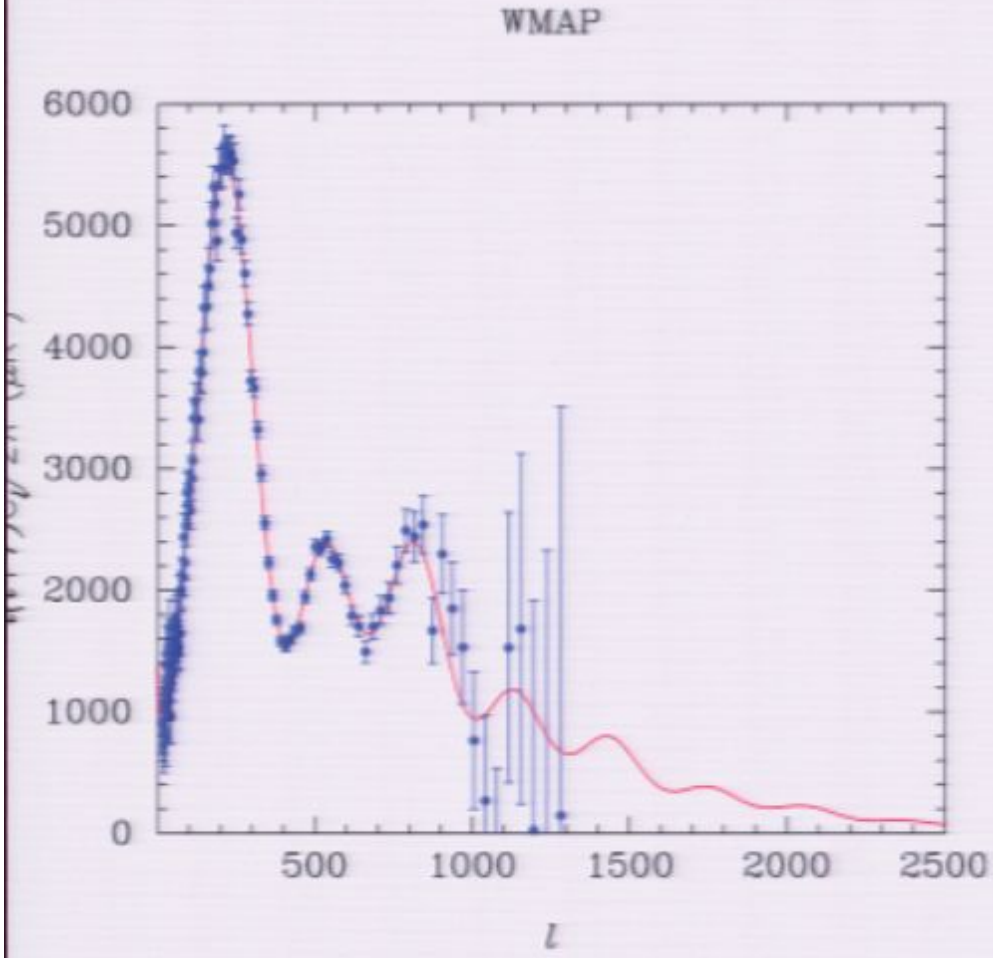
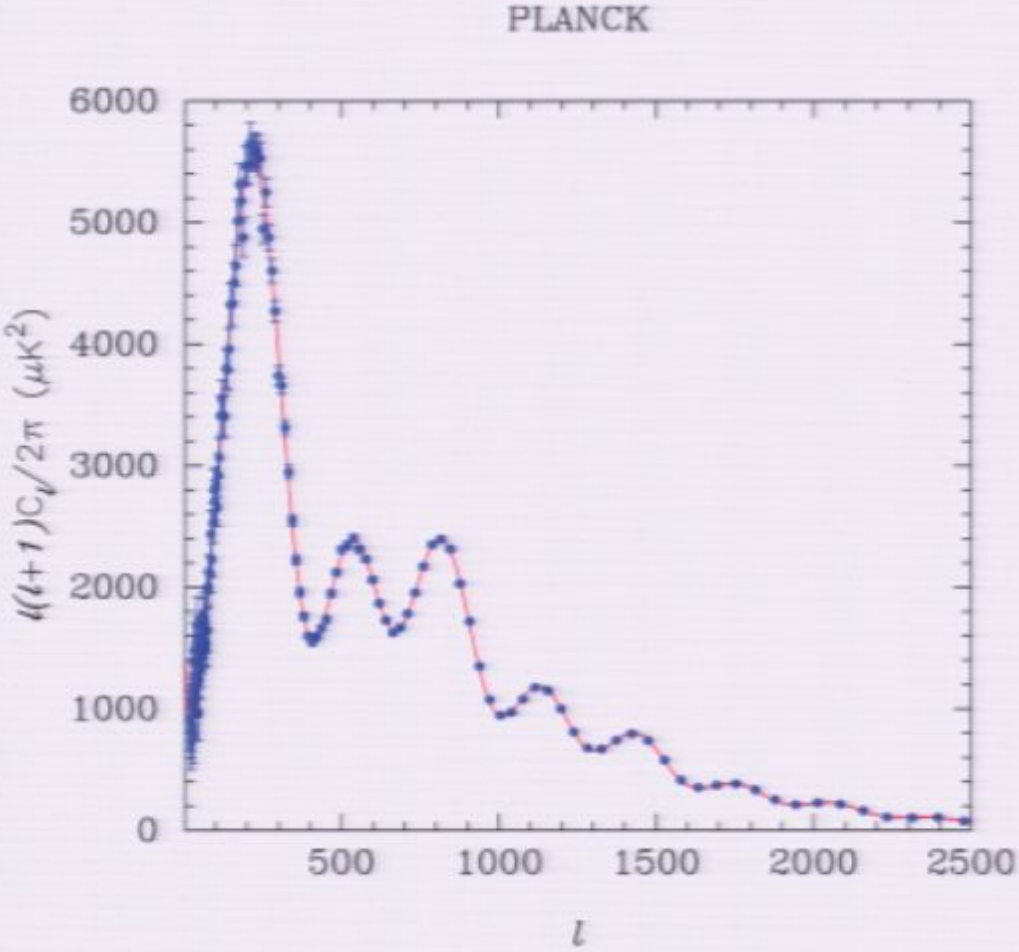


From Planck website

Planck: the ultimate (~2009)





The holy grail, BB

- Why bother measuring EE?
  - isocurvature modes
  - develops technology for BB
- Primordial BB ↔ primordial gravity waves
- Predicted by some inflation models
  - predicted not to exist by ekpyrotic models

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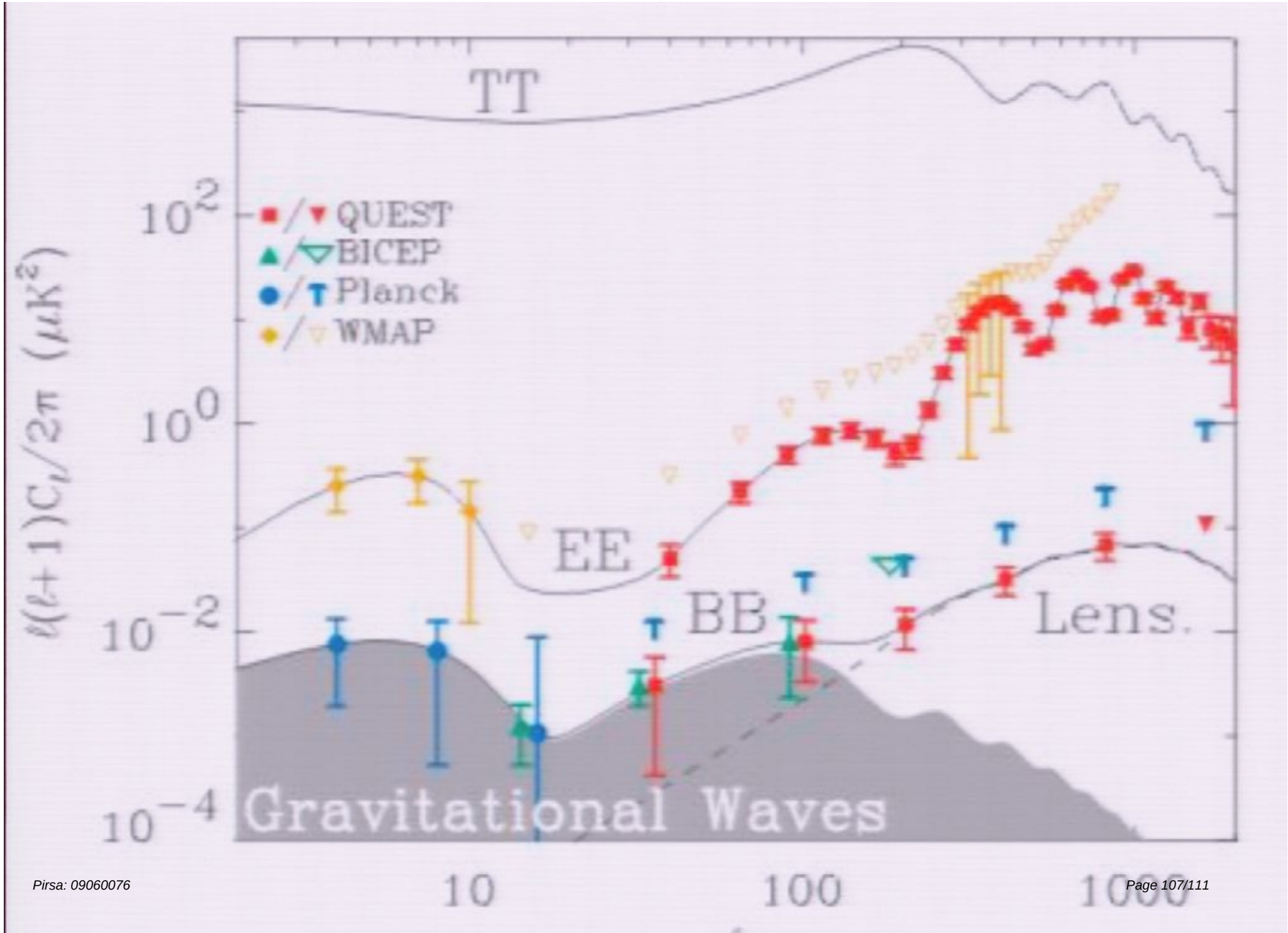
TT
EE
BB
Lens.
Gravitational Waves
QUEST
BICEP
Planck
WMAP
10^2
10^0
10^{-2}
10^{-4}
$\ell(\ell+1)C_\ell/2\pi$ (μK^2)
10
100
1000


ROOM

The holy grail, BB

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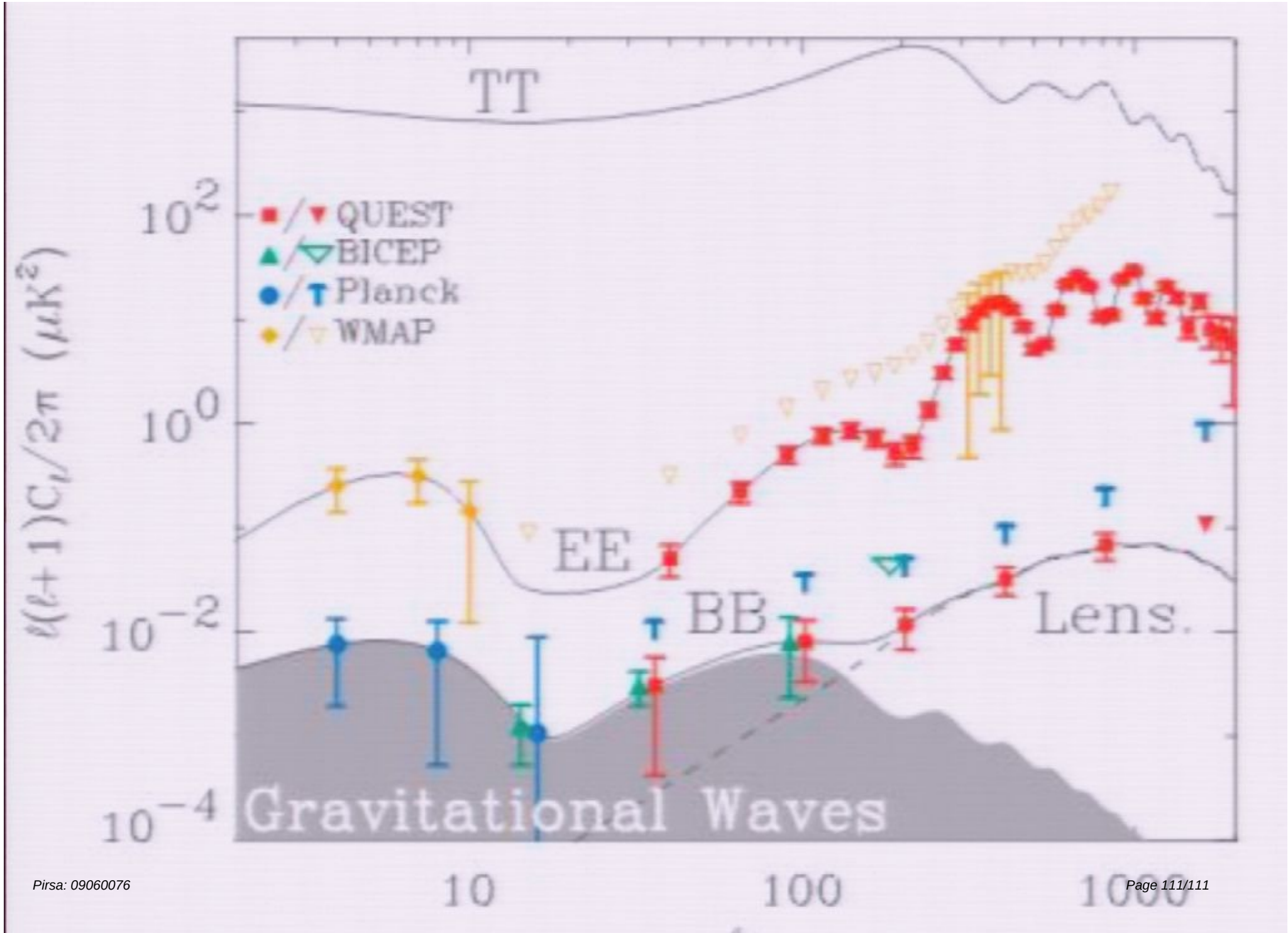
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