In the name of Allah

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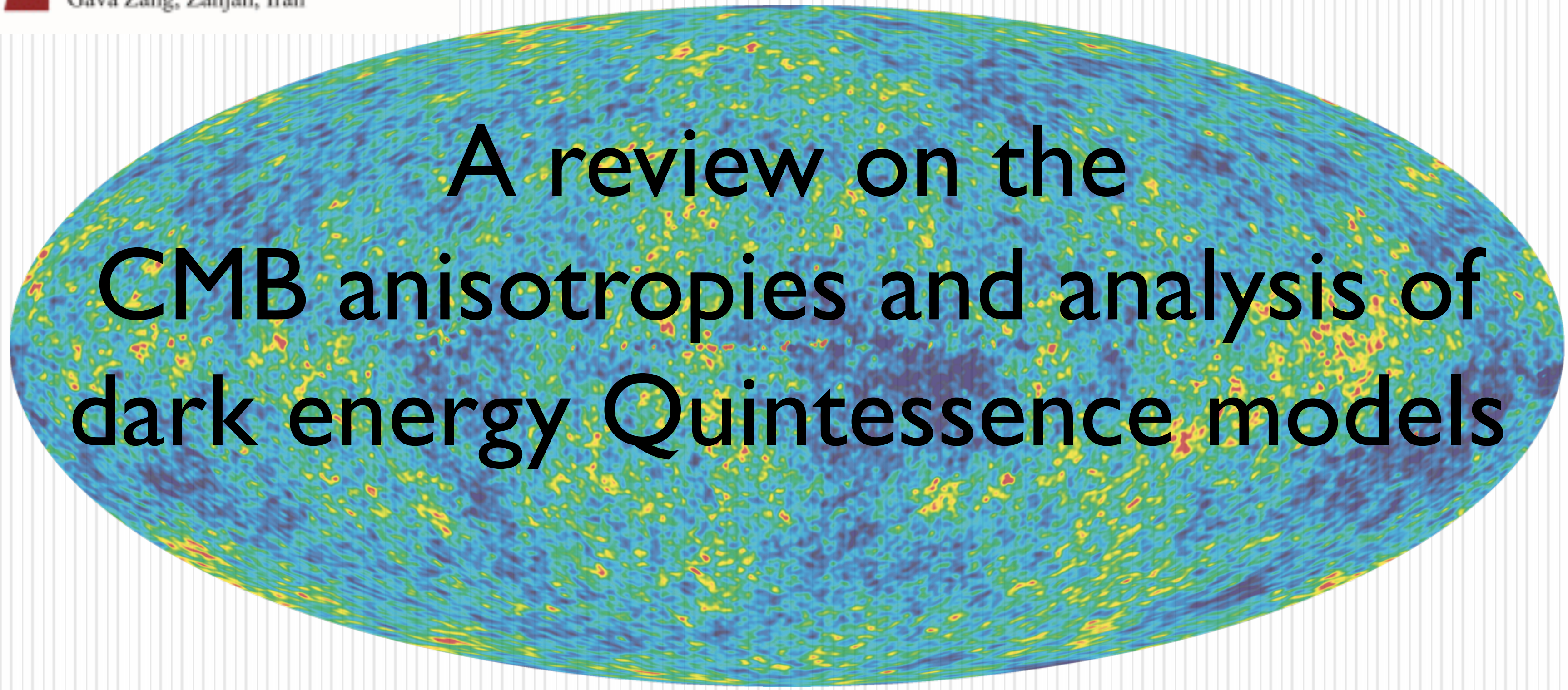

A review on the CMB anisotropies and analysis of dark energy Quintessence models

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October, 2011

Institute for Advanced Studies in Basic Sciences (IASBS)

Outline:

- Brief review on the Standard Cosmology
- Brief history of CMB
- Physics of CMB
- CMB anisotropies
- Power Spectrum
- CMB polarization
- CMB maps
- Observations
- Analysis of Qu dark energy models

Review on the Standard Cosmology

- Cosmology is the study of the whole of the Universe as a physical system.
- **Cosmological Principle:** There is no preferred place in space, the Universe should look the same from anywhere.
- The Universe is **HOMOGENEOUS** and **ISOTROPIC**.
- Galaxies are constituent elements of this system.
- On the cosmic scale the only relevant interaction among galaxies is gravitation
- The study of cosmology depends crucially on our understanding of the gravitational interaction.

Need to General Relativity

- The framework required to study the Universe as a physical system is general relativity (GR)

Relative size of Schwarzschild radius to the distance scale R

$$\frac{2G_N M}{c^2 R} \equiv \psi$$

$\psi_\odot = O(10^{-6})$ **Non-GR**

$\psi_{bh} = O(1)$ **GR**

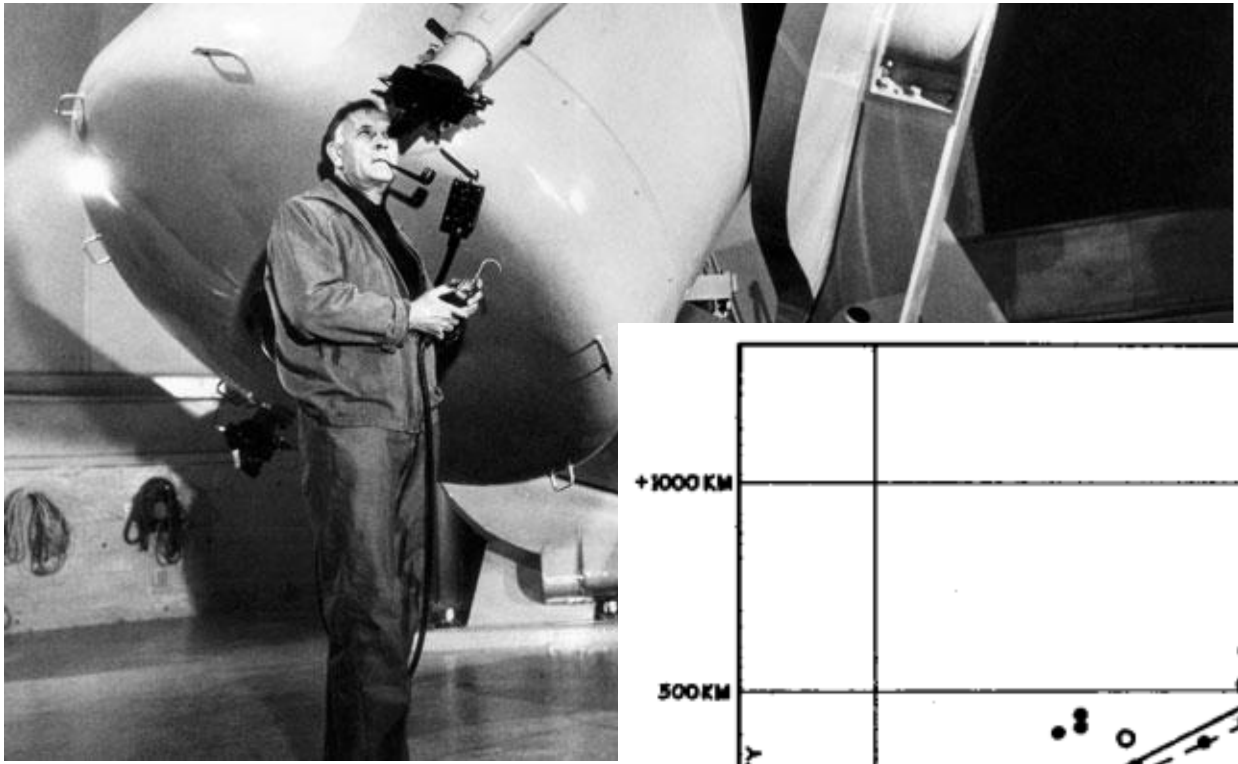
$\psi_{universe} = O(1)$ **GR**

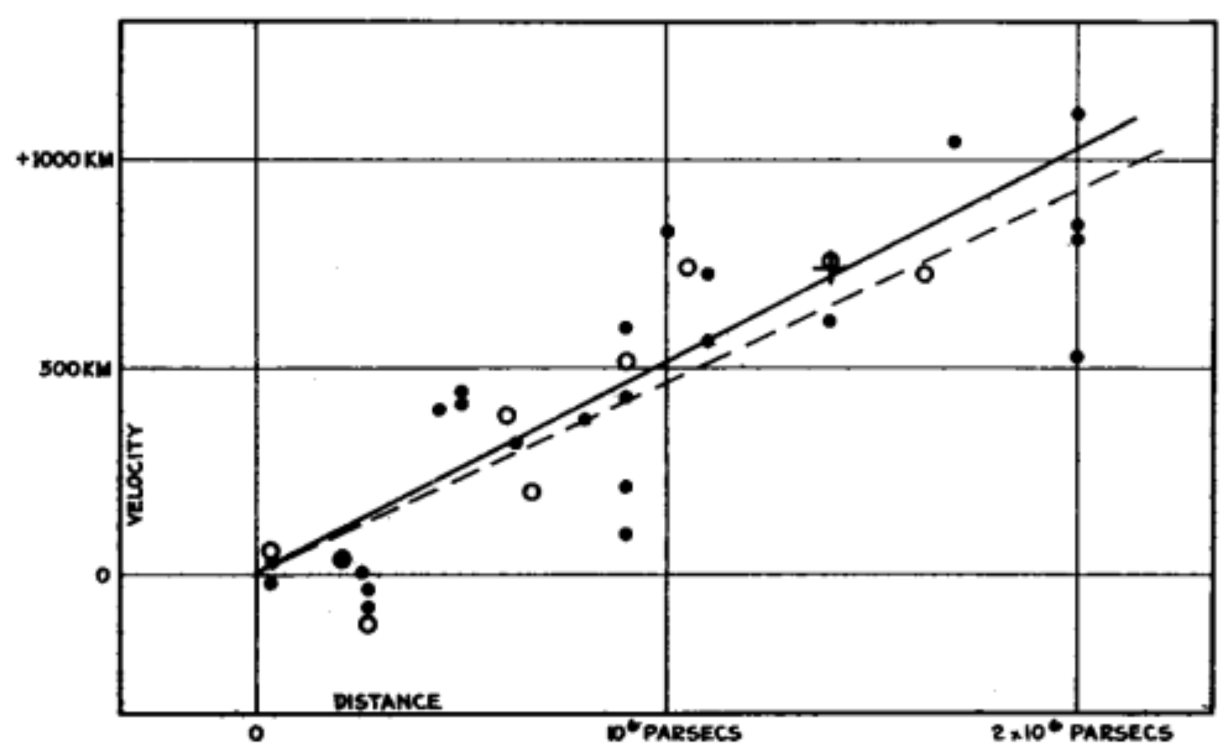
Hubble expansion

$$z \equiv \frac{\Delta\lambda}{\lambda_{em}} = \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}}$$

$$v = H_0 d$$

$$z = \frac{H_0}{c} d$$





Standard Cosmology

$$\text{Lagrangian:} \quad \mathcal{L} = \frac{1}{16\pi G}\mathcal{R}\sqrt{-g}$$

$$\text{Einstein Eq:} \quad G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}\mathcal{R}g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$$\text{Metric:} \quad ds^2 = c^2dt^2 - a^2(t)\left(\frac{dr^2}{1-Kr^2} + r^2\left(d\theta^2 + \sin^2\theta d\phi^2\right)\right)$$

$$ds^2 = c^2dt^2 - a^2(t)\left(d\chi^2 + Sinn^2(\chi)\left(d\theta^2 + \sin^2\theta d\phi^2\right)\right)$$

$$Sinn(\chi) \equiv \begin{cases} \sinh(\chi) & \text{for } K = -1 \\ \chi & \text{for } K = 0 \\ \sin(\chi) & \text{for } K = +1 \end{cases}$$

Standard Cosmology

Energy-Momentum Tensor : $T_{\mu\nu} = (\rho + P)u_\mu u_\nu + Pg_{\mu\nu}$

First Fridmann Eq : $\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P) + \frac{\Lambda}{3}$

Second Fridmann Eq : $\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3} - \frac{K}{a^2}$

Hubble Parameter: $H = \frac{\dot{a}}{a}$

Continuity Eq : $\dot{\rho} + 3\frac{\dot{a}}{a}(\rho + P) = 0$

Equation of state: $P = w\rho$

Radiation: $w = \frac{1}{3}$

Dark Matter: $w = 0$

Dark Energy: $w = -1$

Standard Cosmology

$$\text{Conservation of Energy:} \qquad T^{\mu}_{\nu,\mu} = 0$$

$$\text{Continuity Eq :} \qquad \dot{\rho} + 3\frac{\dot{a}}{a}(\rho + P) = 0$$

$$\text{Equation of state:} \qquad P = w\rho$$

$$\rho_m \propto a^{-3}$$

$$\rho_r \propto a^{-4}$$

$$\rho_\Lambda = \text{const.}$$

$$\mathrm{T}_r \propto a^{-1}$$

$$1 + z = \frac{1}{a}$$

Matter-Radiation equality

- Special significance for the generation of large-scale structure and CMB anisotropies
- As the amount of matter in the universe today goes up, the redshift of equality also goes up.
- We expect photons to decouple when the universe is already well into the matter-dominated era.

$$\rho_c = 1.88 h^2 \times 10^{-26} \;\; kg m^{-3}$$

$$H_0 = 100 \times h \;\; km s^{-1} Mpc^{-1}$$

$$h = 0.71^{+0.04}_{-0.03}$$

$$\frac{\rho_r}{\rho_c} = \frac{4.15 \times 10^{-5}}{h^2 a^4} \equiv \frac{\Omega_r}{a^4}$$

$$a_{eq} = \frac{4.15 \times 10^{-5}}{\Omega_m h^2}$$

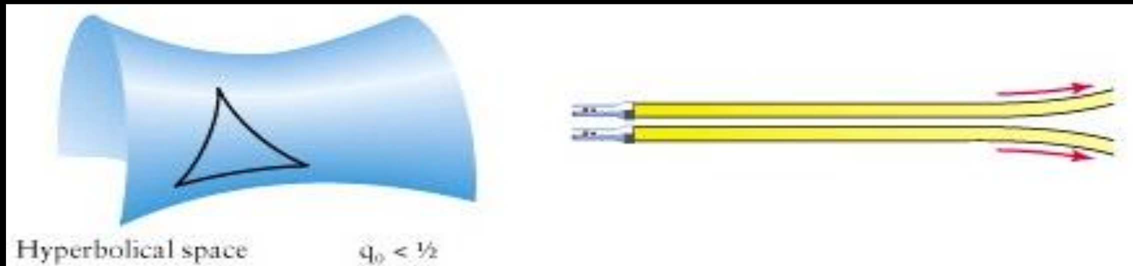
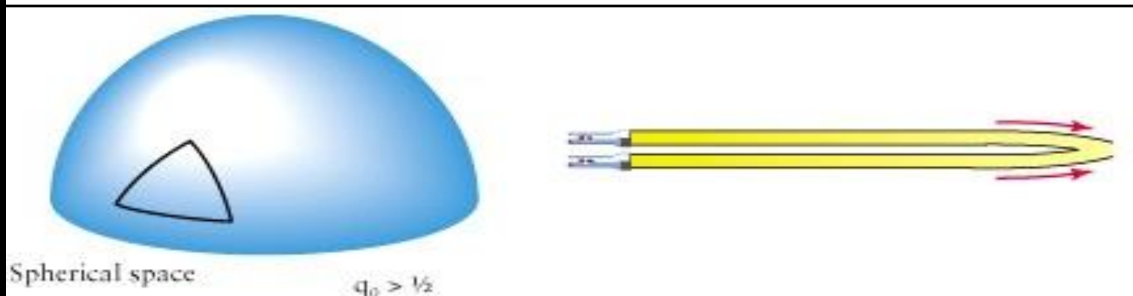
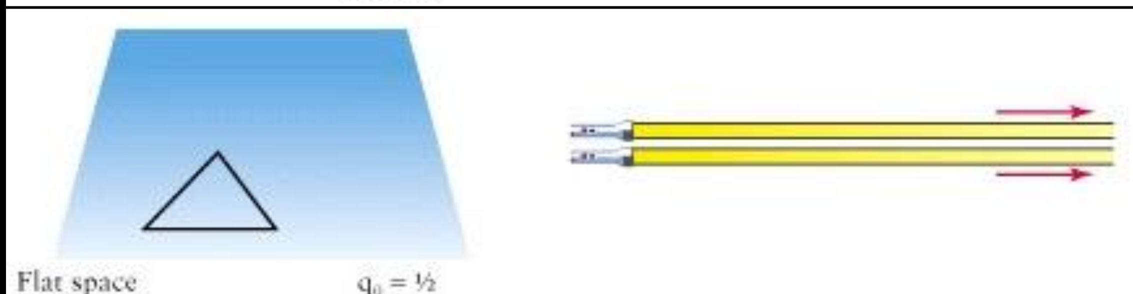
$$1 + z_{eq} = 2.4 \times 10^4 \Omega_m h^2$$

$$z_* \simeq 10^3$$

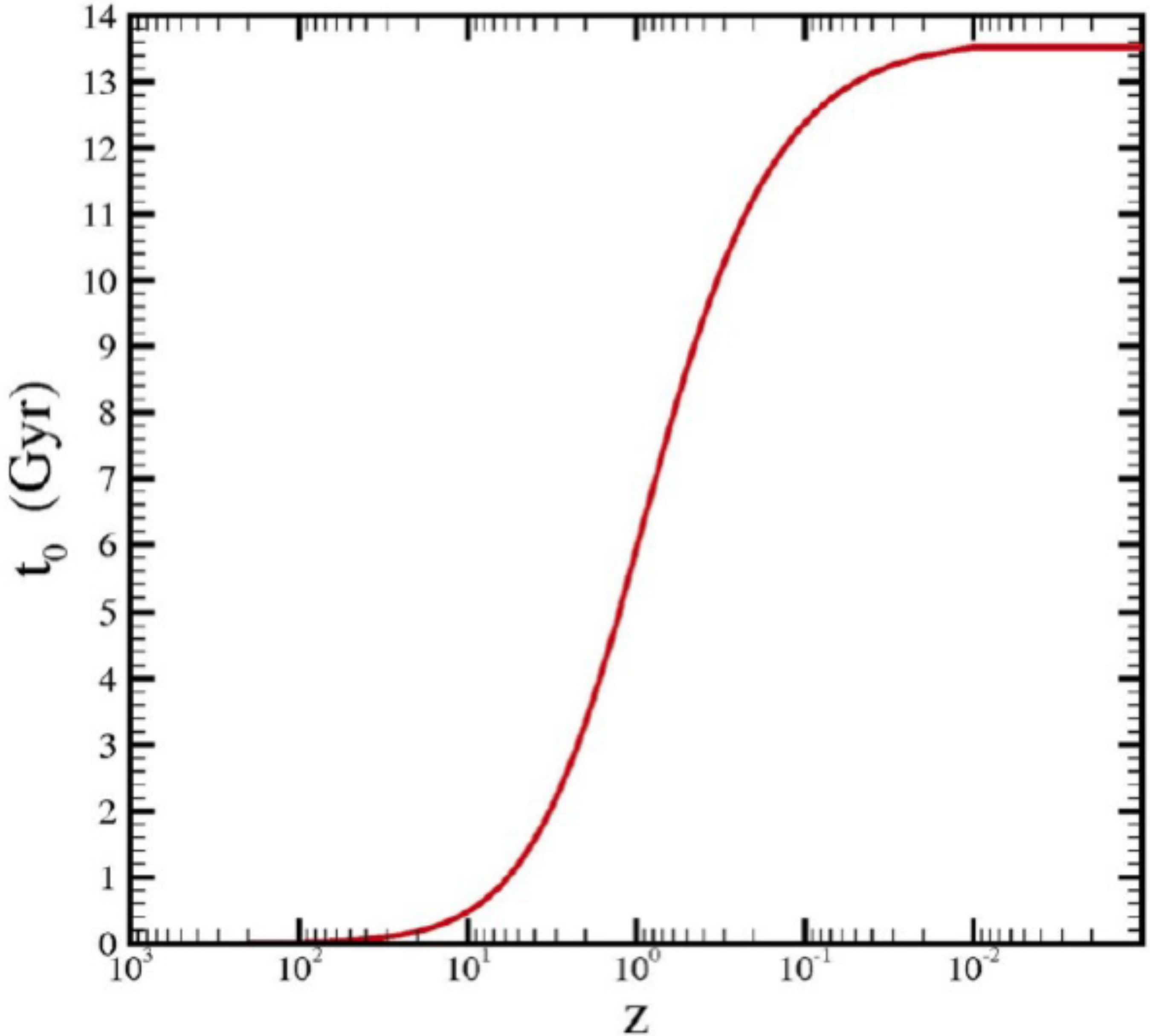
$$z_{eq} \simeq 3270$$

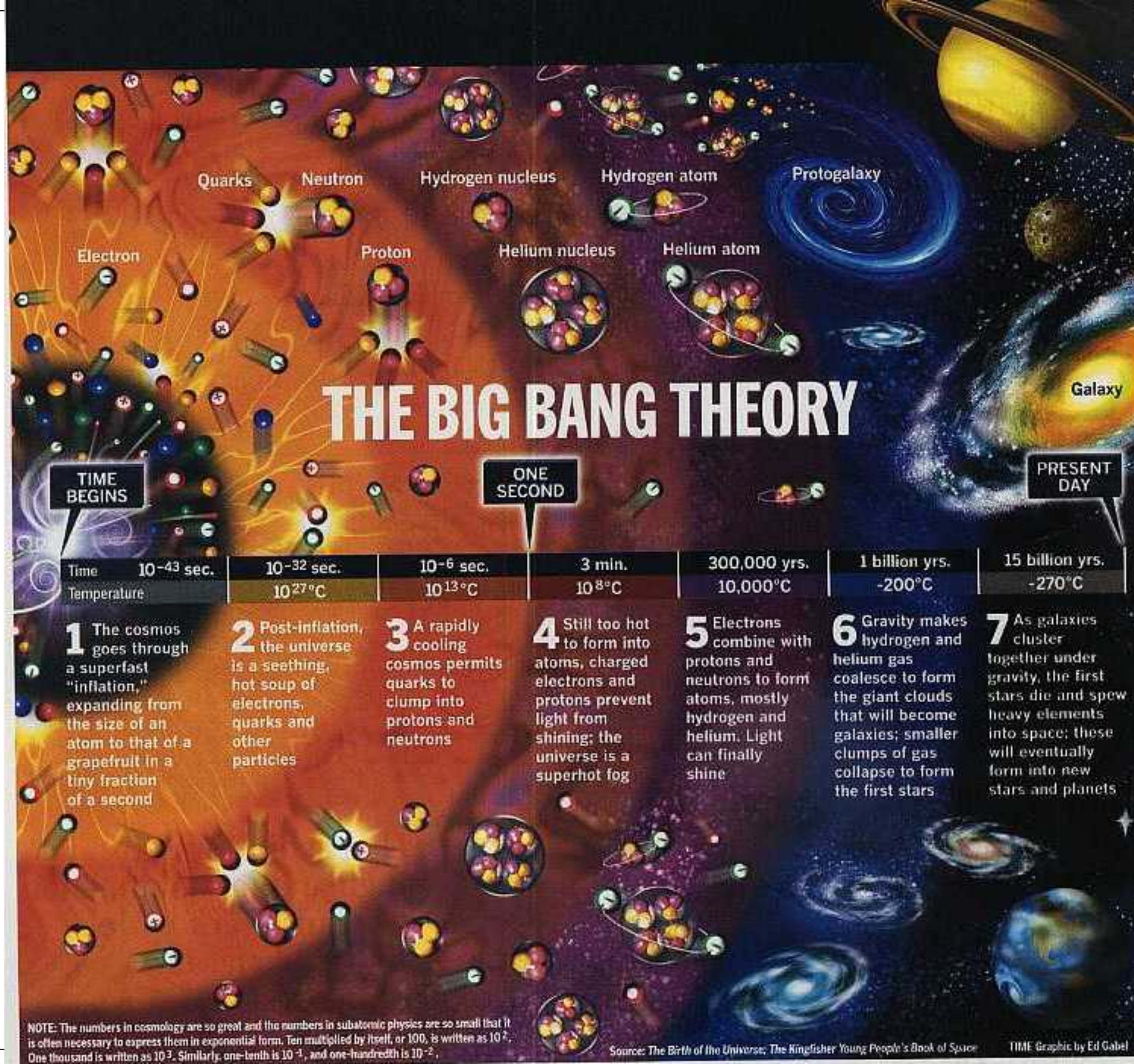
The Shape of the Universe

According to Einstein, mass bends space. This means that the universe has a shape. This shape is related to the amount of matter in the universe.

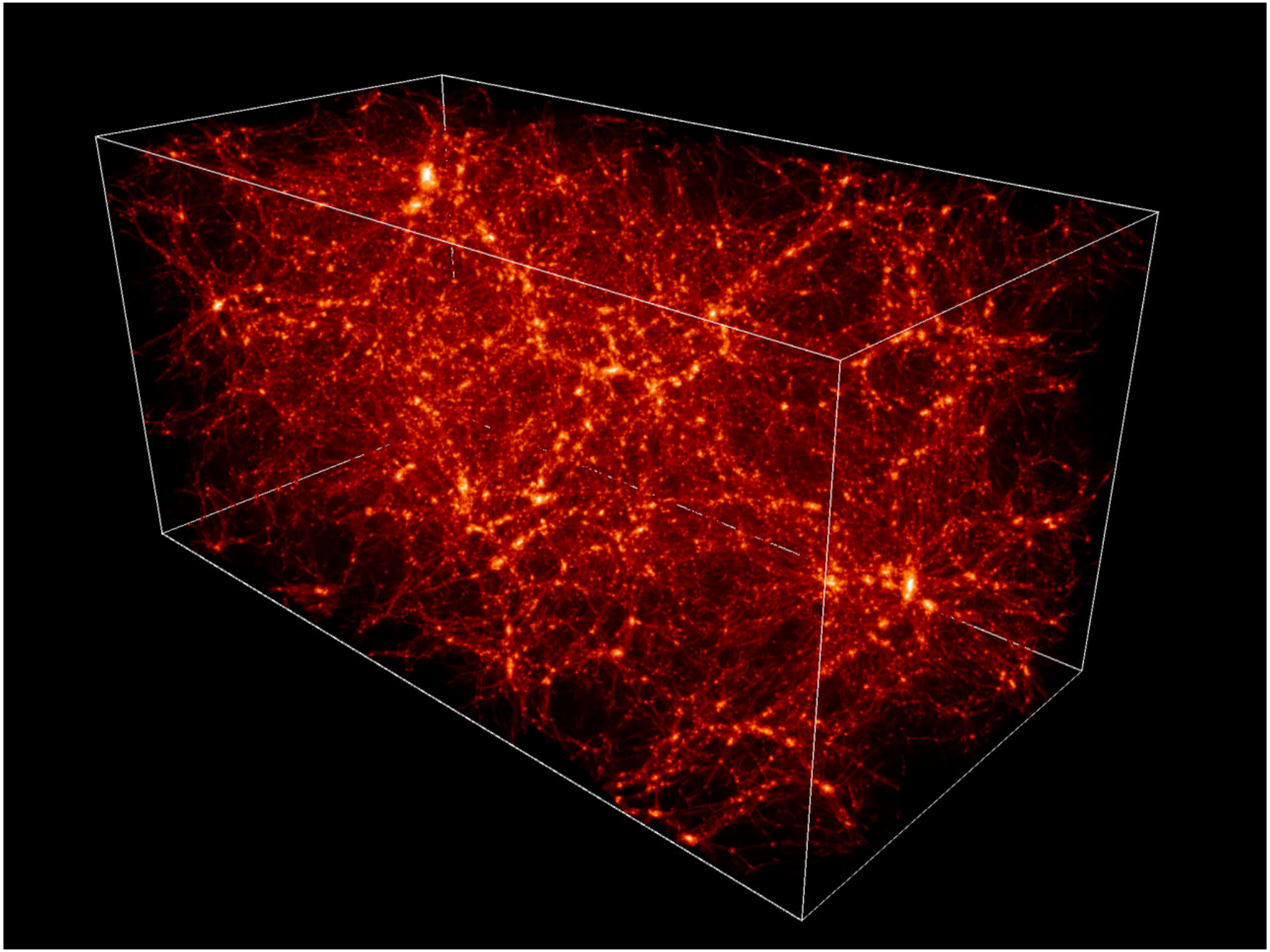
Type	Shape of Universe
Open Universe	
Closed Universe	
Flat Universe	

Age vs. Redshift

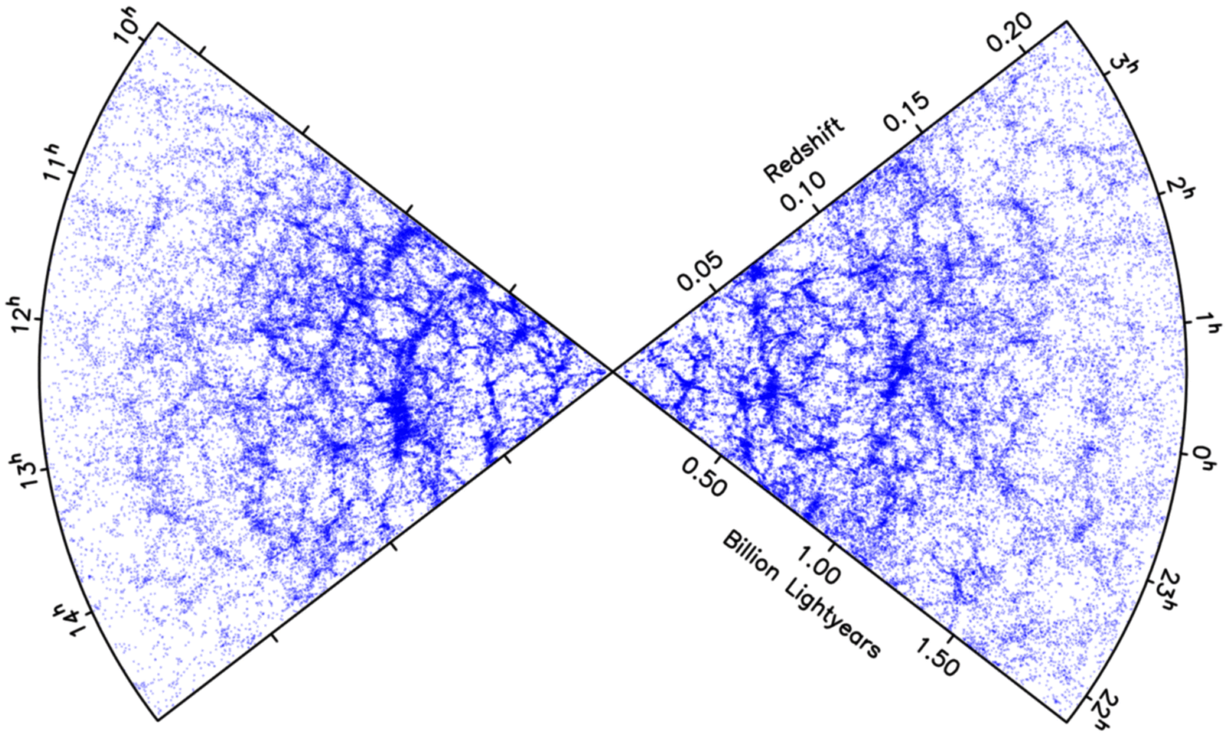



THE BIG BANG THEORY
Quarks
Neutron
Hydrogen nucleus
Hydrogen atom
Protogalaxy
Electron
Proton
Helium nucleus
Helium atom
Galaxy
TIME BEGINS
ONE SECOND
PRESENT DAY
Time: 10^{-43} sec. | 10^{-32} sec. | 10^{-6} sec. | 3 min. | 300,000 yrs. | 1 billion yrs. | 15 billion yrs.
Temperature: 10^{27}°C | 10^{13}°C | 10^{8}°C | 10,000°C | -200°C | -270°C
1 The cosmos goes through a superfast "inflation," expanding from the size of an atom to that of a grapefruit in a tiny fraction of a second
2 Post-inflation, the universe is a seething, hot soup of electrons, quarks and other particles
3 A rapidly cooling cosmos permits quarks to clump into protons and neutrons
4 Still too hot to form into atoms, charged electrons and protons prevent light from shining; the universe is a superhot fog
5 Electrons combine with protons and neutrons to form atoms, mostly hydrogen and helium. Light can finally shine
6 Gravity makes hydrogen and helium gas coalesce to form the giant clouds that will become galaxies; smaller clumps of gas collapse to form the first stars
7 As galaxies cluster together under gravity, the first stars die and spew heavy elements into space; these will eventually form into new stars and planets
NOTE: The numbers in cosmology are so great and the numbers in subatomic physics are so small that it is often necessary to express them in exponential form. Ten multiplied by itself, or 100, is written as 10^2. One thousand is written as 10^3. Similarly, one-tenth is 10^{-1}, and one-hundredth is 10^{-2}.
Source: The Birth of the Universe; The Kingfisher Young People's Book of Space
TIME Graphic by Ed Gabel

Homogeneity and Isotropy

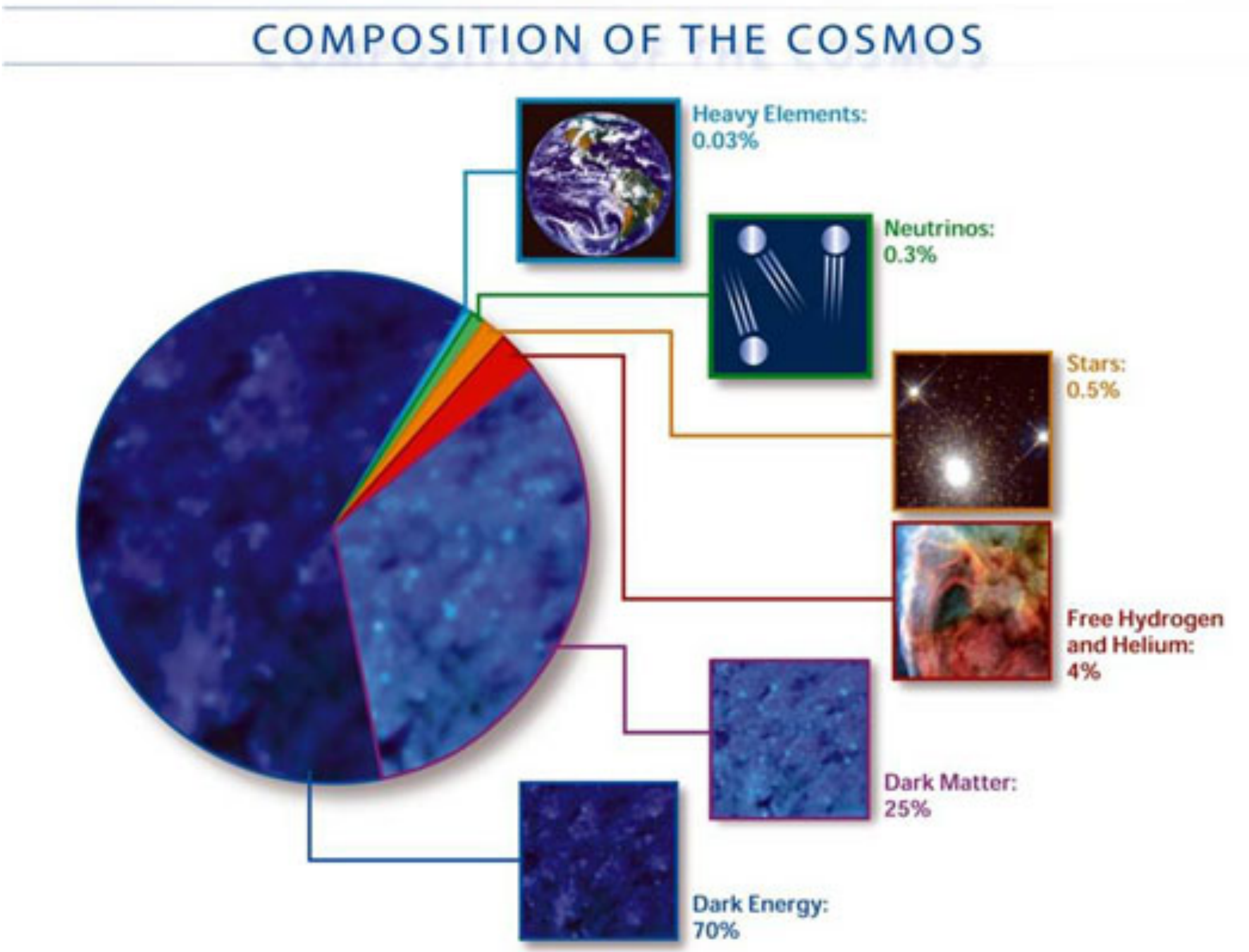


Distribution of Galaxies

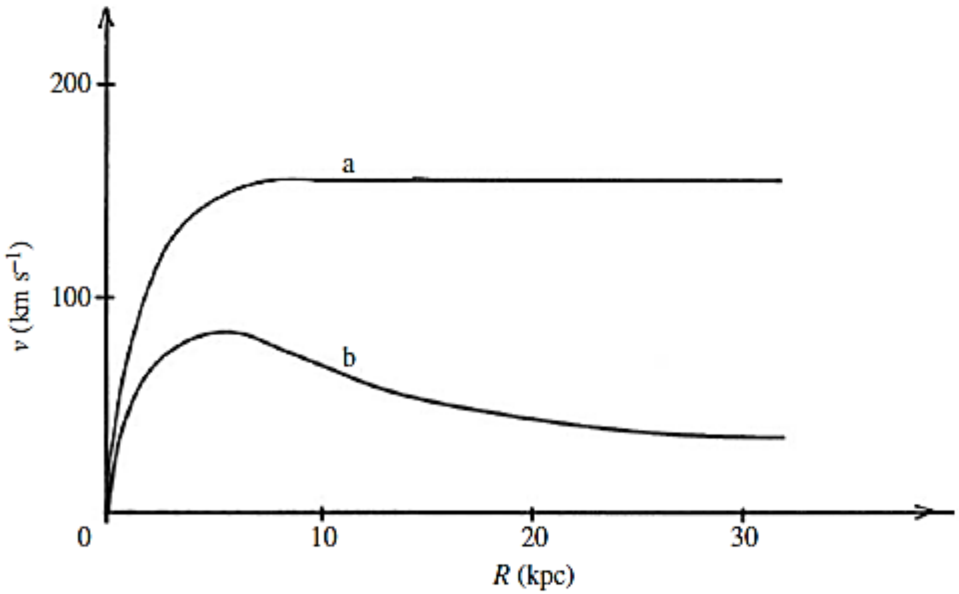


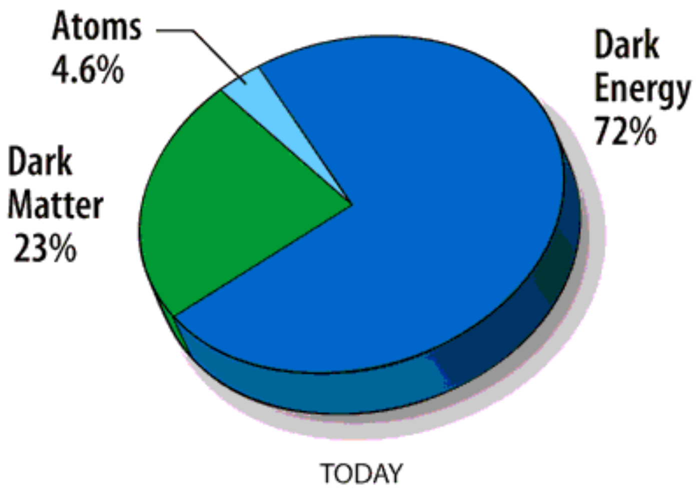
Galaxy distribution out to 858 Mpc. Based on SDSS and 2dF surveys

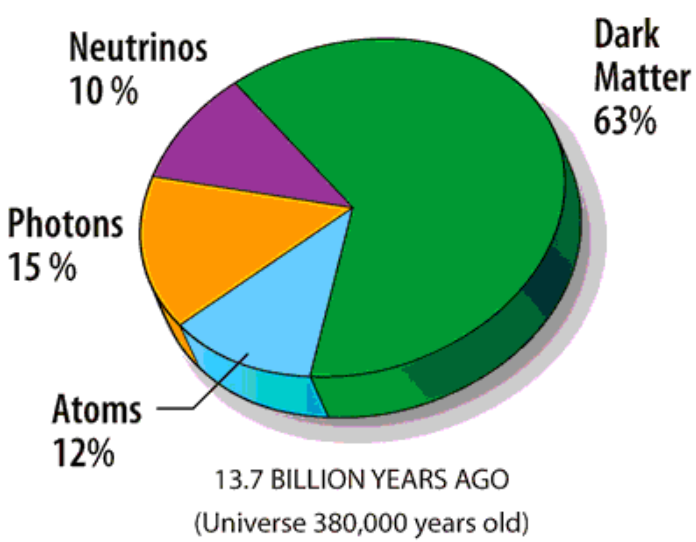
Constituents of the Cosmos



Dark Energy and Dark Matter

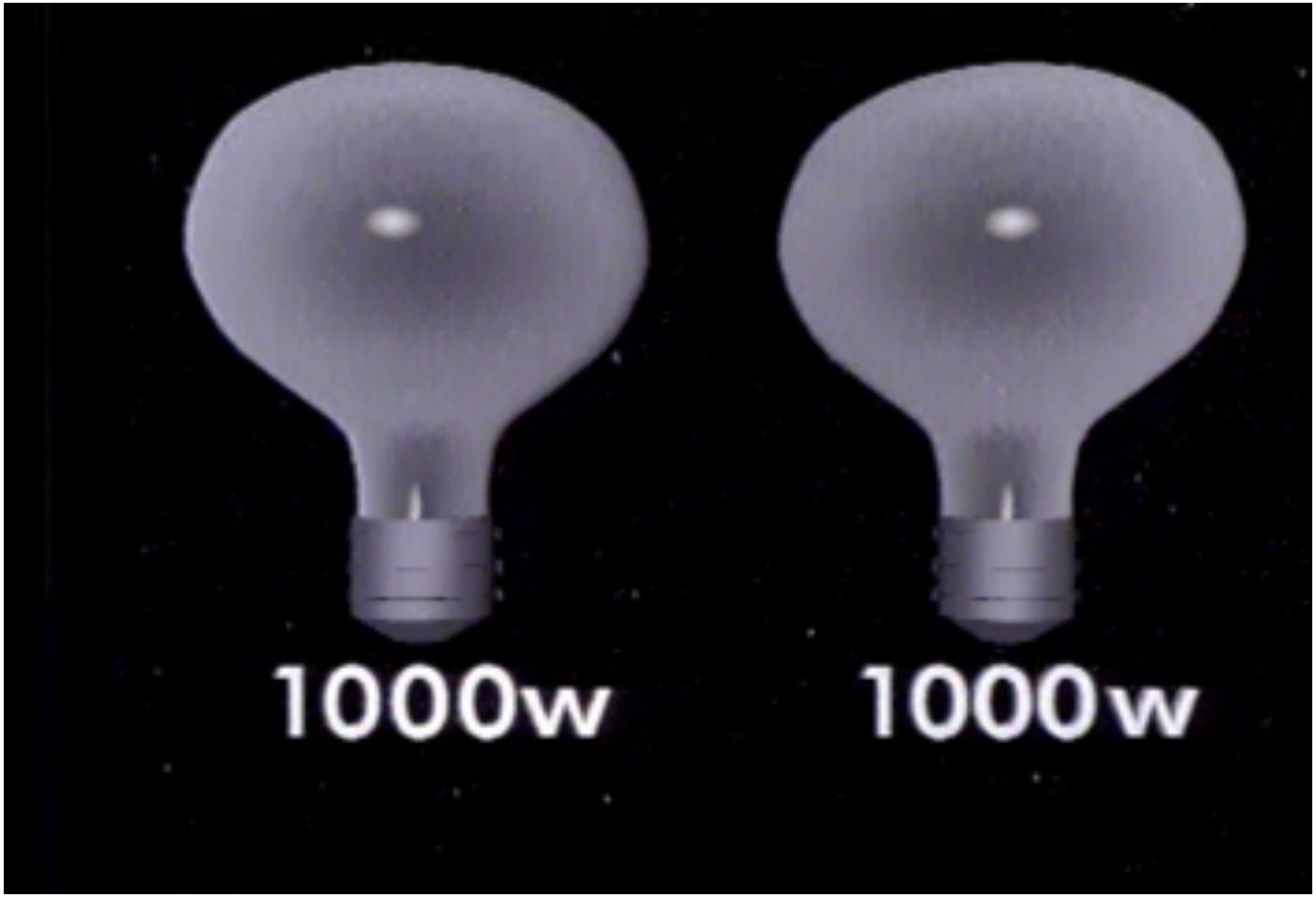




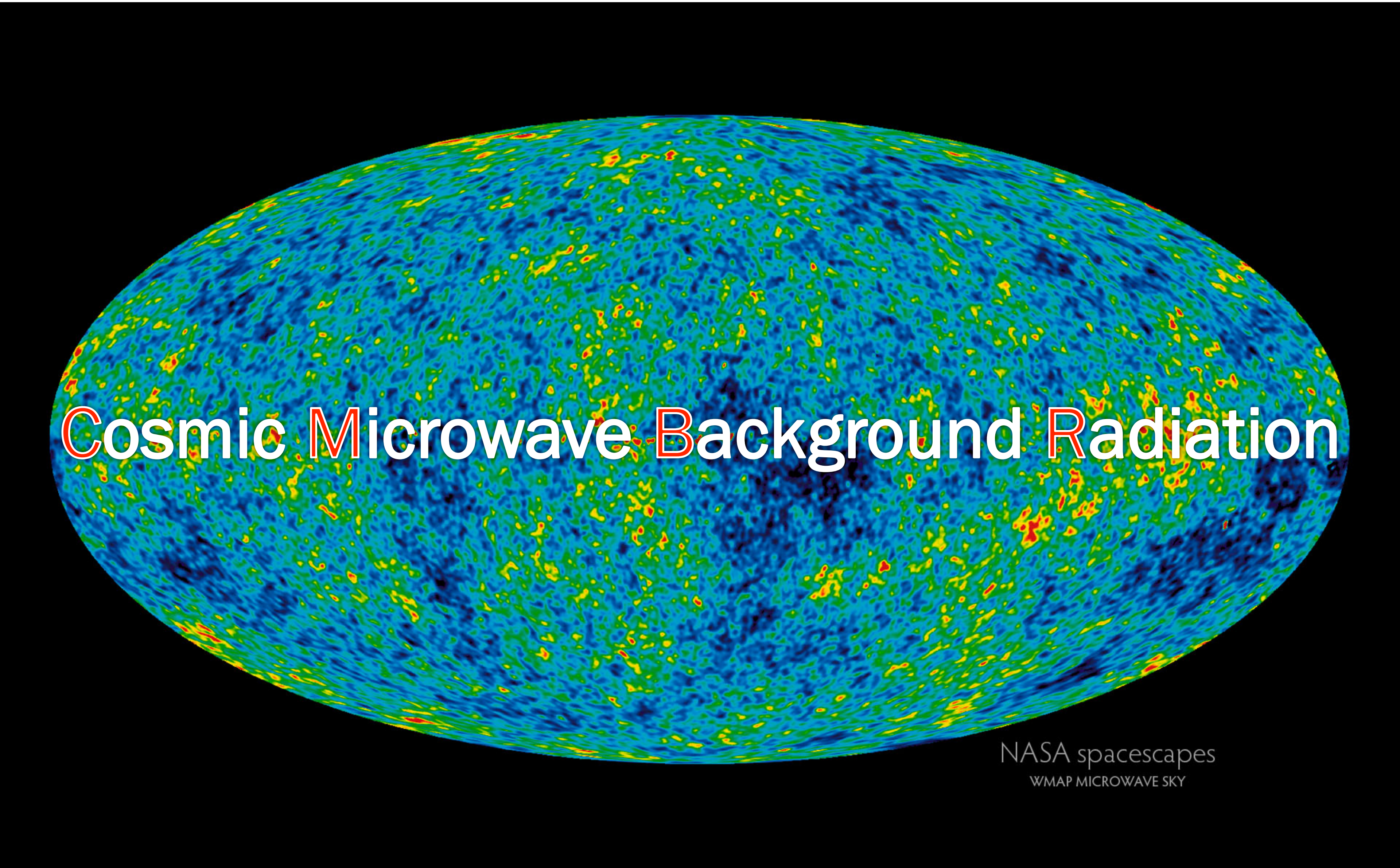


Supernovae Explosion

SN Type Ia Observations



Cosmic Microwave Background Radiation



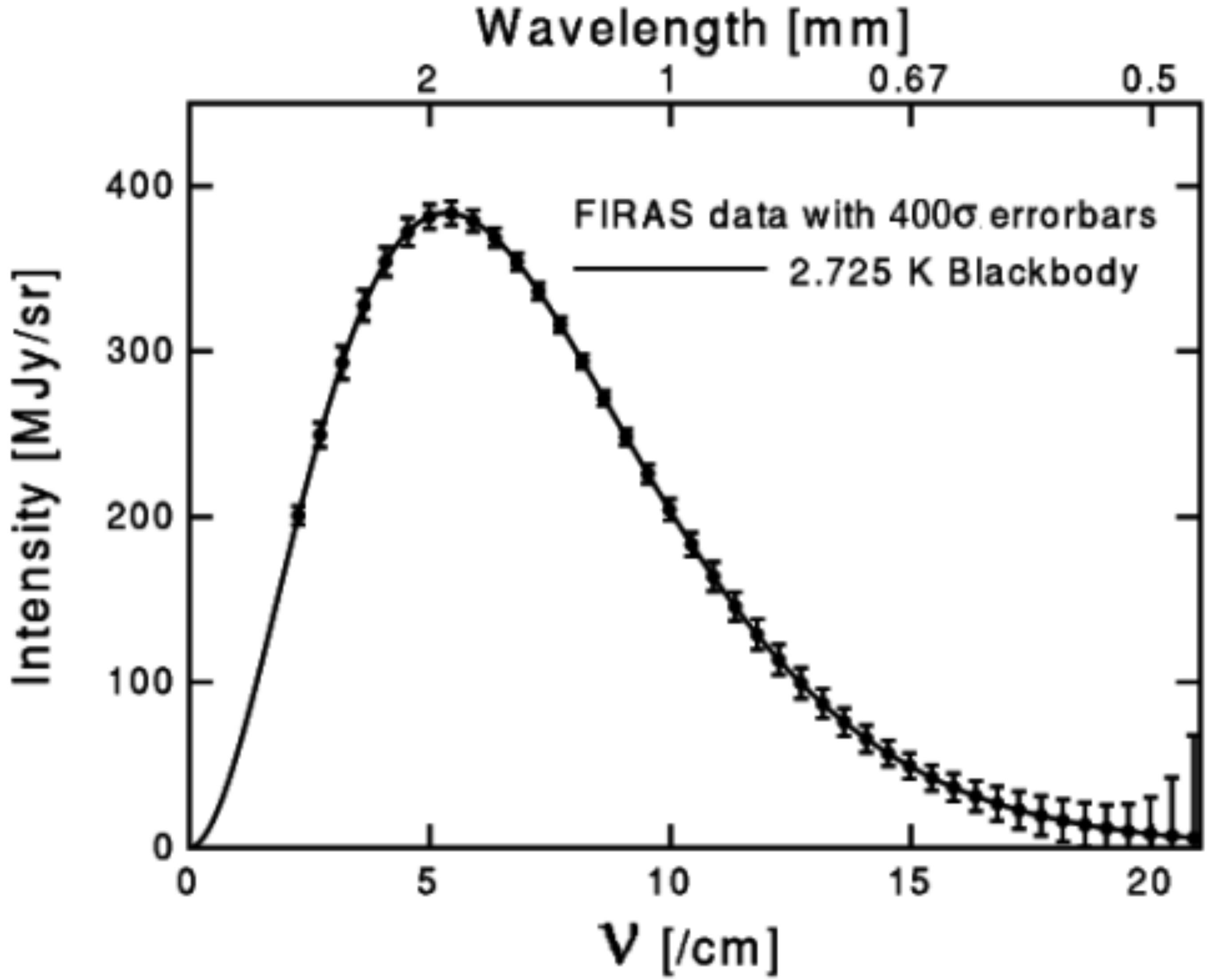
CMB History

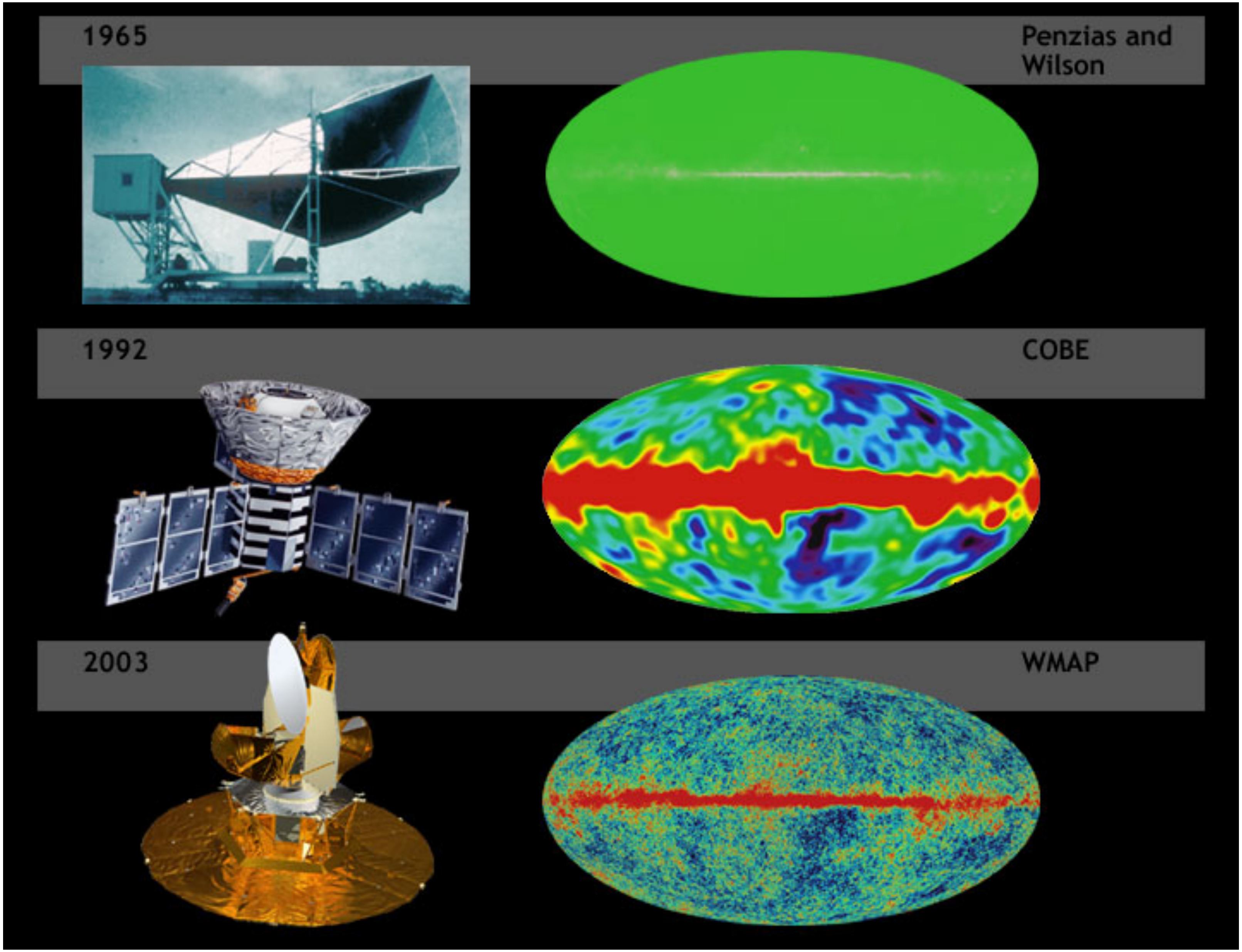
- 1948 George Gamow calculates a temperature of 50 K (assuming a 3-billion year old Universe).
- 1948 Ralph Alpher and Robert Herman estimate "the temperature in the Universe" at 5 K. Although they do not specifically mention microwave background radiation, it may be inferred.
- 1956 George Gamow estimates 6 K.
- 1957Tigran Shmaonov reports that "the absolute effective temperature of the radioemission background … is 4+/- 3K“
- 1965 Arno Penzias and Robert Woodrow Wilson measure the temperature to be approximately 3 K. Robert Dicke, P. J. E. Peebles, P. G. Roll and D. T. Wilkinson interpret this radiation as a signature of the big bang.

CMB History

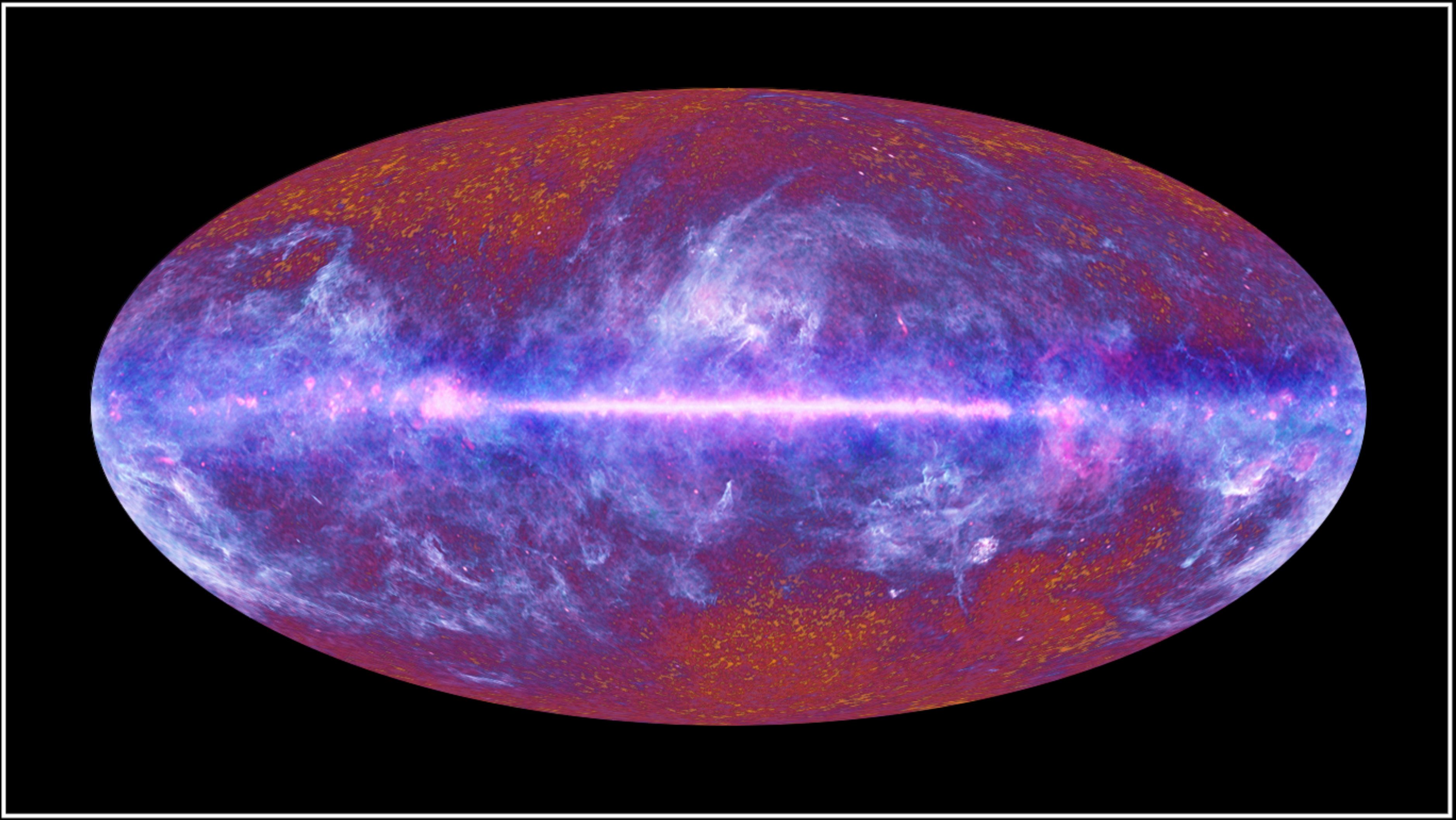
- 1983 RELIKT-1 Soviet CMB anisotropy experiment was launched.
- 1990 FIRAS measures the black body form of the CMB spectrum with exquisite precision.
- January, 1992 Scientists who analyzed data from RELIKT-1 spacecraft report the discovery of anisotropy at the Moscow astrophysical seminar.
- April, 1992 Scientists who analyzed data from COBE DMR announce the discovery of the primary temperature anisotropy.
- 1999 First measurements of acoustic oscillations in the CMB anisotropy angular power spectrum from the TOCO, BOOMERANG, and Maxima Experiments.
- 2001 WMAP satellite launched.
- 2002 Polarization discovered by DASI.
- 2009 Planck satellite began its mission.

CMB black body spectrum



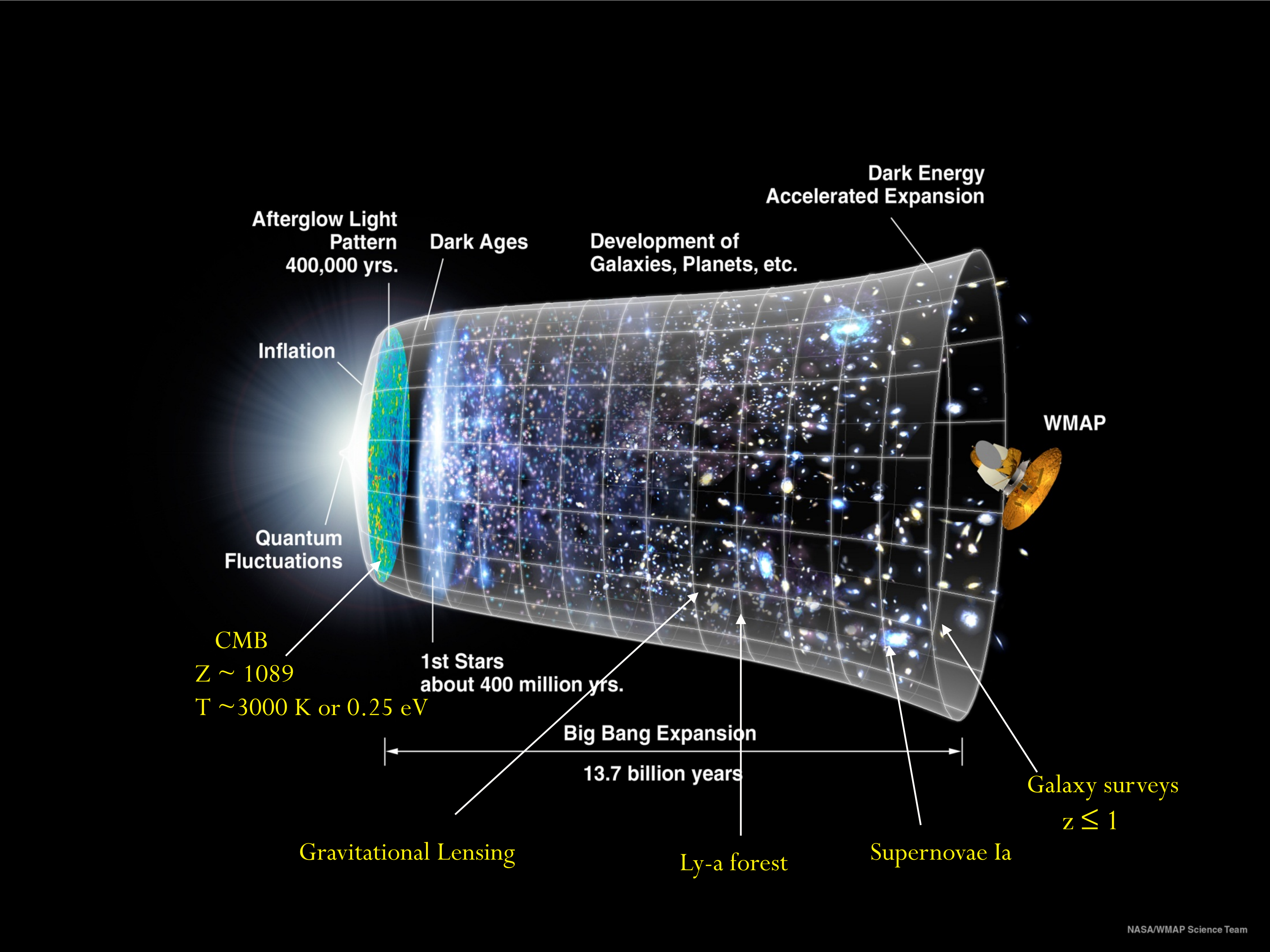


1965
Penzias and Wilson
1992
COBE
2003
WMAP

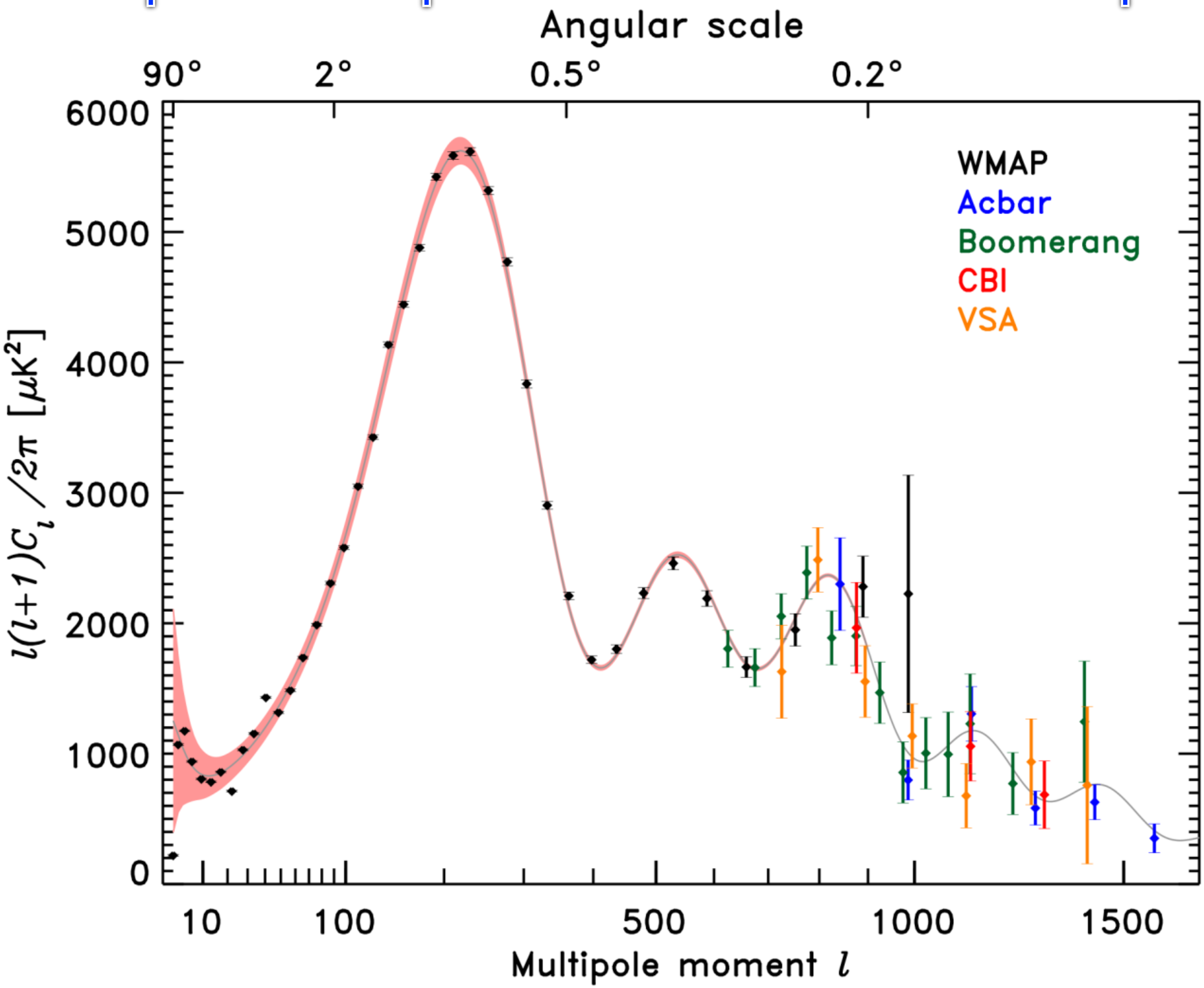


The Planck one-year all-sky survey

esa


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
CMB
Z ~ 1089
T ~3000 K or 0.25 eV
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
Galaxy surveys
z ≤ 1
Gravitational Lensing
Ly-a forest
Supernovae Ia
NASA/WMAP Science Team

The power spectrum of anisotropies



CMB Anisotropies

- **Primary anisotropies**
  - Sachs-Wolfe effect
  - Doppler effect
  - Intrinsic temperature variations
- **Secondary anisotropies**
  - Integrated Sachs-Wolfe (ISW) effect
  - Sunyaev- Zel'dovich (SZ) effect
  - Lensing
  - …

The Sachs-Wolfe effect

- Ordinary Sachs-Wolfe effect → $\frac{\Delta T}{T}(\hat{n}) = \frac{1}{3}\phi(\hat{n})|_{LSS}$

  ↓

  At the surface of last scattering

- Integrated Sachs-Wolfe effect → **Depends on the change of gravitational potential while CMB photons are passing through potential well**
  - Early ISW effect
  - Late ISW effect

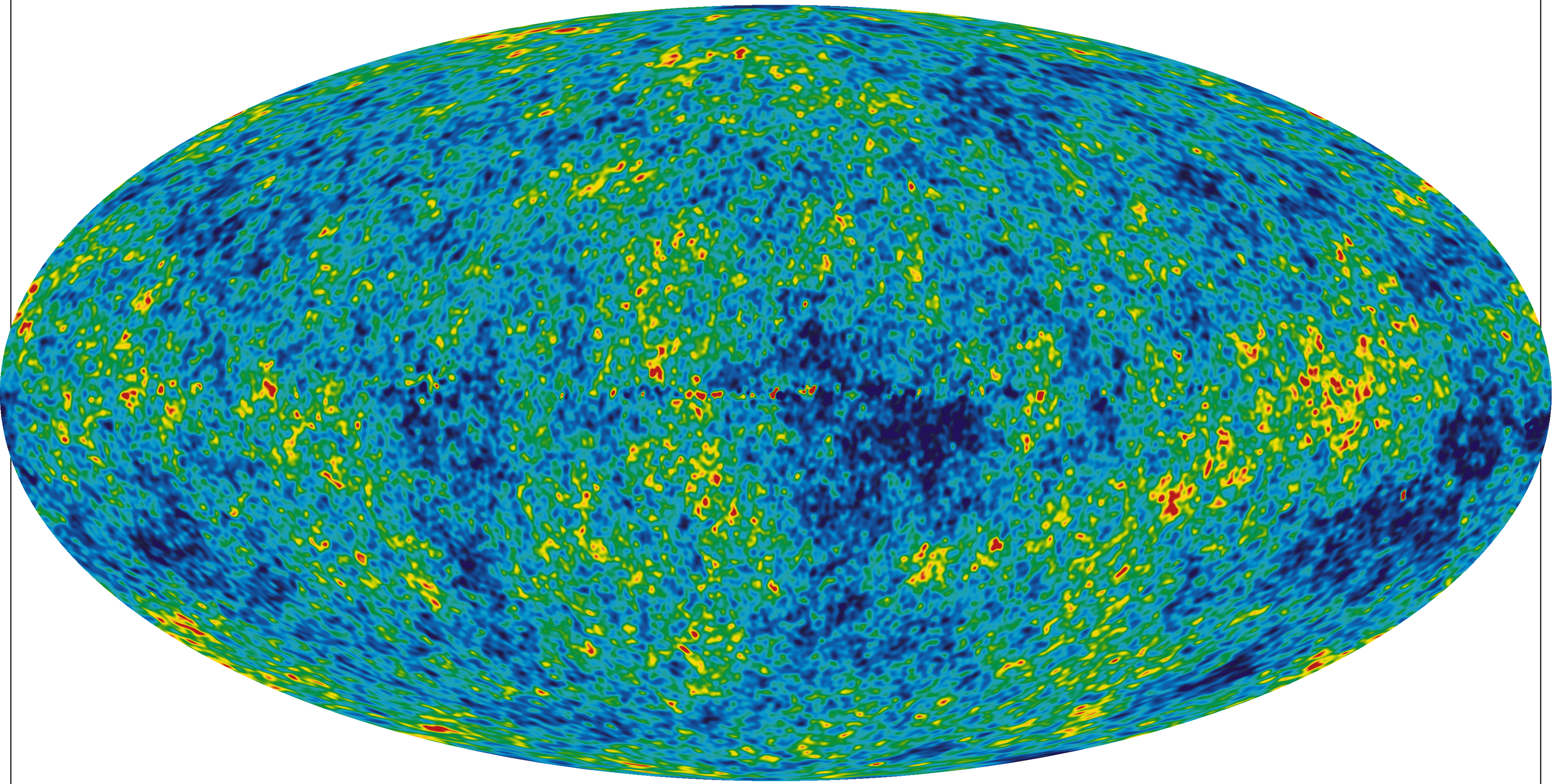
$$\frac{\Delta T}{T}(\hat{n}) = 2\int_{t_{LSS}}^{t_0} dt\Phi'(t,\mathbf{x})$$

Non-linear structures → Non- linear ISW effect (Rees-Sciama effect)

Secondary anisotropies

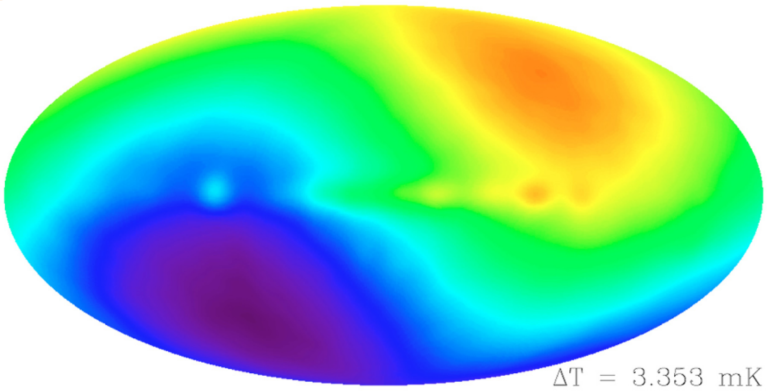
- ISW effect $$\frac{\Delta T}{T}(\hat{n}) = 2\int_{t_{LSS}}^{t_0} dt\Phi'(t,\mathbf{x})$$
- Sunyaev-Zel'dovich (SZ) effect $$\frac{\Delta T}{T} \sim -2k_B \frac{T_e}{m_e c^2}$$
- Lensing
- …

Observed ΔT as a random field on the sphere



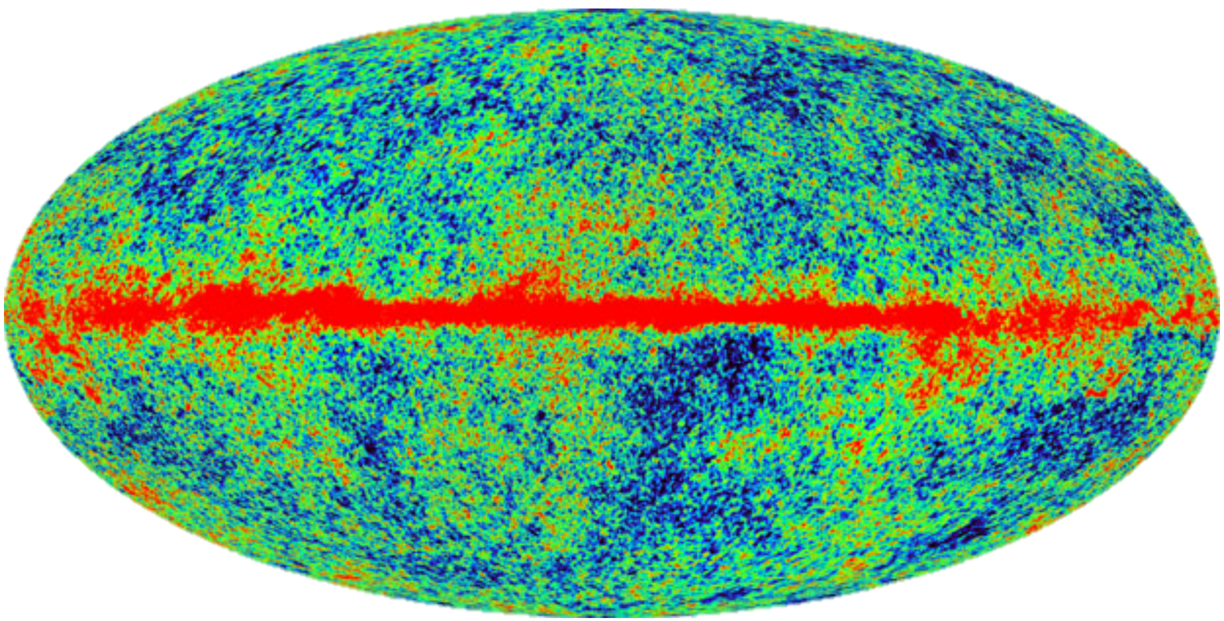
Source: NASA/WMAP Science Team

(almost) uniform 2.726K blackbody



Dipole (local motion)

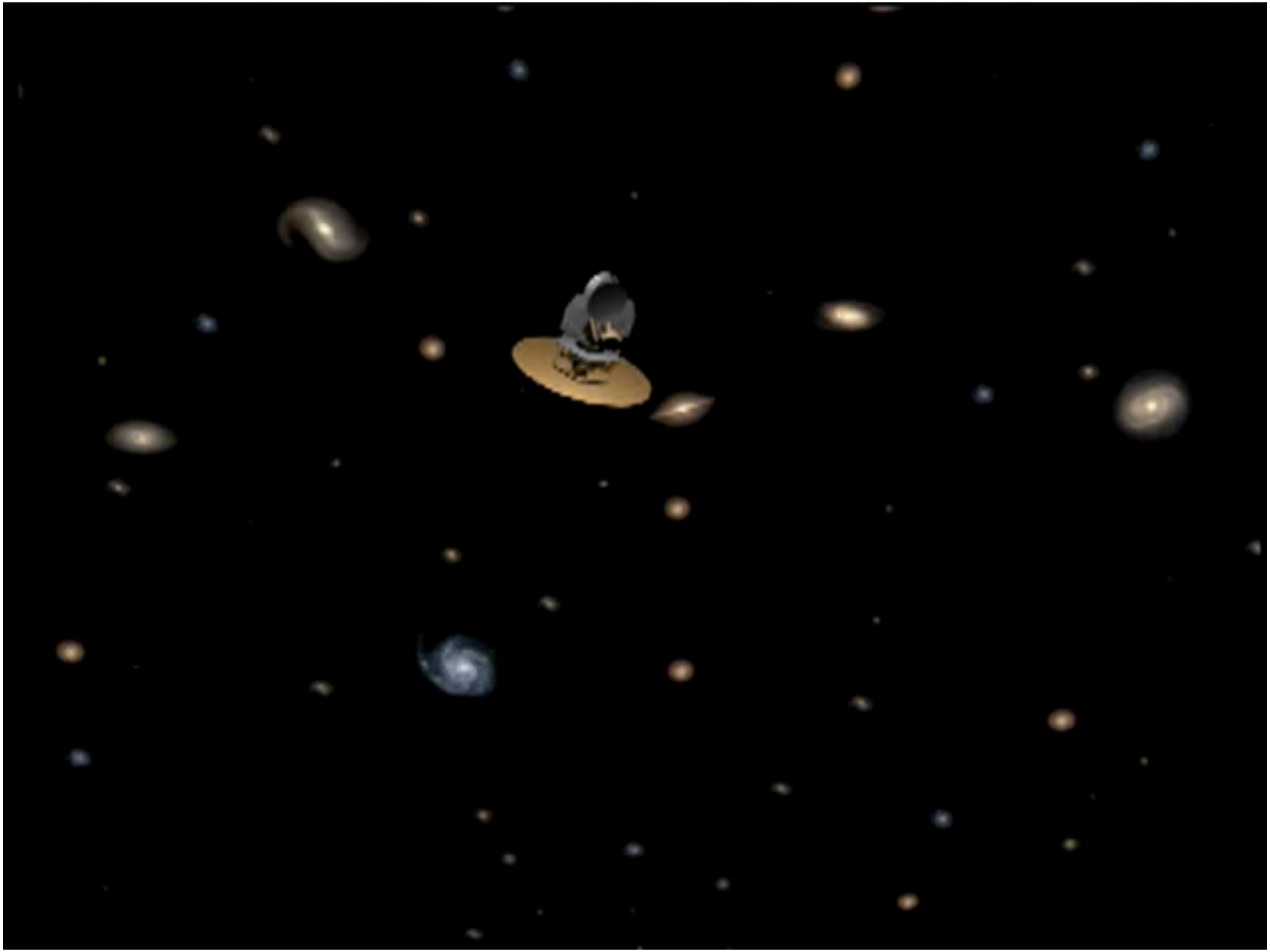
$O(10^{-5})$ perturbations (structures)



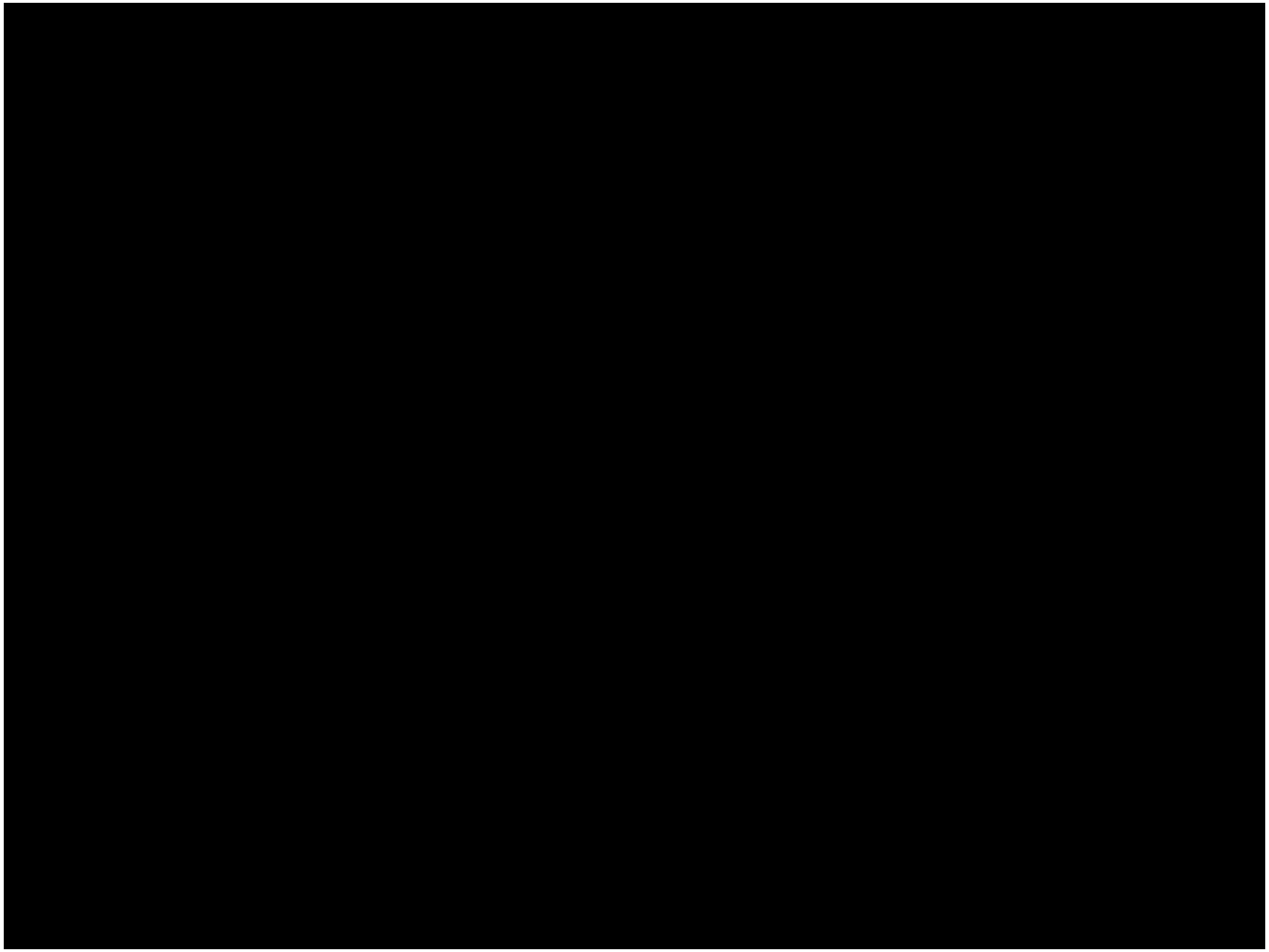
Observations: the microwave sky today

Source: NASA/WMAP Science Team

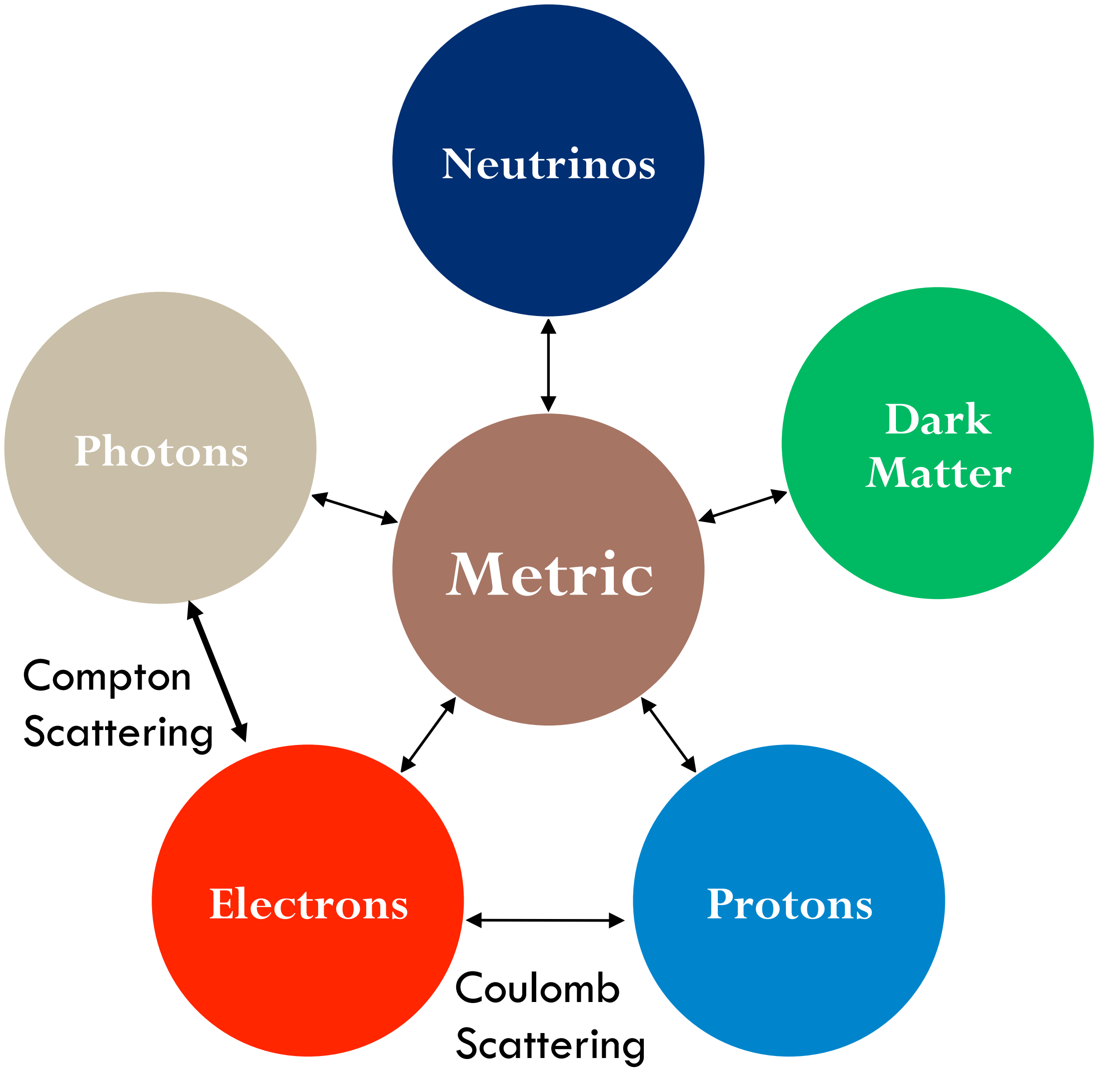
CMB & Geometry of the Universe



CMB as a fingerprint of the Cosmos



Sources of perturbations



Einstein- Boltzmann equations

Boltzmann equation

$$\frac{df}{dt} = C[f]$$

Photons (2 equations)

1) $\dot{\Theta} + ik\mu\Theta = -\dot{\Phi} - ik\mu\Psi - \dot{\tau}[\Theta_0 - \Theta + \mu v_b - \frac{1}{2}\mathcal{P}_2(\mu)\Pi]$

2) $\dot{\Theta}_P + ik\mu\Theta_P = -\dot{\tau}[-\Theta_P + \frac{1}{2}(1 - \mathcal{P}_2(\mu))\Pi]$

$\Pi = \Theta_2 + \Theta_{P2} + \Theta_{P0}$

CDM (2 equations)

3) $\dot{\delta} + ikv = -3\dot{\Phi}$

4) $\dot{v} + \frac{\dot{a}}{a}v = -ik\Psi$

Baryons (2 equations)

5) $\dot{\delta}_b + ikv_b = -3\dot{\Phi}$

6) $\dot{v}_b + \frac{\dot{a}}{a}v_b = -ik\Psi + \frac{\dot{\tau}}{R}[v_b + 3i\Theta_1]$

$$\frac{1}{R} \equiv \frac{4\rho_\gamma^{(0)}}{3\rho_b^{(0)}}$$

Neutrinos (1 equation)

7) $\dot{\mathcal{N}} + ik\mu\mathcal{N} = -\dot{\Phi} - ik\mu\Psi$

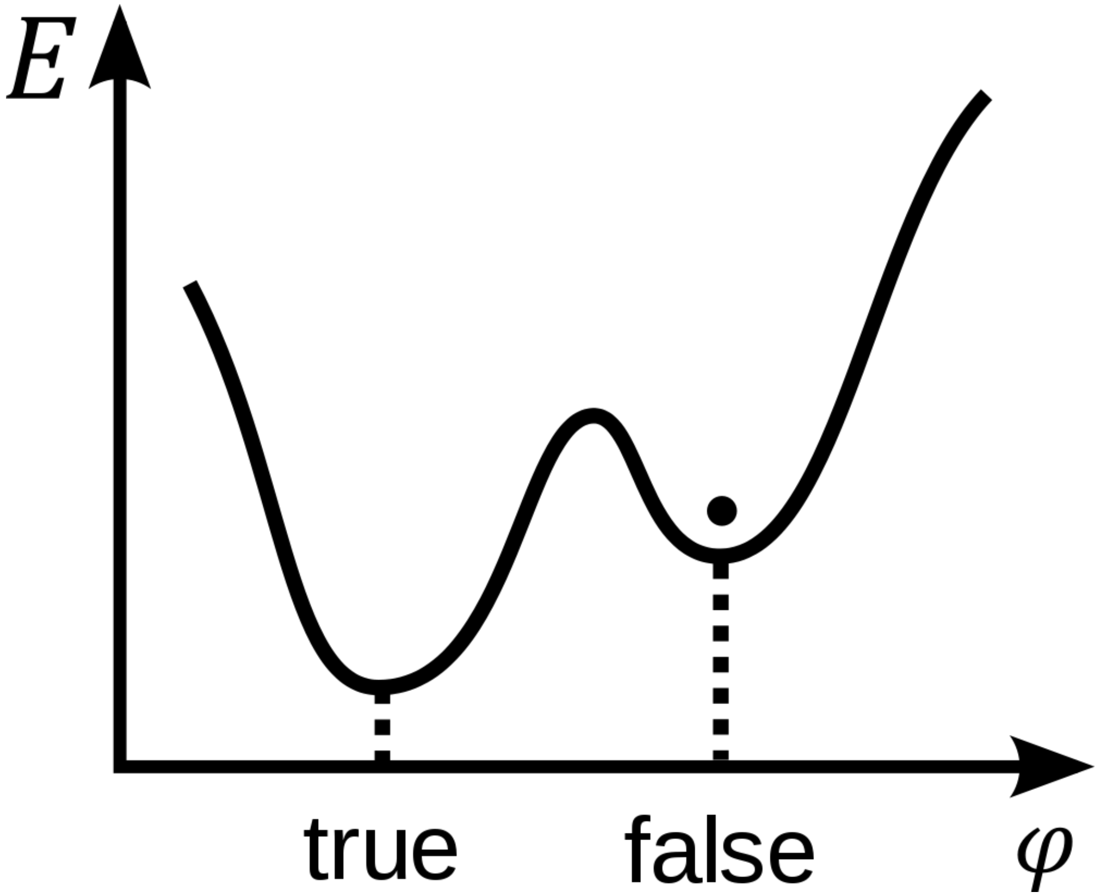
Einstein-perturbed equation (2 equation)

8) $k^2\Phi + 3\frac{\dot{a}}{a}(\dot{\Phi} - \Psi\frac{\dot{a}}{a}) = 4\pi G a^2[\rho_{CDM}\delta + \rho_b\delta_b + 4(\rho_\gamma\Theta_0 + \rho_\nu\mathcal{N}_0)]$

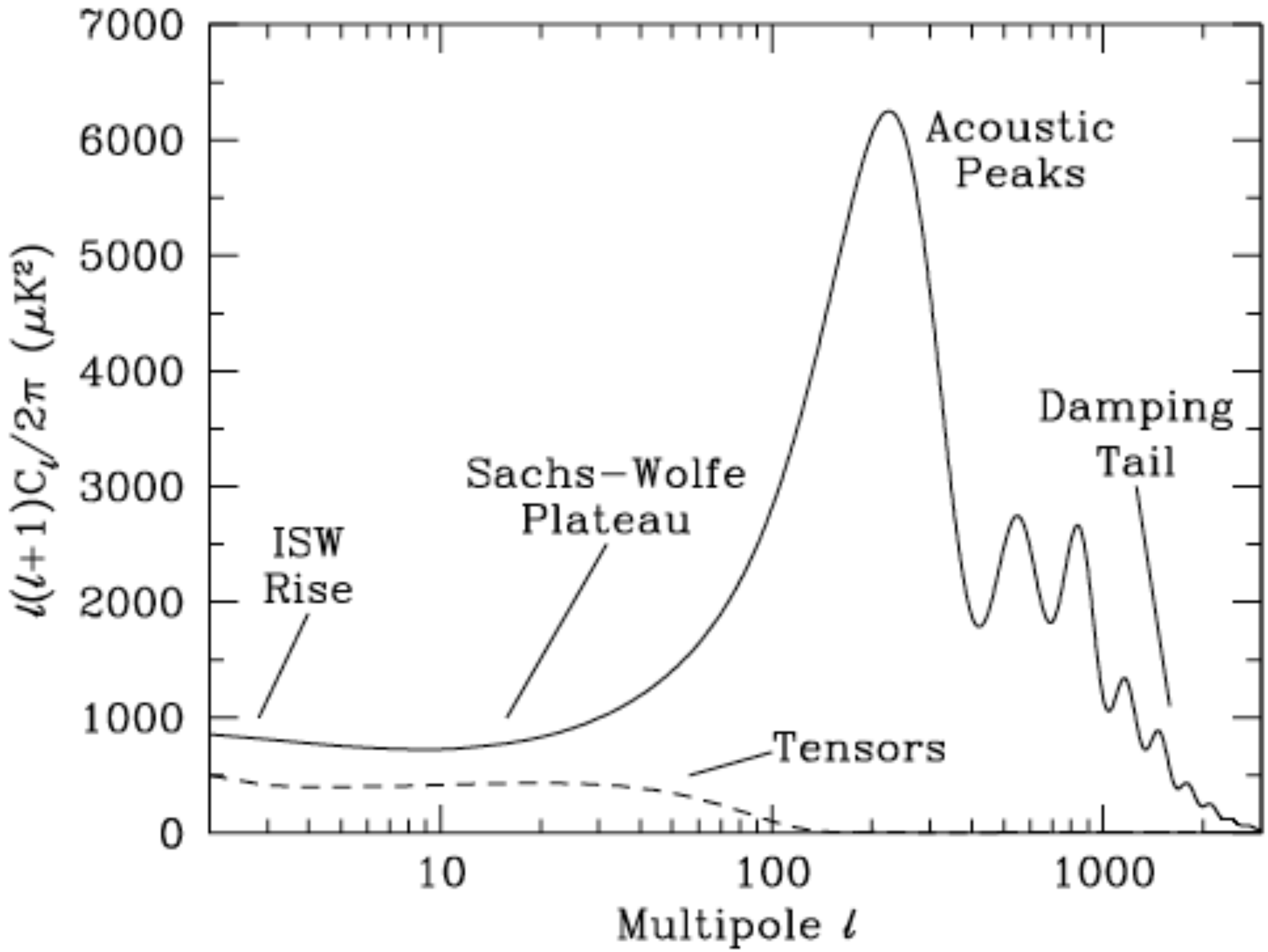
9) $k^2(\Phi + \Psi) = -32\pi G a^2(\rho_\gamma\Theta_2 + \rho_\nu\mathcal{N}_2)$

Initial Conditions

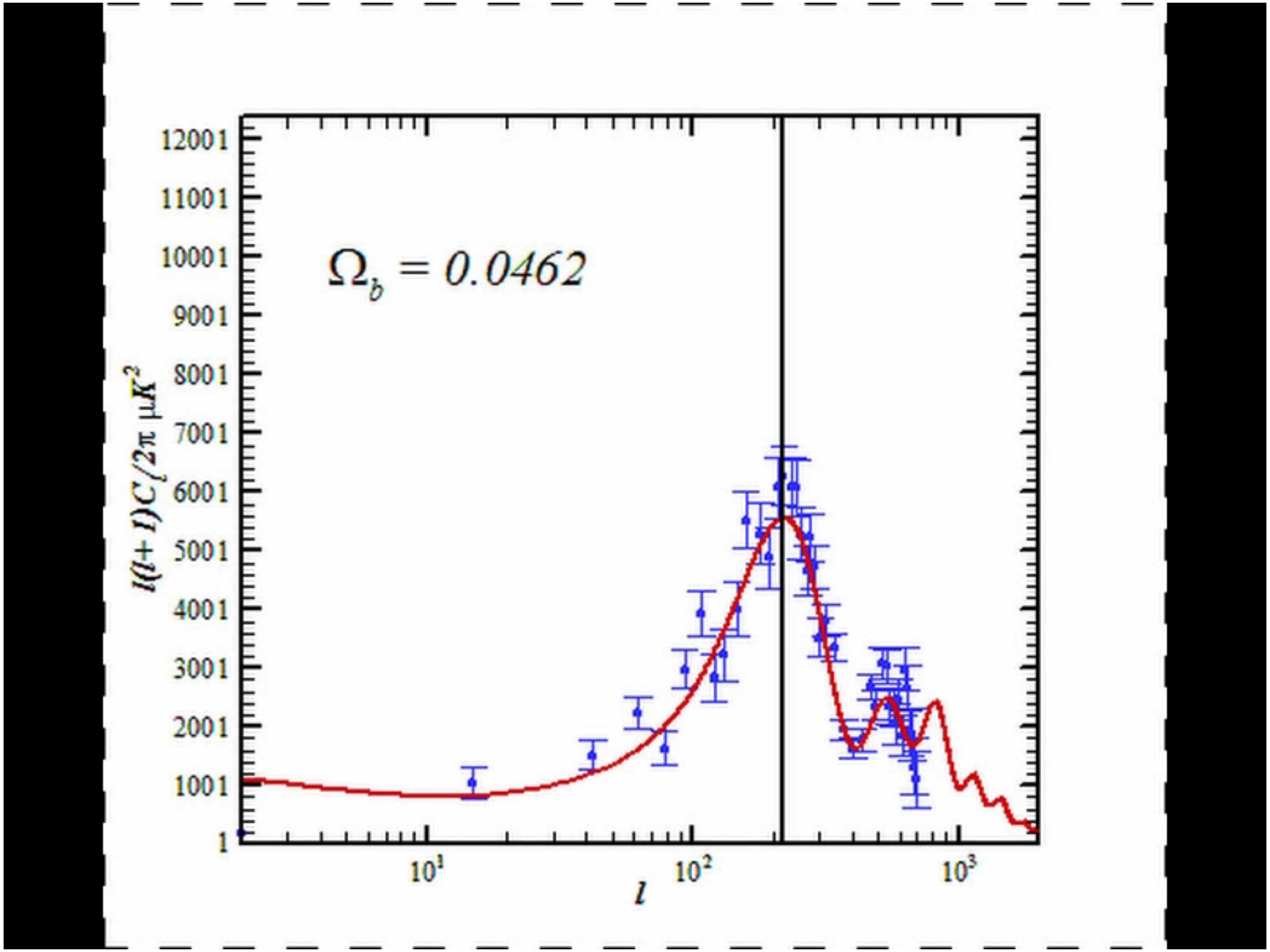
- Slow-roll Inflation



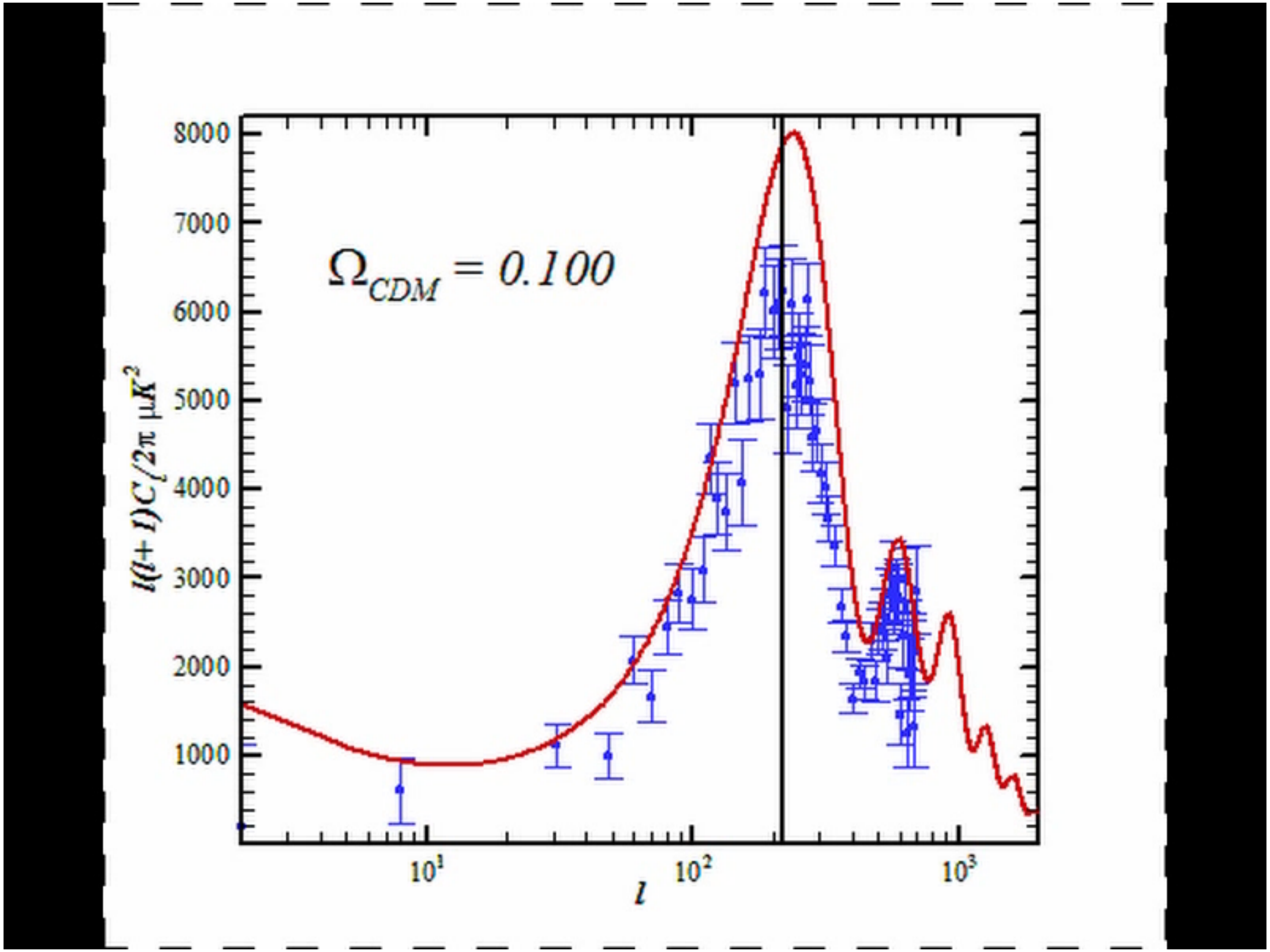
Theoretical anisotropy power spectrum



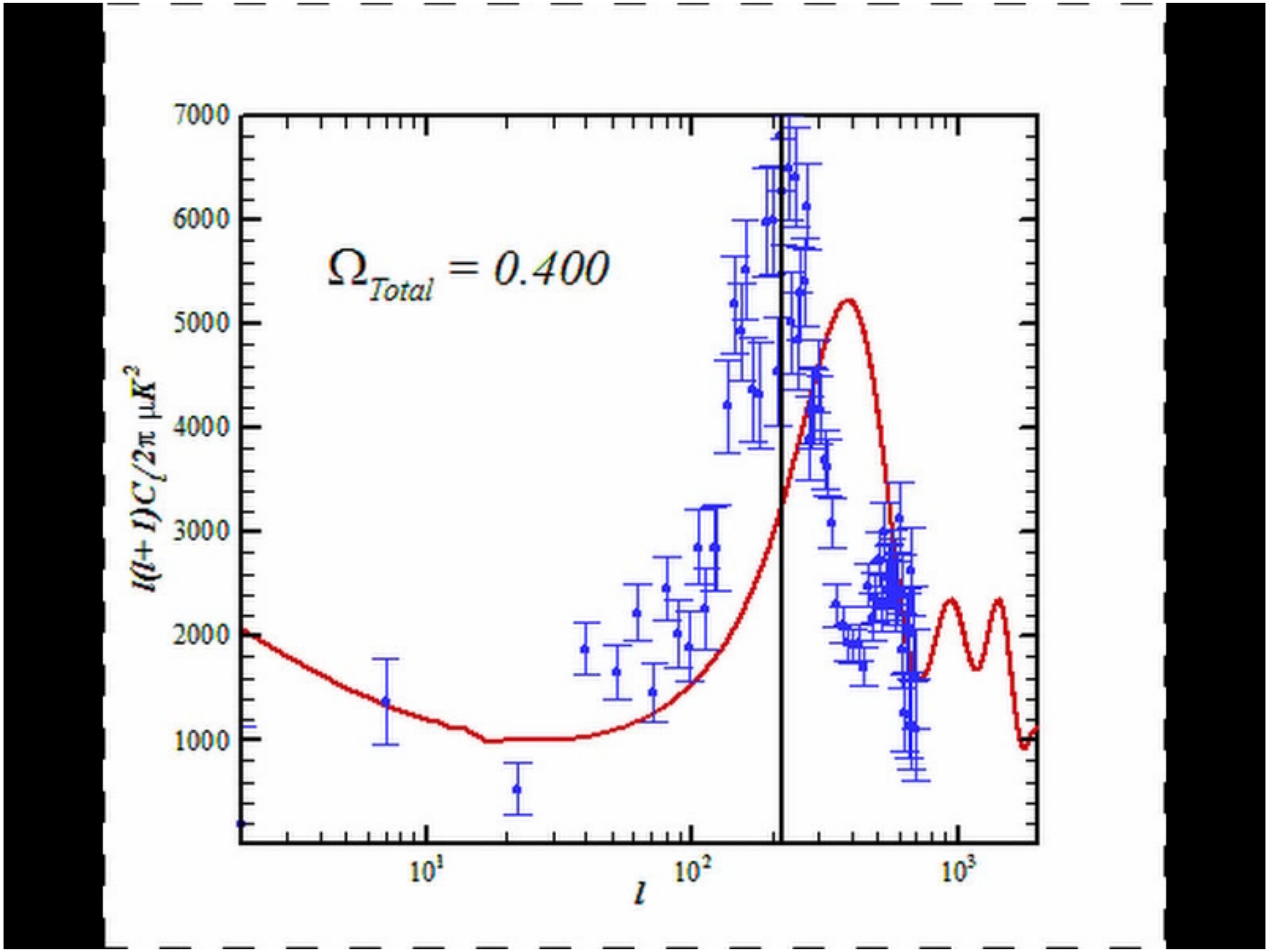
Effect of baryonic matter



Effect of dark matter

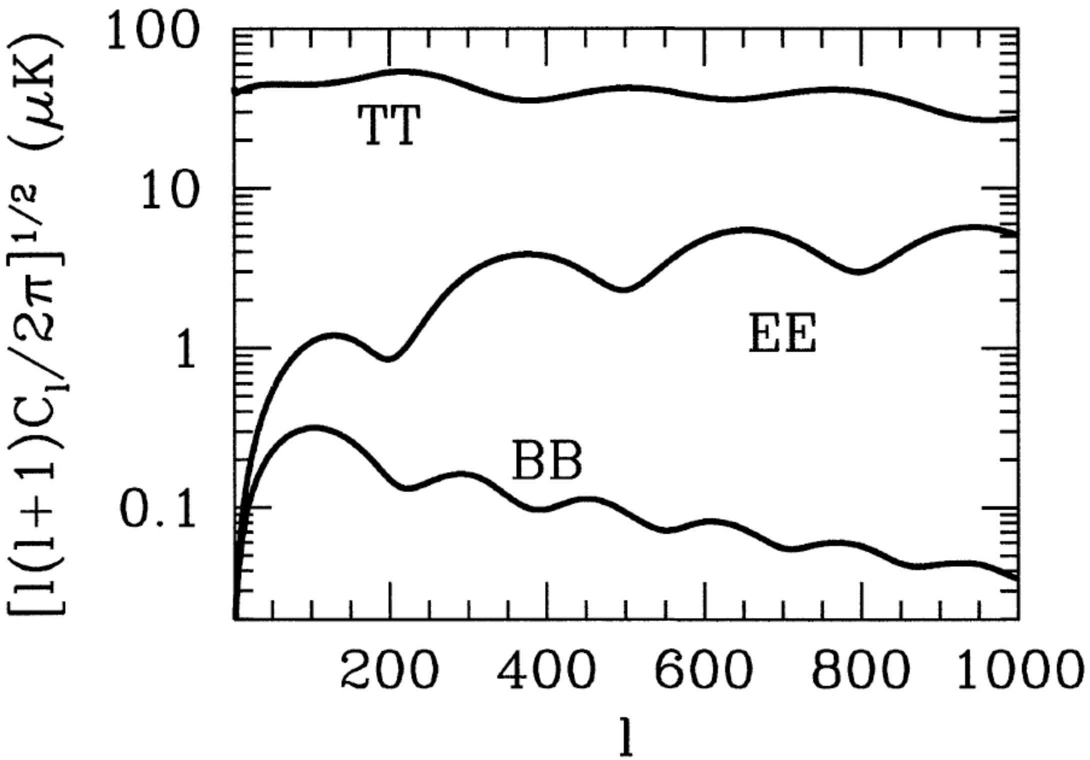


Effect of dark energy



CMB polarization

Thomson scattering at the recombination produces polarization of CMB



$$\frac{d\sigma}{d\Omega} = \frac{3\sigma_T}{8\pi} \left| \epsilon_i . \epsilon_s \right|^2$$

$$\langle E^*_{lm} E_{l'm'} \rangle = \delta_{ll'} \delta_{mm'} C_l^{EE}$$

$$\langle B^*_{lm} B_{l'm'} \rangle = \delta_{ll'} \delta_{mm'} C_l^{BB}$$

$$\langle T^*_{lm} E_{l'm'} \rangle = \delta_{ll'} \delta_{mm'} C_l^{TE}$$

Observable parameters

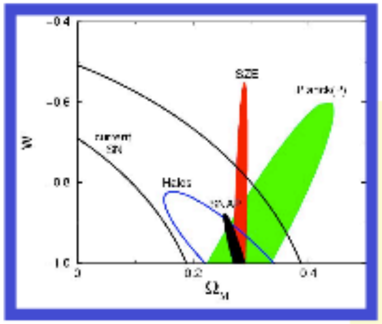
- First set: Related to the background evolution. About 10 parameters:

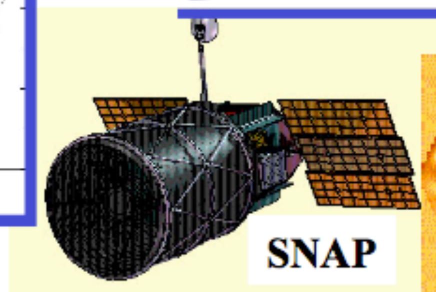
$$\Omega_{cdm}, \Omega_b, \Omega_\nu, \Omega_K, \Omega_\Lambda, w, t_0, H_0, q_0, T_{CMB}$$

- Second set: Describe deviation from perfect homogeneity and isotropy. About 6 parameters:

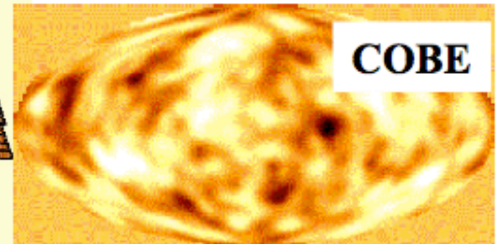
$$\sigma_8, A_s, A_t, n_s, n_t, dn / d\ln k$$

Looking Ahead





SNAP

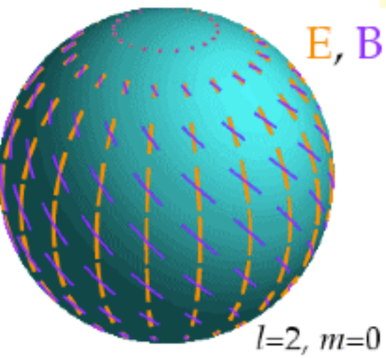


COBE

Predicted Planck

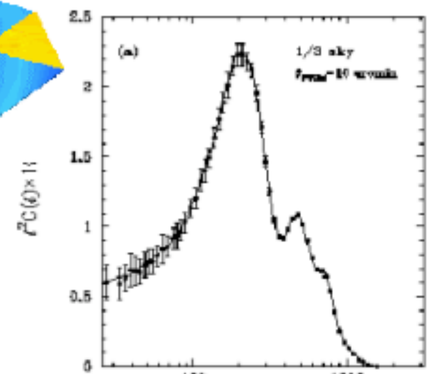
Fermilab

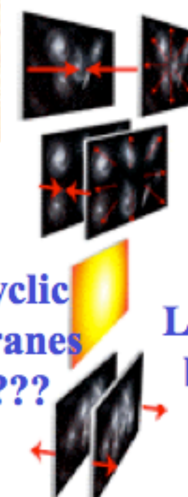
CERN



CMB Polarization

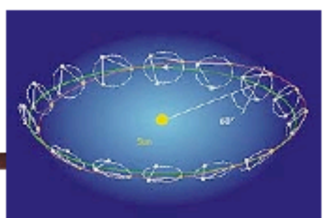
Planck

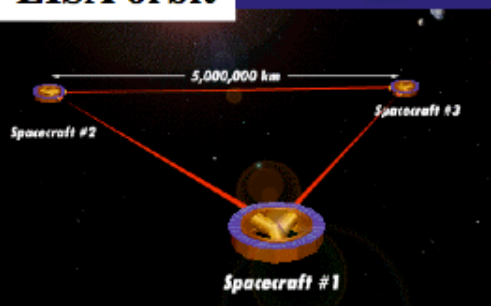




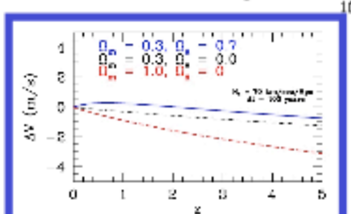
Cyclic Branes ???

LHC prototype beam collider

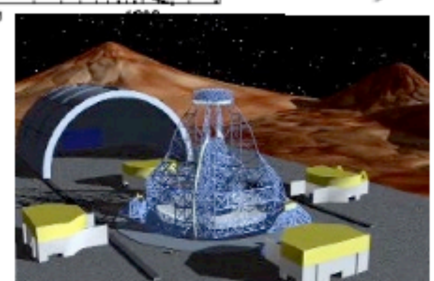




LISA orbit



Direct expansion rate: 2 m/s/century!

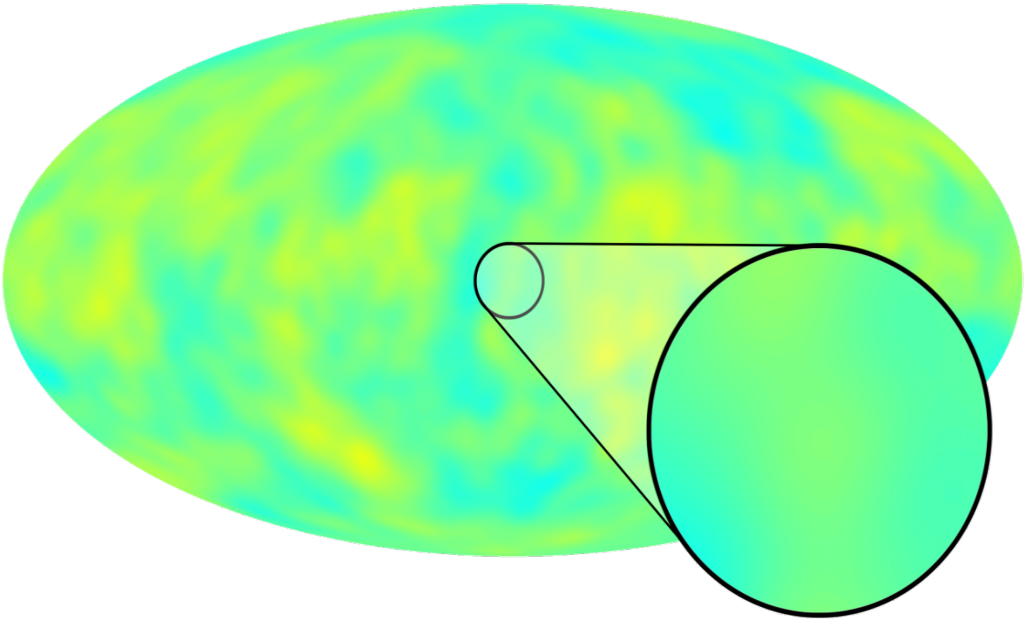


OWL – 100m telescope

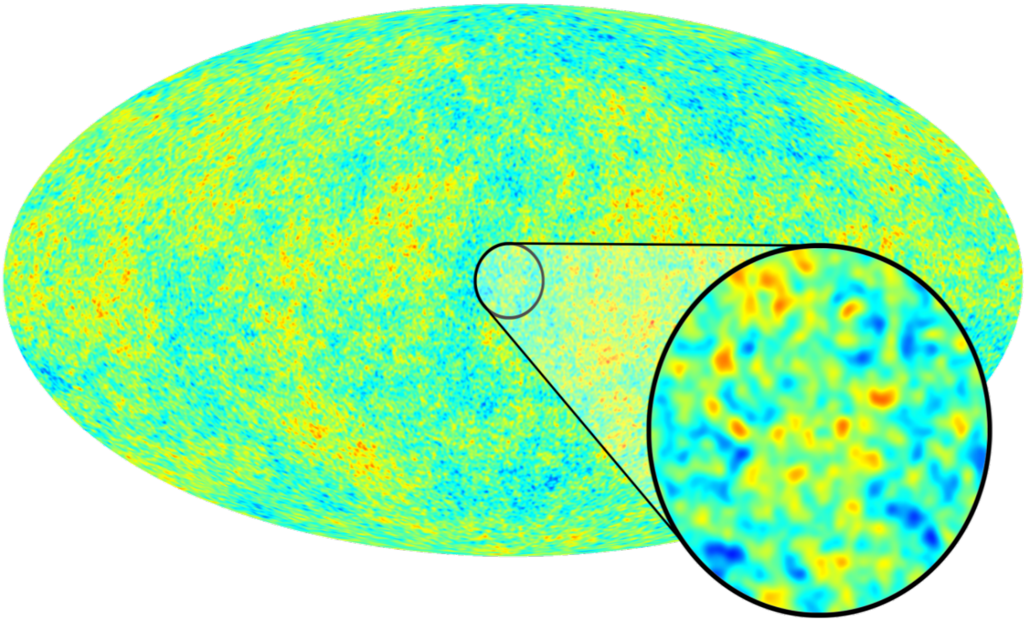
CDMS in the Soudan mine

CMB missions

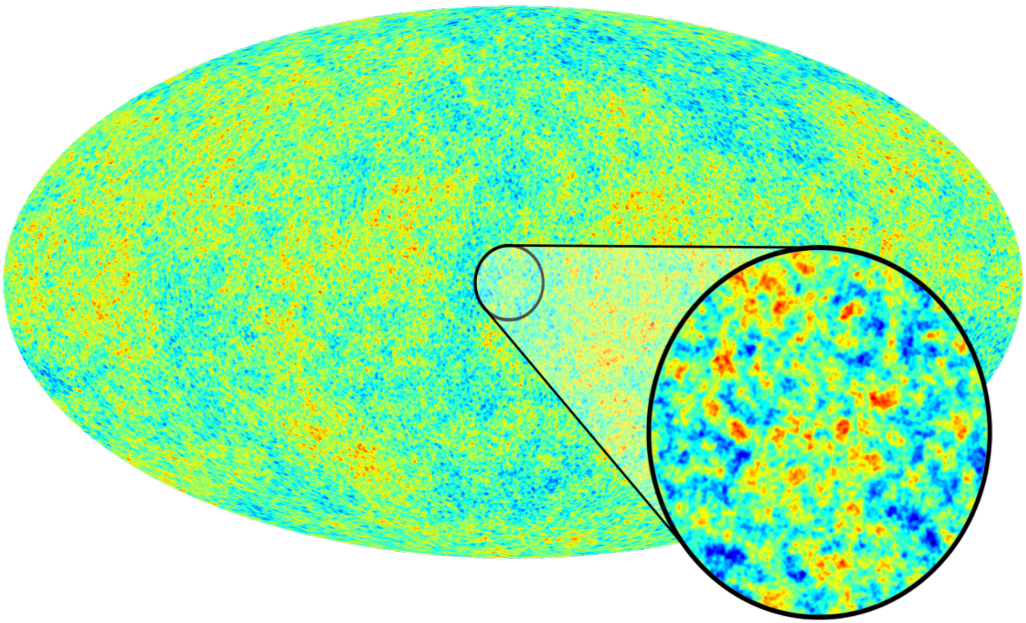
- Space based experiments: COBE(1992), WMAP(2001), PLANCK(14 May 2009)
- Ground based experiments: DASI, QUaD, South Pole, ATCA, BICEP,…
- Balloon based experiments: ARCADE, Archepos, BOOMERanG, EBEX, MAXIMA, PIQUE, TopHat, SPIDER,…



COBE resolution for anisotropies
7 degrees resolution



WMAP resolution for anisotropies
13 arc minute resolution



PLANCK resolution for anisotropies
5 arc minute resolution

Power-law Quintessence model

$$w(a) = w_0 a^{\alpha}(1+\ln a^{\alpha})$$

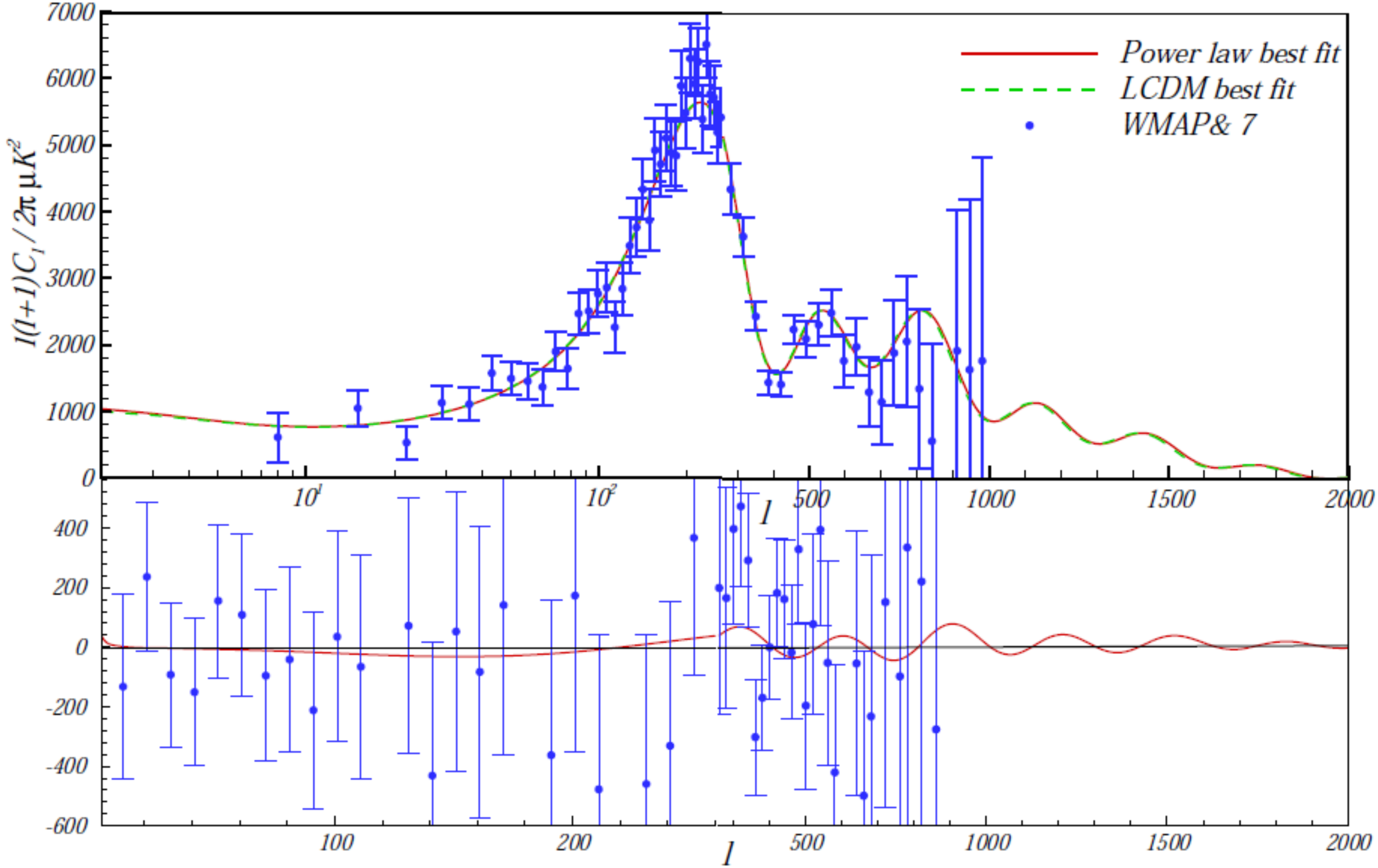
$$\text{Generalized EOS} \rightarrow \bar{w}(a;\alpha,w_0) = \frac{\int_1^a w(a';\alpha,w_0)\,d\ln(a')}{\int_1^a d\ln(a')}$$

$$\bar{w}(a;\alpha,w_0) = w_0 a^{\alpha}$$

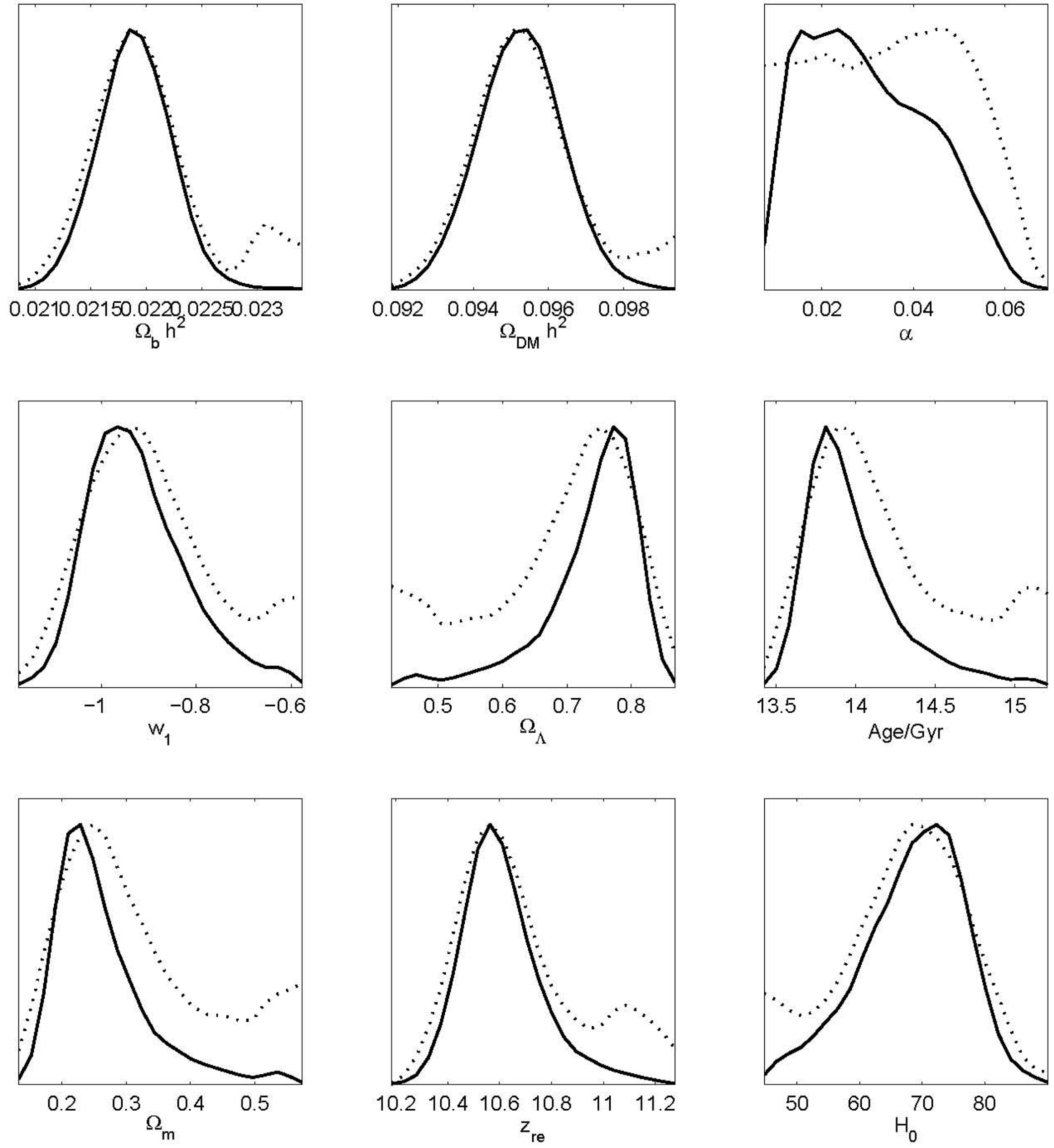
$$\rho_\lambda(z;\alpha,w_0) = \rho_\lambda(1+z)^{3[1+\bar{w}(a)]}$$

$$H = H_0\sqrt{\Omega_r a^{-4} + (\Omega_{dm}+\Omega_b)a^{-3} + \Omega_Q a^{-3(1+\bar{w}(a))} + \Omega_K a^{-2}}$$

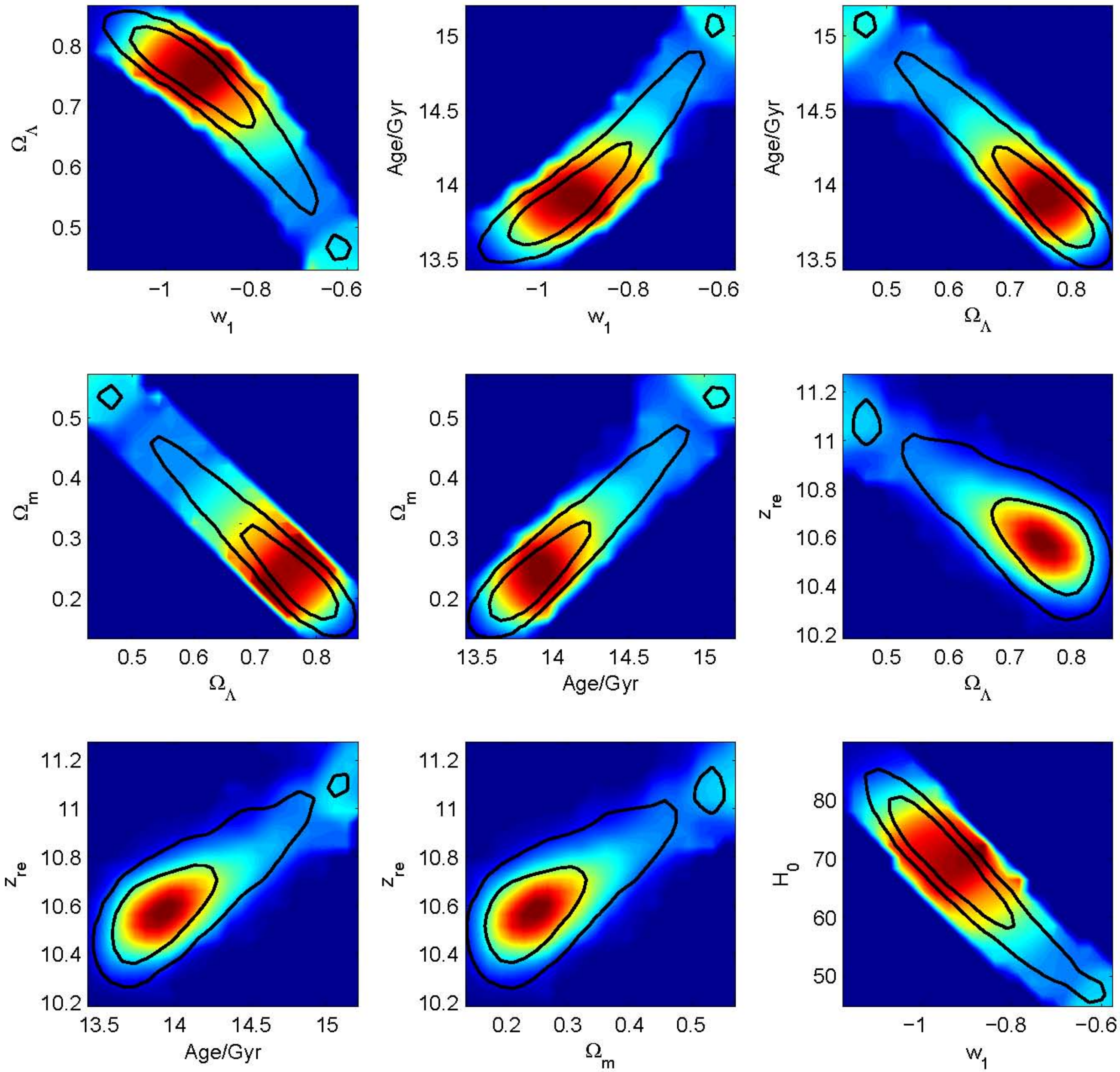
Power Spectrum of Anisotropies



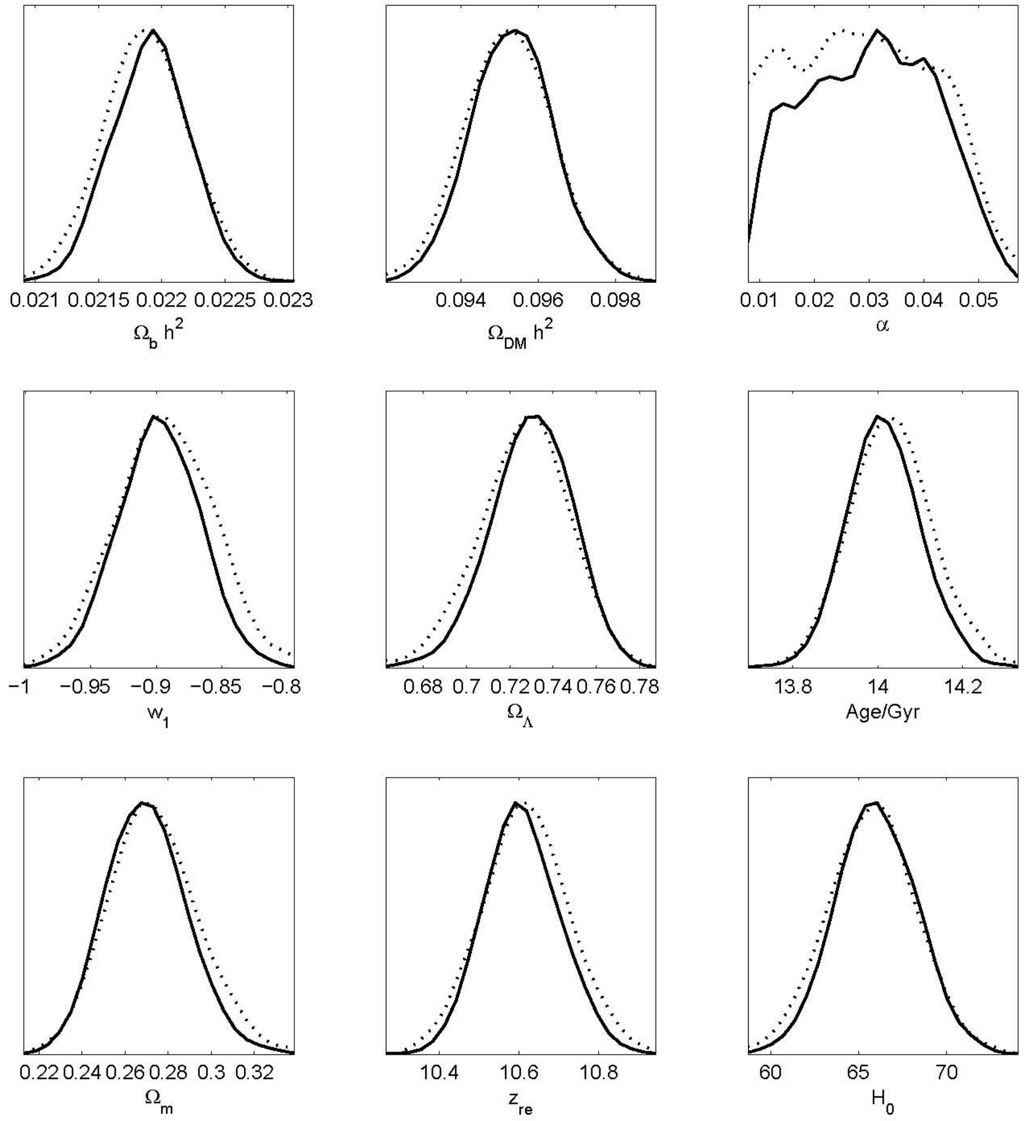
CMB-Likelihoods



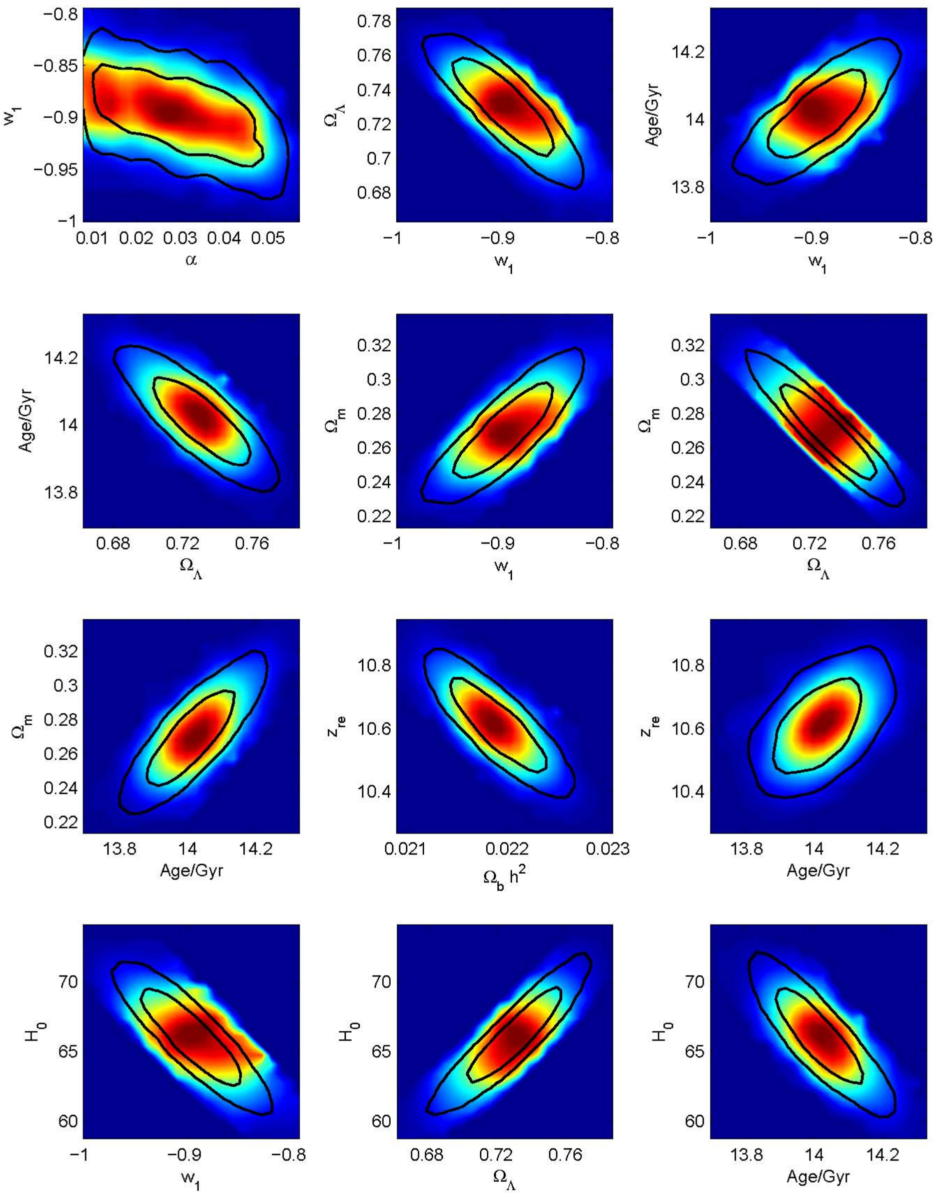
CMB-contours



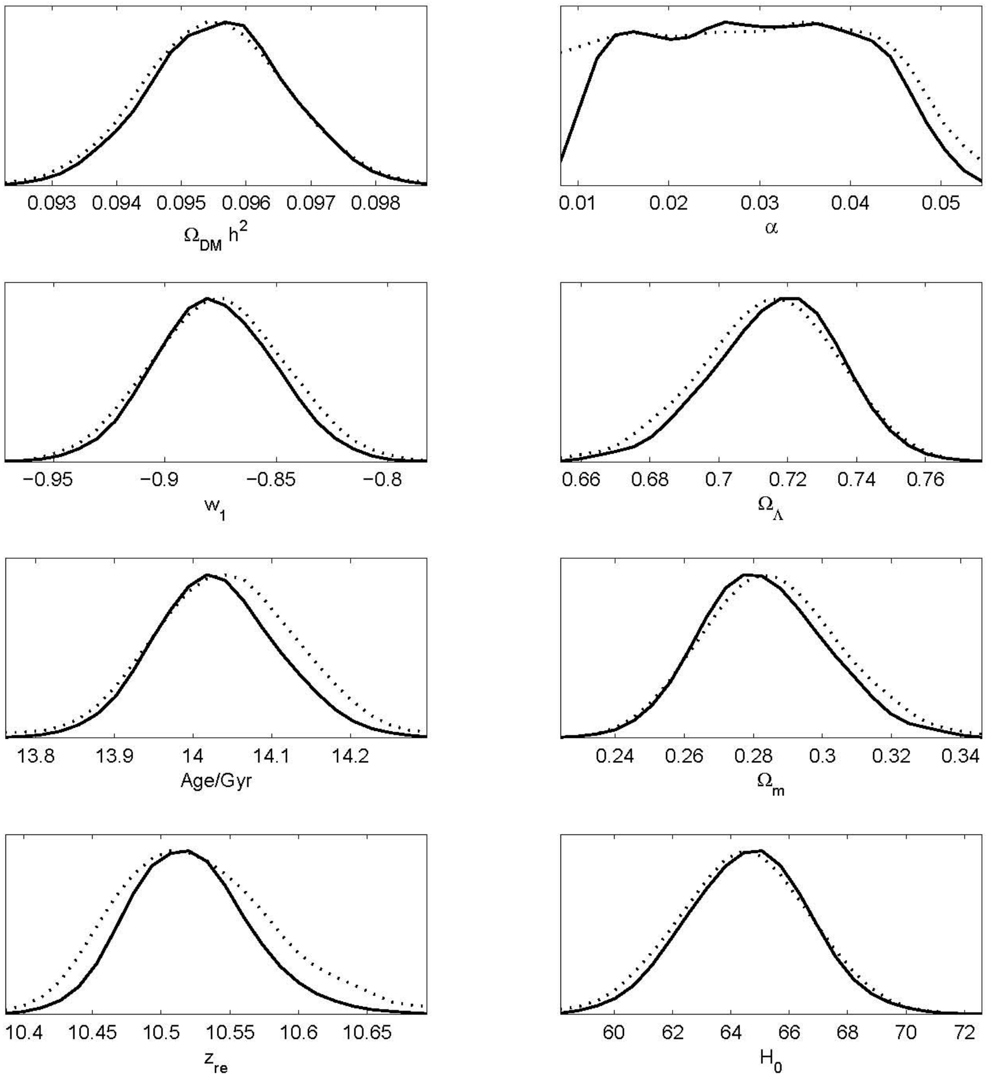
CMB+BAO-Likelihoods



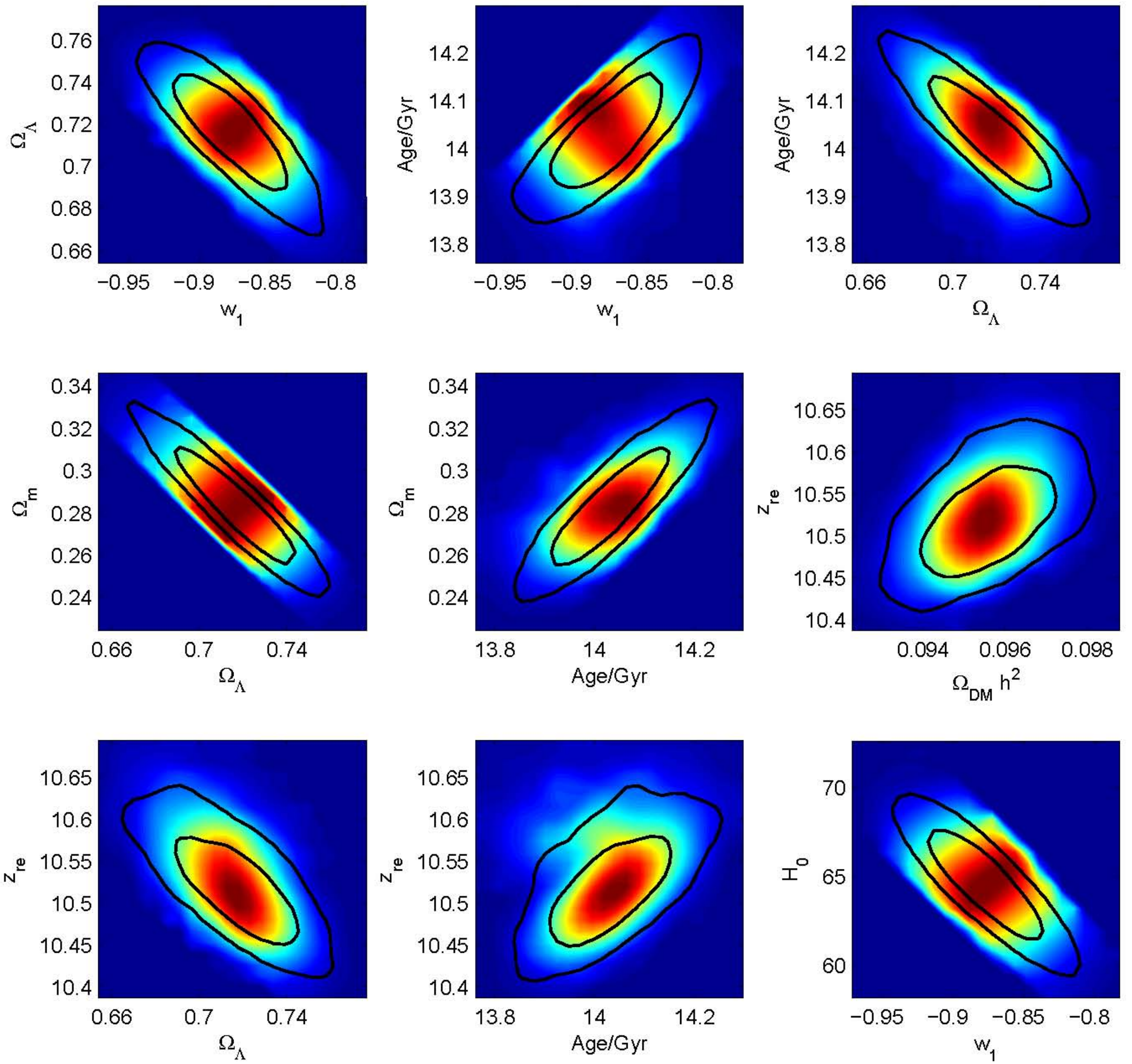
CMB+BAO-contours



CMB+SN-Likelihoods



CMB+SN-contours



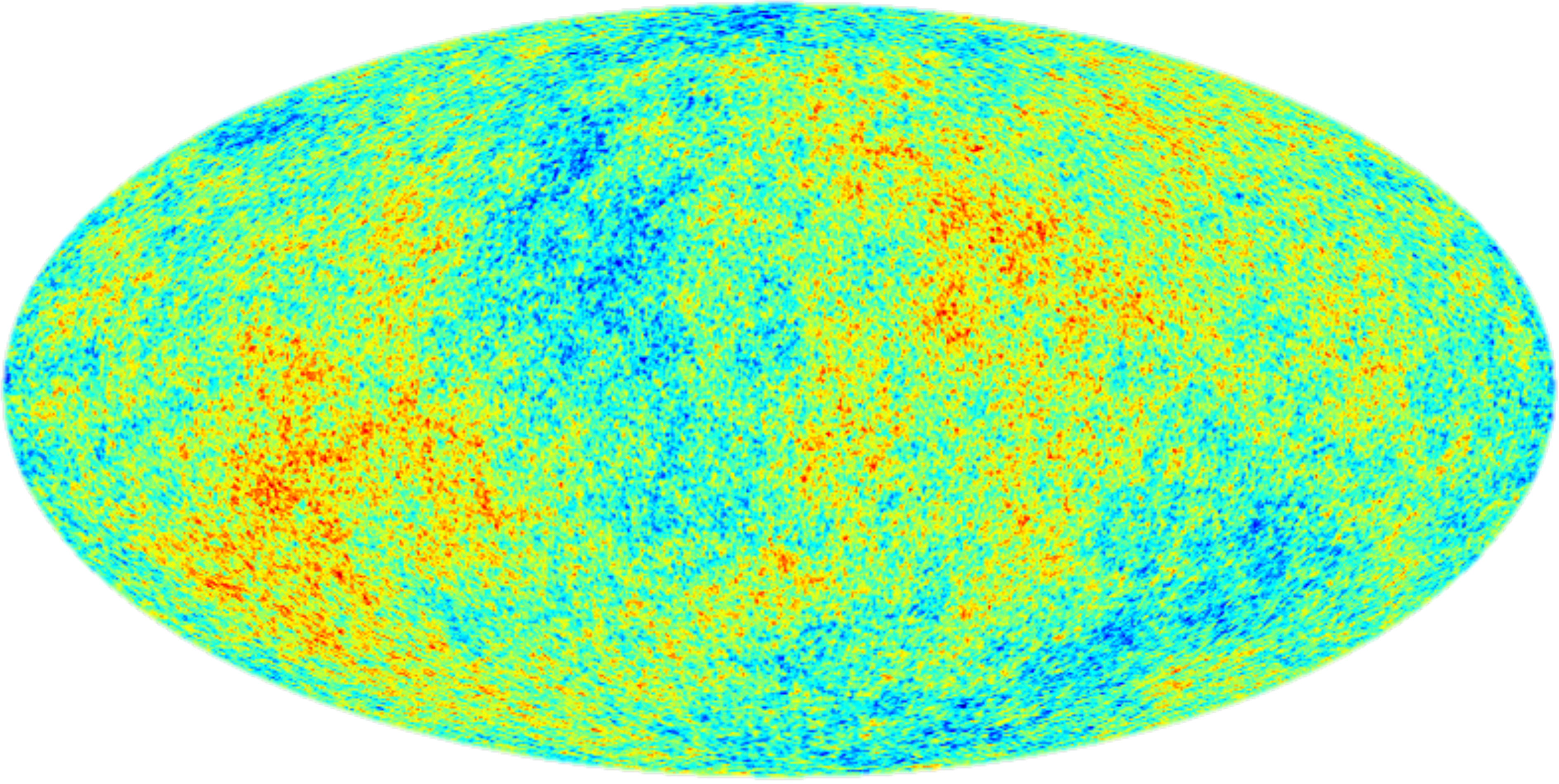
Observational Constraints

Parameter	CMB	CMB+SN
$\Omega_b h^2$	$0.0219^{+0.0006}_{-0.0003}$	0.0223
$\Omega_{cdm} h^2$	$0.0952^{+0.0010}_{-0.0010}$	$0.0955^{+0.001}_{-0.001}$
α	$0.030^{+0.015}_{-0.020}$	$0.029^{+0.012}_{-0.013}$
w_0	$-0.921^{+0.100}_{-0.096}$	$-0.877^{+0.026}_{-0.026}$

Observational Constraints

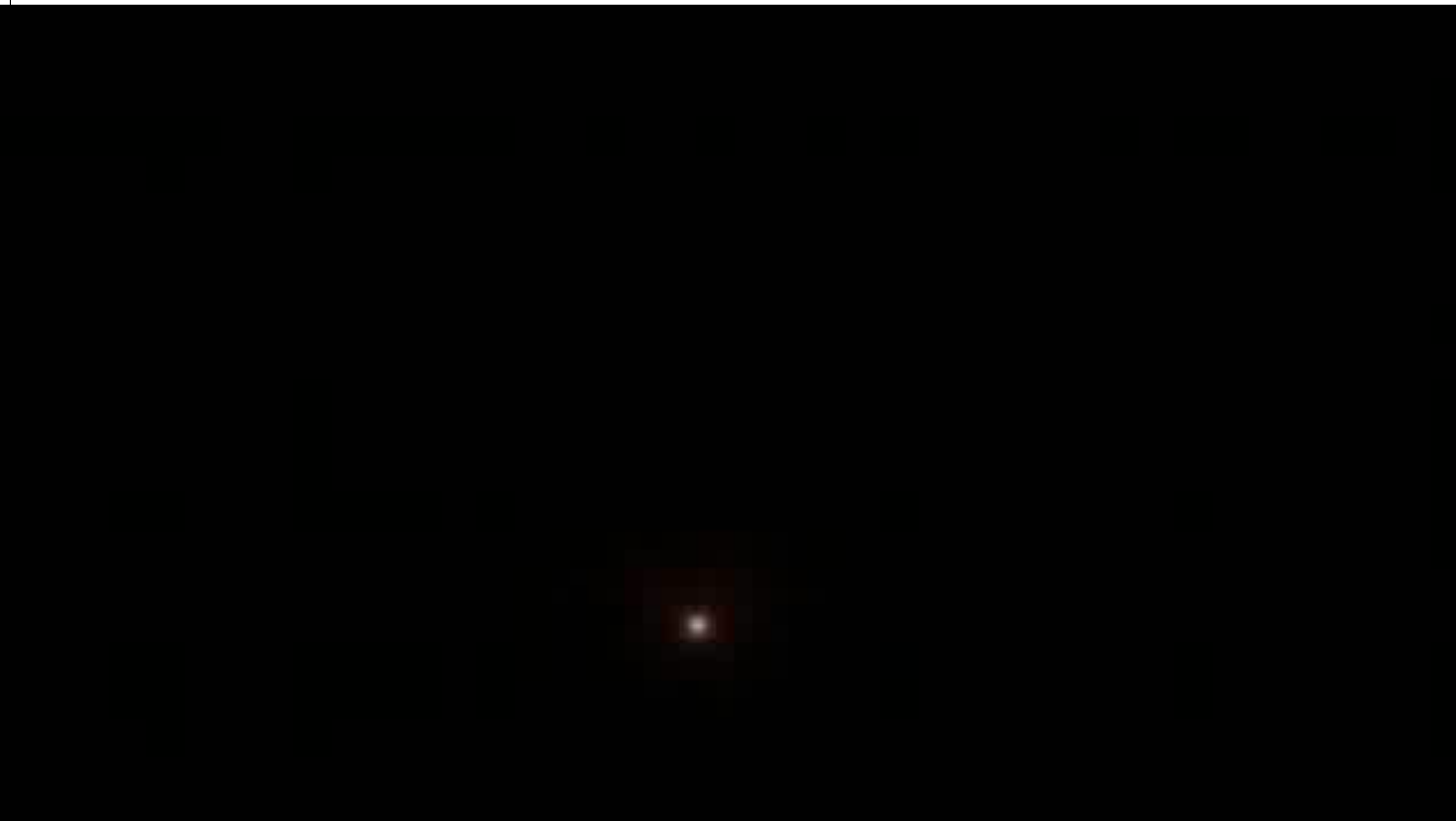
Parameter	CMB+BAO	CMB+MPK
$\Omega_b h^2$	$0.0219^{+0.0003}_{-0.0003}$	0.0224
$\Omega_{cdm} h^2$	$0.0953^{+0.0010}_{-0.0010}$	0.1161
α	$0.029^{+0.012}_{-0.019}$	$0.021^{+0.006}_{-0.006}$
w_0	$-0.897^{+0.030}_{-0.030}$	$-0.648^{+0.050}_{-0.032}$
σ_8		$0.572^{+0.016}_{-0.020}$

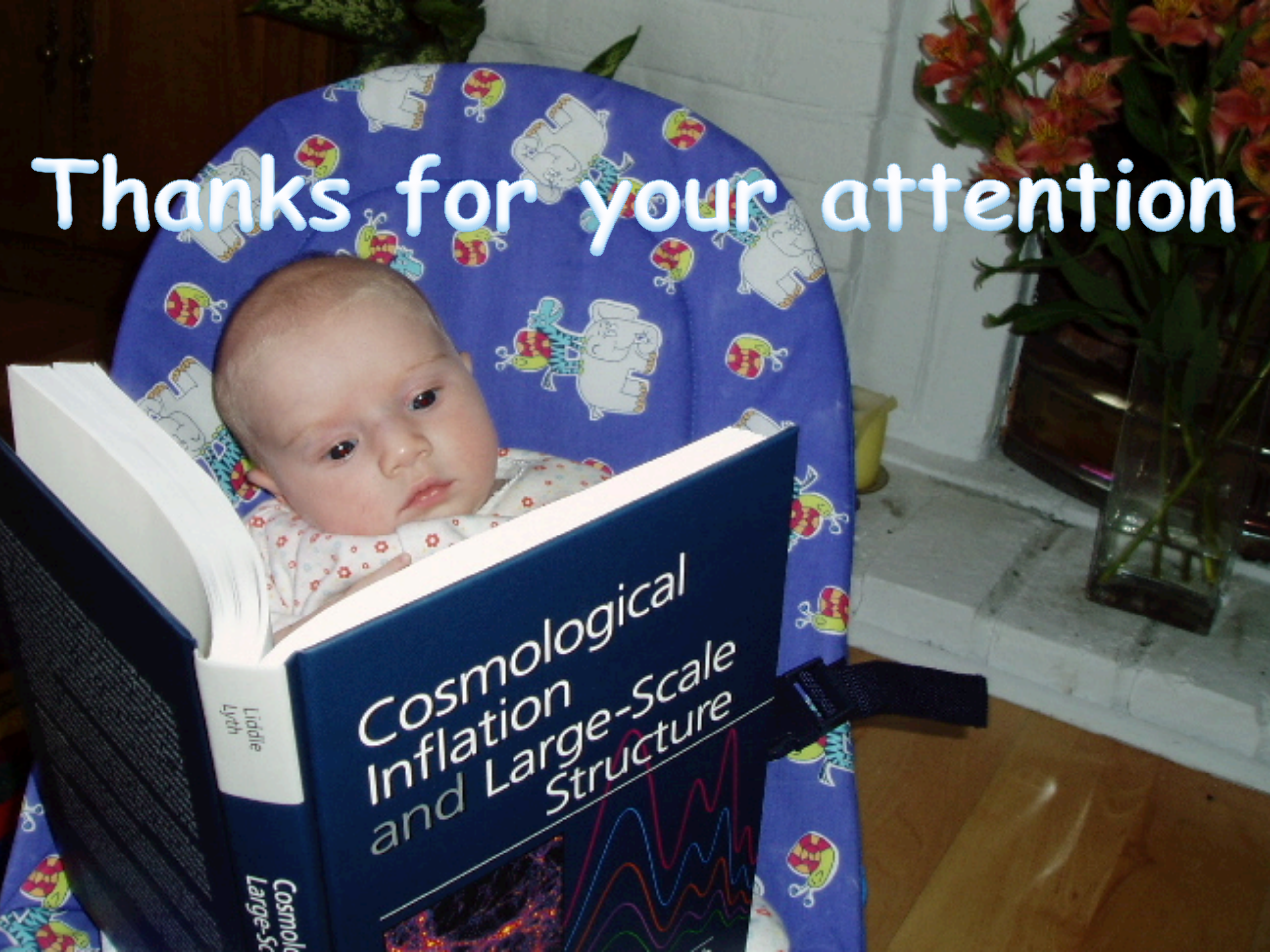
Temperature Anisotropy Map for Power-law model



Produced by HEALPix

Planck CMB probe




Thanks for your attention
Cosmological
Inflation
and Large-Scale
Structure
Liddle
Lyth