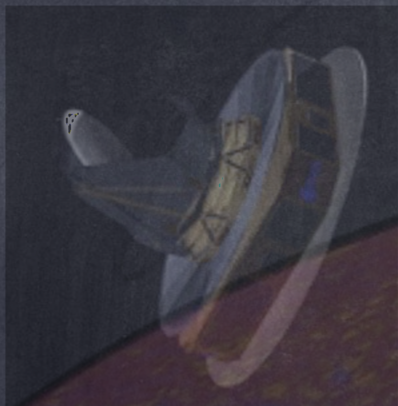
Fundamentos de
Cosmologia
AST-413 - 4



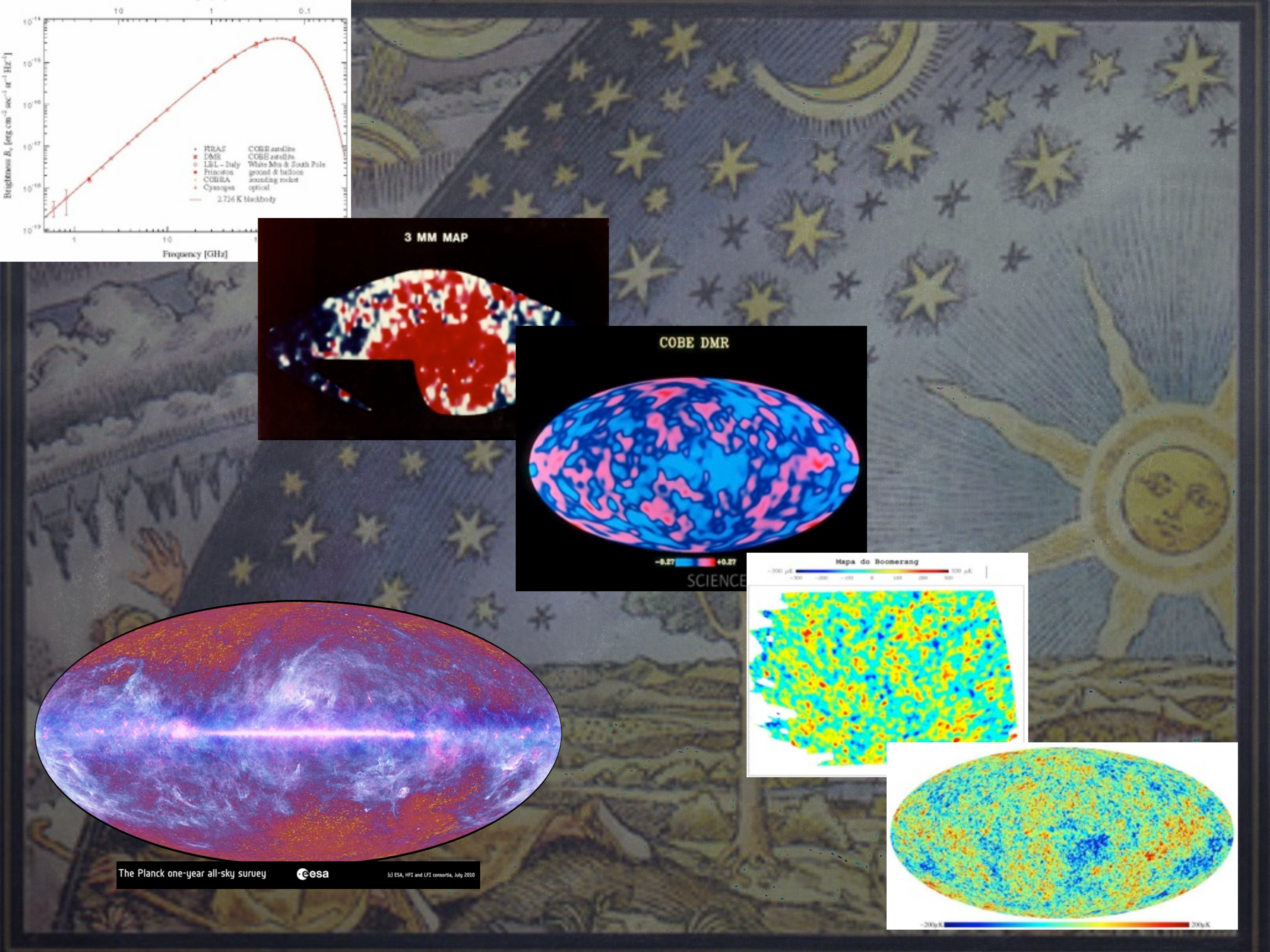
Lecture 8
The Cosmic Microwave Background

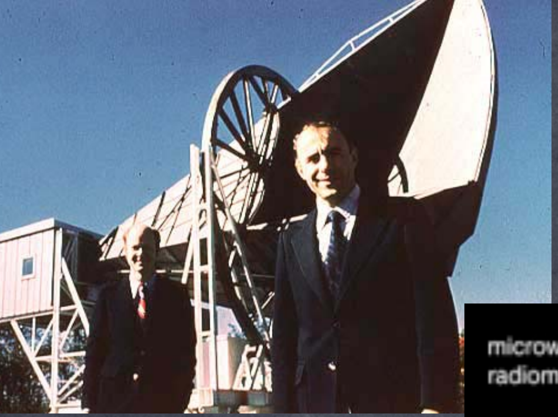
Carlos Alexandre Wuensche / Christine Córdula Dantas
INPE - Divisão de Astrofísica
ca.wuensche@inpe.br

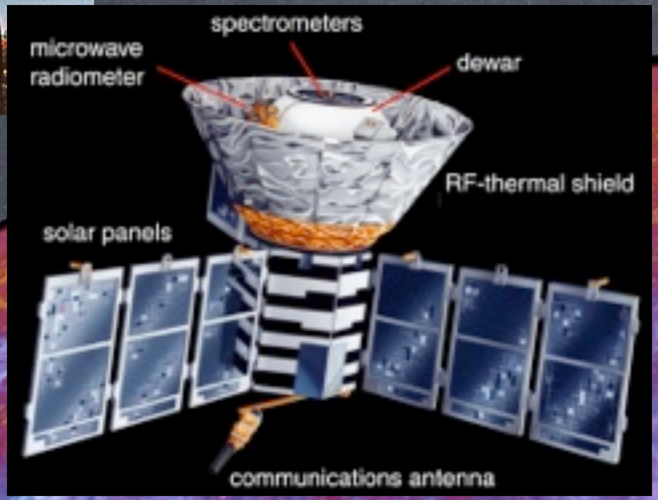
The Planck one-year all-sky survey esa

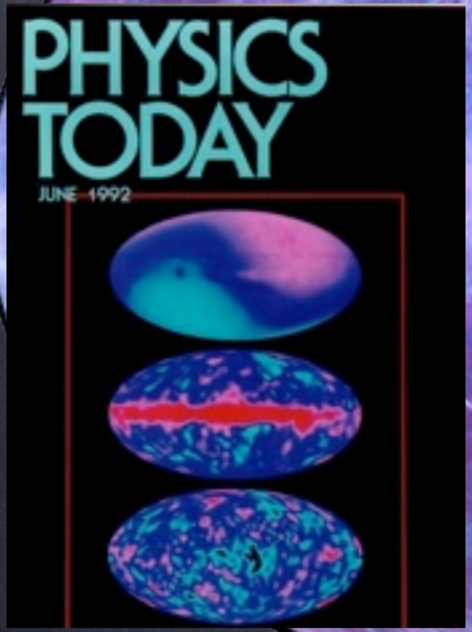
Outline

- Lecture 1: Introduction to the Cosmic Microwawe Background
- Lecture 2: The CMB spectrum
- Lecture 3: The CMB angular distribution and polarization
- Lecture 4: Secondary anisotropies: the Sunyaev-Zeldovich effect, CMB lensing and foreground emission
- Lecture 5: CMB observations and instrumentation

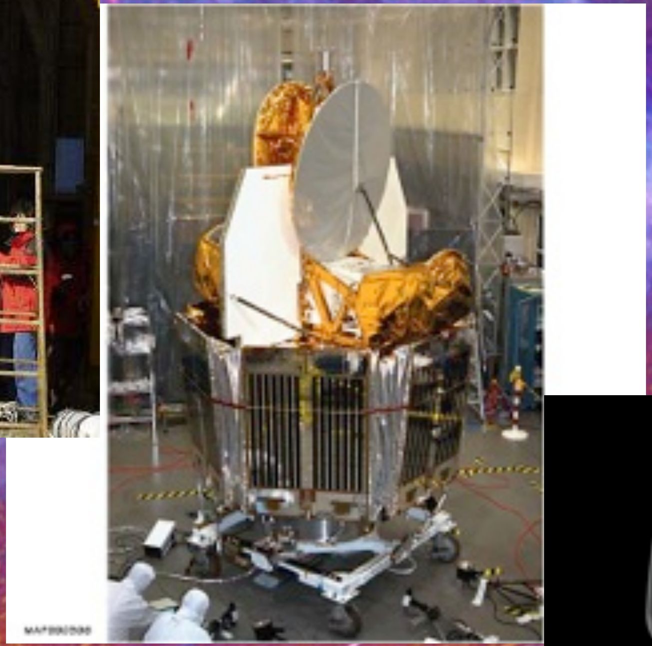

Brightness B_ν [erg cm^-2 sec^-1 sr^-1 Hz^-1]
Frequency [GHz]
FIRAS COBE satellite
DMR COBE satellite
LBL – Italy White Mtn & South Pole
Princeton ground & balloon
COBRA sounding rocket
Cyanogen optical
2.726 K blackbody
3 MM MAP
COBE DMR
-0.27 +0.27
SCIENCE
Mapa do Boomerang
The Planck one-year all-sky survey
esa
(c) ESA, HFI and LFI consortia, July 2010
-200μK
200μK

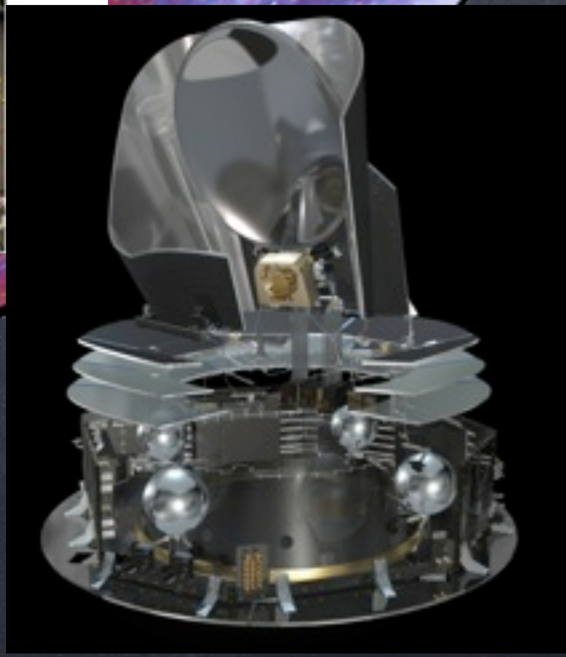



spectrometers
microwave radiometer
dewar
RF-thermal shield
solar panels
communications antenna

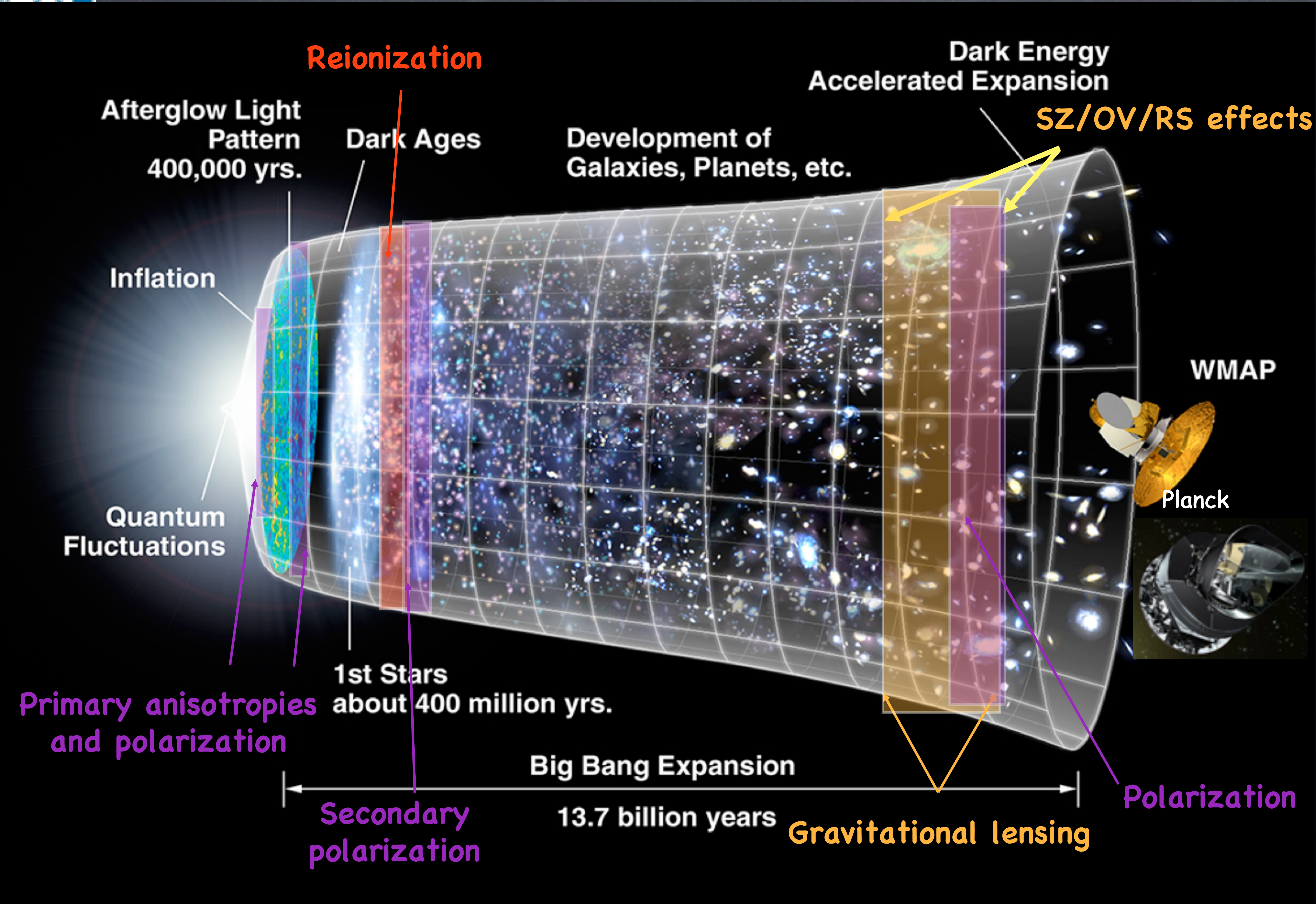

PHYSICS TODAY
JUNE 1992


nature
Background to a flat Universe

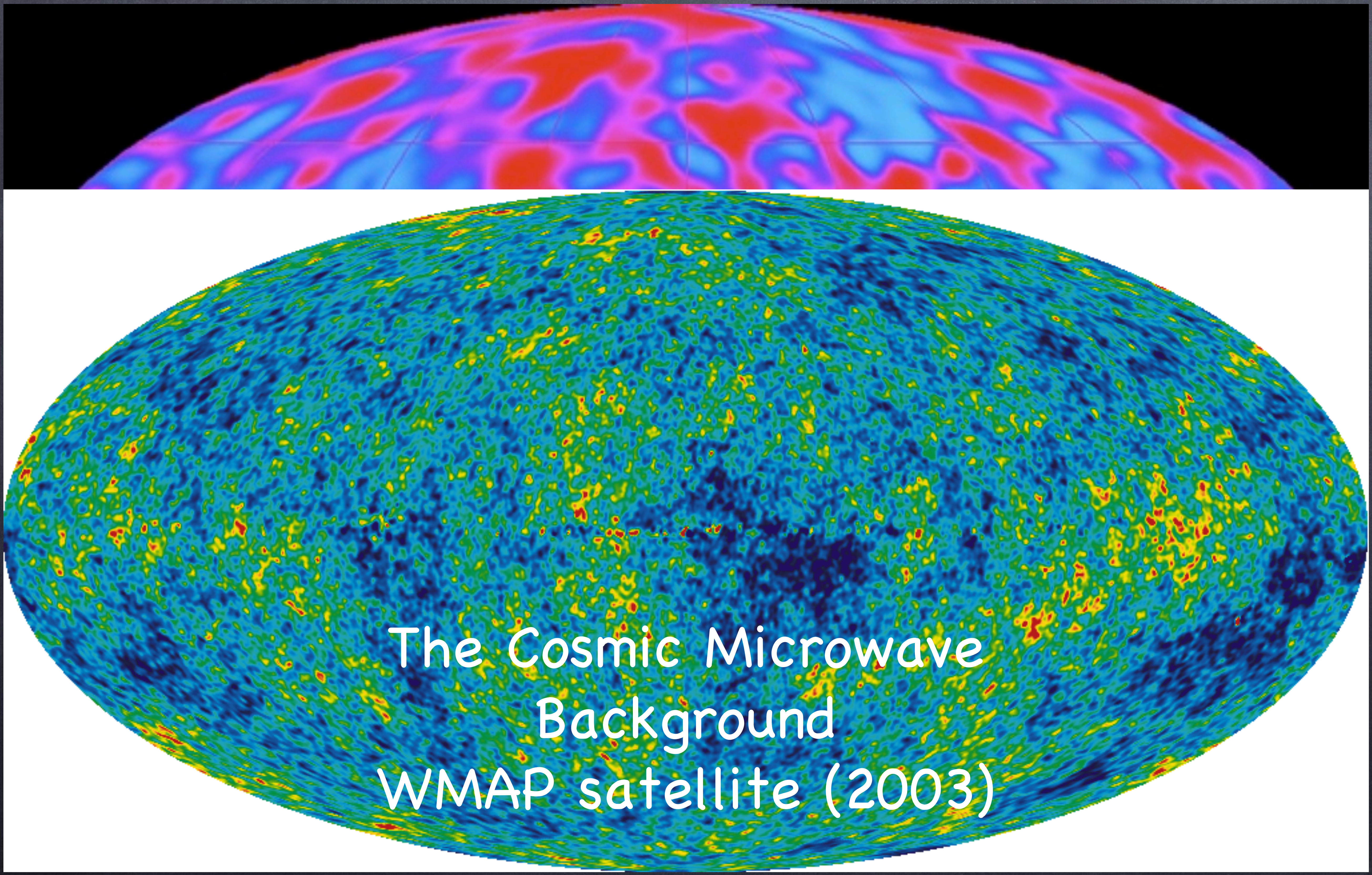





The Planck one-year all-sky survey
esa
(c) ESA, HFI and LFI consortia, July 2010



Reionization
Dark Energy
Accelerated Expansion
SZ/OV/RS effects
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Planck
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Primary anisotropies
and polarization
Big Bang Expansion
13.7 billion years
Secondary
polarization
Gravitational lensing
Polarization



The Cosmic Microwave Background
WMAP satellite (2003)

Modern cosmology is presently based upon:

- General relativity, the cosmological “principle” and particle physics
- Observations that support the theoretical framework above:
  - **expansion of the Universe**
  - **the synthesis of light elements**
  - **cosmic microwave background (CMB)**

The Cosmic Microwave Background

- Oldest electromagnetic signal we can observe!
- Picture of the Universe at 380.000 years after the Big Bang
- Described by a **blackbody spectrum** at **T = 2,725 (± 0,001) K**
- CMB temperature fluctuations, **ΔT ~ 10^{-5}** K, linked to primordial density fluctuations, shed light on the physics of large structure formation in the Universe
- CMB observables: spectral distribution, angular distribution (anisotropies) and polarization

A few interesting numbers...

- T = 2,725 ± 0,001 Kelvin (Mather et al. 1999, ApJ, 512, 511).
- Integral characteristics of the radiation
  - Energy density: $u_\gamma = \sigma T^4 = 4.244 \times 10^{-13}$ erg/cm^3
  - Number density: $n = 0.244\,(kT_0/\hbar c)^3 = 414$ cm^{-3}
  - Density: $\rho = 4{,}6417 \times 10^{-34}\,(T/2{,}725)$ g.cm^{-3}

    1 out of 3 photons from open TV is a CMB photon!!!
  - Entropy: $4/3\; u_\gamma / kT_0 = 1.496 \times 10^3$ cm^{-3}

    0,0000000000000000000000000000000001 cm^{-3} of water!
  - Quantum energy averaged over spectrum: $\bar{E}_\gamma = u_\gamma / n_\gamma = 1.02 \times 10^{-15}$ erg
  - $P_{CMB} \sim 10^{-18}$ W
  - Speed of the Sun respect to the CMB = 369,3 ± 2,5 km/s

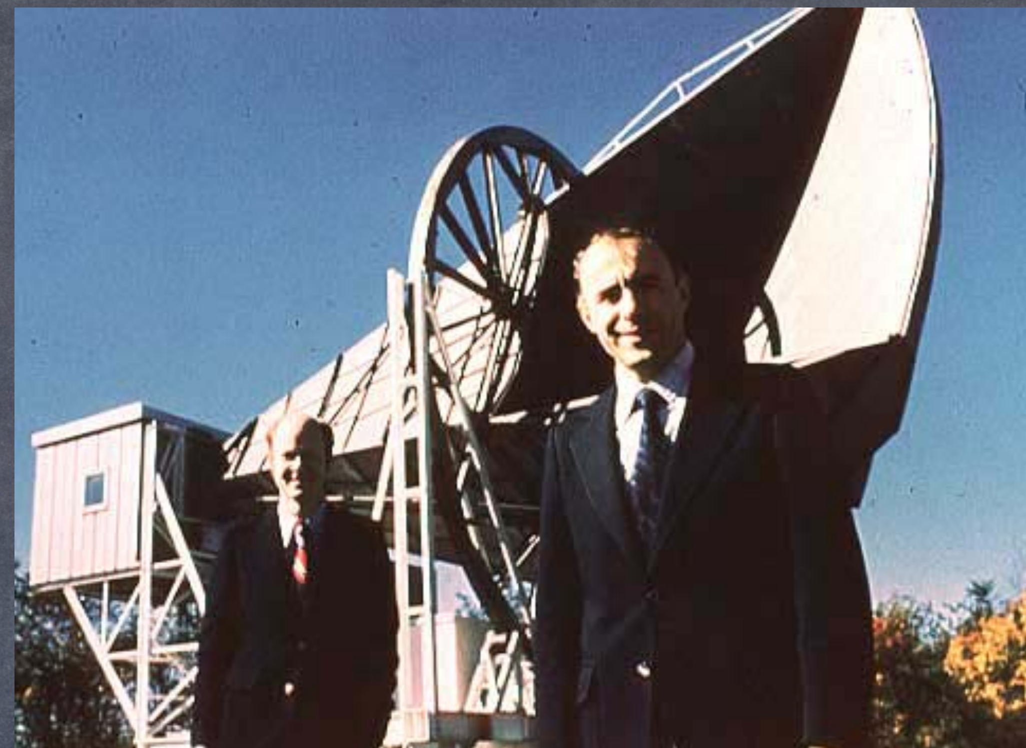
    0,00000000000000000001 100 W light bulb!!!

1933

Radioastronomy

1964

Cosmic Microwave Background

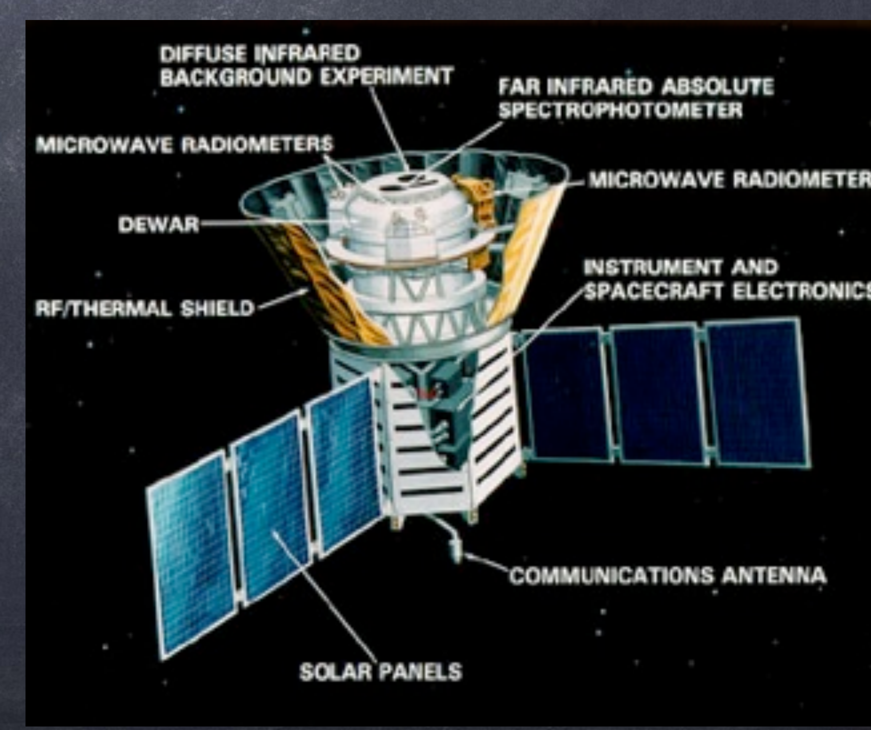


Physics Nobel Prize
(1978)

1992

Anisotropies

Physics Nobel Prize
(2006)



The 2.7 K Cosmic Background Radiation Timeline

- **1934** R. Tolman shows that CMB in an expanding Universe cools down but keep its thermal distribution and remains as a blackbody
- **1941** A. McKellar was attempting to measure the average temperature of the interstellar medium, and reported the observation of an average bolometric temperature of 2.3 K based on the study of interstellar absorption lines.
- **1946** R. Dicke predicts ".. radiation from cosmic matter" at <20 K but did not refer to background radiation[14]
- **1948** G. Gamow calculates a temperature of 50 K (assuming a 3-billion-year old Universe), commenting it ".. is in reasonable agreement with the actual temperature of interstellar space", but does not mention background radiation.
- **1948** R. Alpher and R. Herman estimate "the temperature in the Universe" at 5 K. Although they do not specifically mention microwave background radiation, it may be inferred.
- **1950** R. Alpher and R. Herman re-estimate the temperature at 28 K.
- **1950** George Gamow estimates 7 K.

The 2.7 K Cosmic Background Radiation Timeline

- **1955** Émile Le Roux of the Nançay Radio Observatory, in a sky survey at λ=33 cm, reported a near-isotropic background radiation of 3±2 K.
- **1956** George Gamow estimates 6 K.
- **1957** T. Shmaonov reports that "the absolute effective temperature of the radioemission background ... is 4±3K". It is noted that the "measurements showed that radiation intensity was independent of either time or direction of observation... it is now clear that Shmaonov did observe the cosmic microwave background at a wavelength of 3.2 cm".
- **1960** Robert Dicke re-estimates a MBR (microwave background radiation) temperature of 40 K
- **1964** A. G. Doroshkevich and Igor Novikov publish a brief paper, where they name the CMB radiation phenomenon as detectable.
- **1964-65** A. Penzias and R. Wilson measure the temperature to be approximately 3 K. R. Dicke, P. J. E. Peebles, P. G. Roll, and D. T. Wilkinson interpret this radiation as a signature of the big bang.

The 2.7 K Cosmic Background Radiation Timeline

- **1966** R. Sachs and A. Wolfe predict amplitude fluctuations in the CMB created by variations of the gravitational potential between the last scattering surface and the observer
- **1967** M. Rees publishes the first calculations about CMB polarization
- **1968** M. Rees e D. Sciama predict amplitude fluctuations in the CMB caused by photons crossing time-dependent gravitational potential barriers
- **1969** R.A. Sunyaev e Y. B. Zel'dovich study the inverse Compton scattering of CMB photons caused by hot electrons, defining the basis of the so-called Sunyaev-Zeldovich effect
- **1978** A. Penzias and R. Wilson receive the Nobel Prize for discovering the CMB
- **1983** RELIKT-1 Soviet CMB anisotropy experiment was launched.
- **1990** FIRAS/COBE measures the black body form of the CMB spectrum with exquisite precision.
- **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.

The 2.7 K Cosmic Background Radiation Timeline

- **2000** Results from the BOOMERANG team state that the Universe is, essentially, Euclidian.
- **2001** The **WMAP** (Wilikinson Microwave Anisotropy Probe) was launched by NASA, Its measurements start to fullfil the hope of measuring/determining cosmological parameters with precision < 10% ⇒ **Precision cosmology**
- **2002** Polarization discovered/measured by DASI.
- **2004** E-mode polarization spectrum obtained by the CBI.
- **2005** Ralph A. Alpher is awarded the National Medal of Science for his groundbreaking work in nucleosynthesis and predictions supporting the Hot Big Bang model.
- **2006** Two of COBE's principal investigators, George Smoot and John Mather, received the Nobel Prize in Physics in 2006 for their work on precision measurement of the CMBR.
- **2009** **Planck** (Max Planck Surveyor, previously COBRAS/SAMBA),the 3rd generation satellite dedicated to CMB studies, was launched by ESA on May, 14 and has released its first results in January 2011. The CMB data from Planck is expected by April 2013

The 2.7 K Cosmic Background Radiation Timeline

- **The Golden Decade – 2010 - 2020** Results from the BOOMERANG team state that the Universe is, essentially, Euclidian.

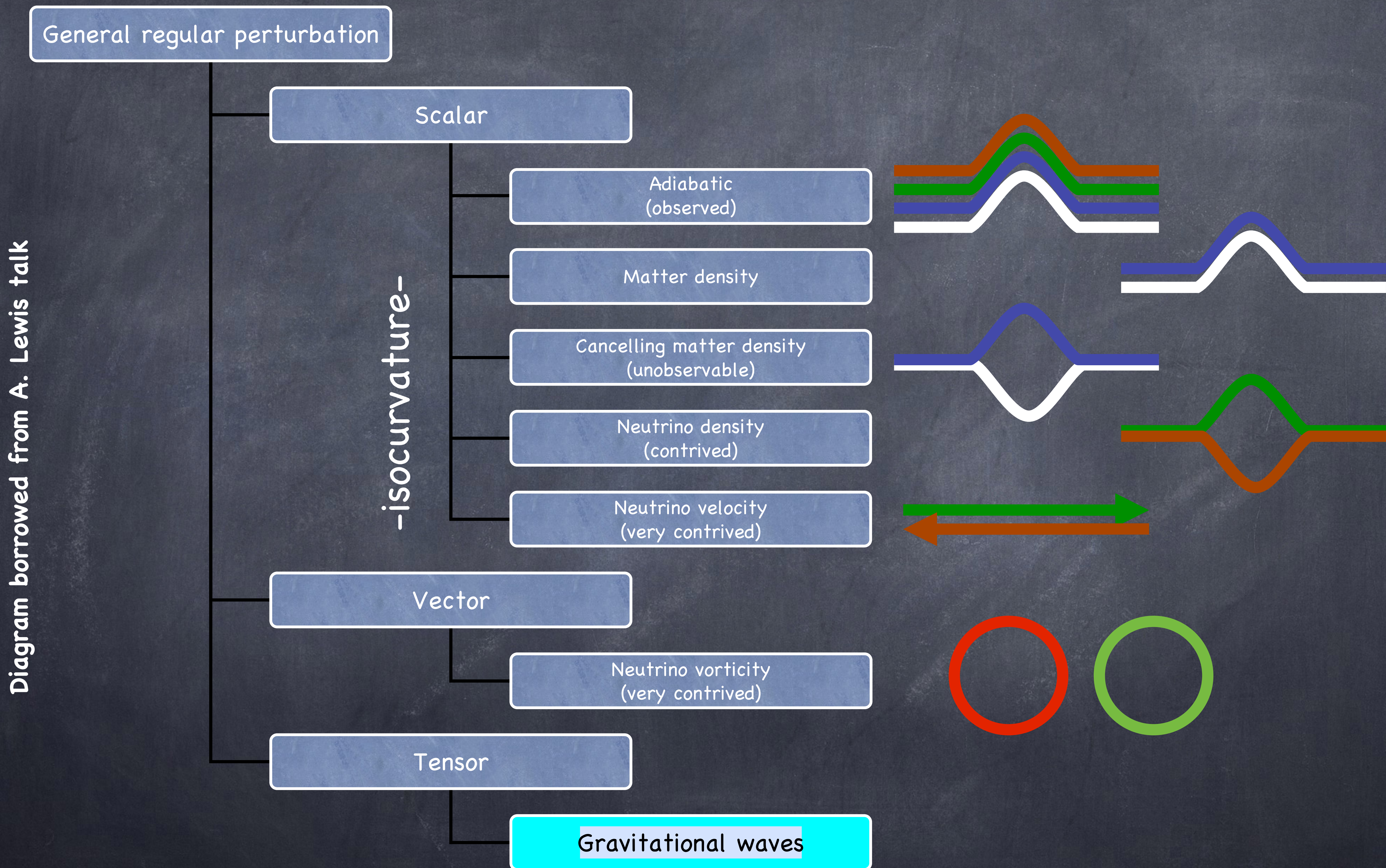
The standard scenario

- Friedmann equations and Robertson-Walker metric describe the space-time where CMB evolves
- Boltzmann equations describe the interplay between all the components and how they affect the growth of perturbations
- Theory of cosmological perturbations describes the evolution of density perturbations from the linear into non-linear regime, setting ground for structure formation scenarios.

Primordial Perturbations: fluid at redshift $z < 10^9$

- **Matter dominated epoch**
  - **Photons**
  - **Nearly massless neutrinos**: free-streaming (no scattering) after neutrino decoupling at $z \sim 10^9$
  - **Baryons + electrons**: tightly coupled to photons by Thomson scattering
  - **Dark Matter**: assume cold. Coupled only via gravity.
  - **Dark energy**: probably negligible before $t < 6{\times}10^9$ years

General regular linear primordial perturbation



+ irregular modes, neutrino n-pole modes, n-Tensor modes Rebhan and Schwarz: gr-qc/9403032

+ other possible components, e.g. defects, magnetic fields, exotic stuff...

The evolution of perturbations

- The early Universe is, for most purposes, in thermal equilibrium, coming from:

  $n_X << n_\gamma$

  $\tau_{inter} << \tau_{exp}$

- Departure from equilibrium (violates **above condition**): not common, but with interesting consequences
  - formation of light elements (T~ 0.1 MeV)
  - recombination of e- and p to form neutral H (T~0.2 eV)
  - formation of dark matter

Previous to CMB creation...

- Nuclesynthesis during radiation dominated Universe
- Matter domination at $\sim 10^4$ years
- Cooling and recombination at $\sim 10^5$ years
- Decoupling of matter and radiation (CMB creation) $\sim 3.8 \times 10^5$ years
- CMB fluctuations

Large scale: deviations from the FL geometry

Small scale: fluctuations in the energy density of the baryon/radiation plasma

The evolution of perturbations

- The tool: Boltzmann equation! In the absence of interactions, annihilation of **species 1** due to reaction with **species 2**, yields species 3 and 4 (reversible reaction): 1 + 2 ↔️ 3 + 4

$$
\begin{aligned}
\frac{1}{a^3}\frac{d(n_1 a^3)}{dt} &= \Pi_{i=1}^{4}\int \frac{d^3 p_i}{(2\pi)^3 2E_i} \times \\
& (2\pi)^4\ \delta^3(p_1+p_2-p_3-p_4) \times \\
& \delta(E_1+E_2-E_3-E_4)|M|^2 \times \\
& \left\{ f_3 f_4 [1\pm f_1][1\pm f_2] - f_1 f_2 [1\pm f_3][1\pm f_4] \right\}
\end{aligned}
$$

Amplitude

$$
f_{B(+)F(-)} = \frac{1}{e^{E/T}\pm 1}
$$

Fermi blocking and Bose enhancement

The evolution of perturbations

- The tool: Boltzmann equation!

Approximations:

✦ Kinetic equilibrium (enforced by scattering processes)

✦ Cases of interest: T << E - μ, minimizes the effects of Fermi blocking/Bose enhancement.

when set=0, defines the equilibrium condition

$$\frac{1}{a^3}\frac{d(n_1 a^3)}{dt} = n_1^0 n_2^0 < \sigma v > \left\{ \frac{n_3 n_4}{n_3^0 n_4^0} - \frac{n_1 n_2}{n_1^0 n_2^0} \right\}$$

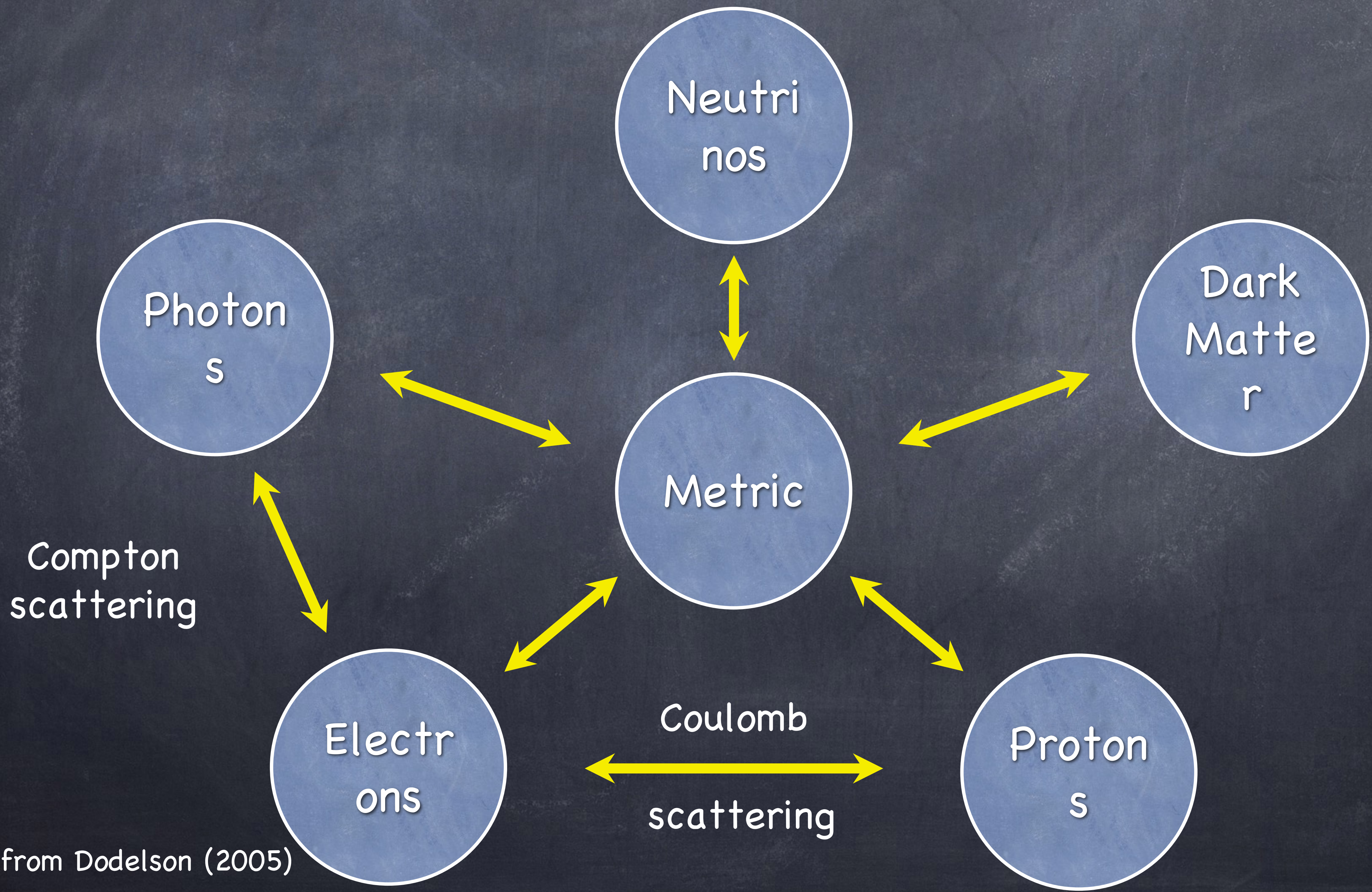
$$< \sigma v > = \Pi_{i=1}^4 \int \frac{d^3 p_i}{(2\pi)^3 2E_i} e^{-(E_1+E_2)/T} \times$$

$$(2\pi)^4 \; \delta^3(p_1 + p_2 - p_3 - p_4) \times$$

$$\delta(E_1 + E_2 - E_3 - E_4)|M|^2$$

The evolution of perturbations

- Boltzmann-Einstein equations govern the evolution of matter inhomogeneities and temperature anisotropies



Adapted from Dodelson (2005)

The evolution of perturbations

- Solution of Boltzmann equations for dark matter, baryons, photons and neutrinos demand the computation of colision terms. They apply to photons through Compton scattering by electrons and to electrons and protons through Coulomb scattering

- Necessary terms are the gravitational Newtonian potential (Ψ), the perturbation to the spatial curvature (Φ) and the perturbations to the photons caused by the metric (Θ)

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

Simplified version of Boltzmann eq.;
RHS represents the colision terms

The evolution of perturbations

$$f(\vec{x}, p, \hat{p}, t) = \left[\exp\left\{\frac{p}{T(t)[1 + \Theta(\vec{x}, \hat{p}, t)]}\right\}\right]^{-1}$$

- **Θ** is the perturbation in temperature distribution T, and is what we usually understand as **ΔT/T**!!!
- In a uniform Universe, T is homogeneous and decreases only with time t, but variations in the direction of propagation of photons (p) and inhomogeneities in space (x) produce second order effects (Θ)

- Similar procedure for the other components: dark matter, baryons and neutrinos

Boltzmann eqs. for all species

P subscript - polarization
. - conformal time derivative

Photons

$$\dot{\Theta} + i\kappa\mu\Theta = -\dot{\Phi} - i\kappa\mu\Psi - \dot{\tau}\Big[\Theta_0 - \Theta + \mu v_b - \frac{1}{2}P_2(\mu)\Pi\Big]$$

$$\Pi = \Theta_2 + \Theta_{P_2} + \Theta_{P_0}$$

$$\dot{\Theta}_P + i\kappa\mu\Theta_P = -\dot{\tau}\Big[-\Theta_P + \frac{1}{2}(1 - P_2(\mu))\Pi\Big]$$

Dark matter

$$\dot{\delta} + i\kappa v = -3\dot{\Phi}, \qquad \dot{v} + \frac{\dot{a}}{a}v = -i\kappa\Psi$$

Baryons

$$\dot{\delta}_b + i\kappa v_b = -3\dot{\Phi}, \qquad \dot{v}_b + \frac{\dot{a}}{a}v_b = -i\kappa\Psi + \frac{\dot{\tau}}{R}\Big[v_b + 3i\Theta_1\Big]$$

Neutrinos

$$\dot{N} + i\kappa\mu N = -\dot{\Phi} - i\kappa\mu\Psi$$

$$\Theta_l \equiv \frac{1}{(-i)^l}\int_{-1}^{1}\frac{d\mu}{2}P_l(\mu)\Theta(\mu)$$

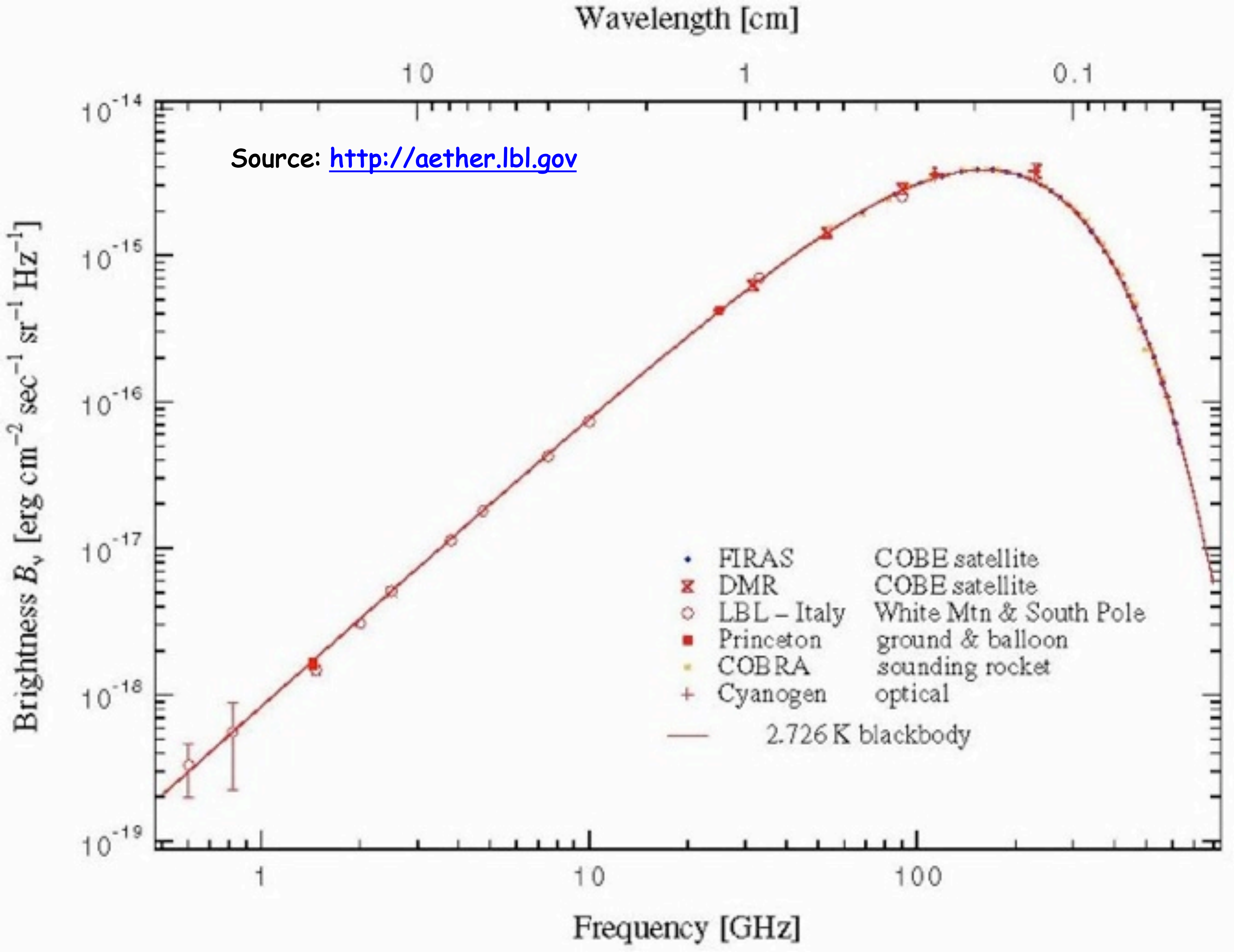
$$\dot{\tau} = n_e\sigma_T a$$
$$\mu = \hat{p} \bullet \hat{k}$$

Further info

- Modern Cosmology. S. Dodelson (2005)
- The Cosmic Microwave Background. R. Durrer (2008)
- For Boltzmann eqs.:
  - Papers from Efsthatiou (1990), Ma & Bertschinger (1995), Kosowsky (1996, for polarization)
- For gauge issues: Kodama & Sasaki (1984), Mukhanov, Feldman & Brandenberger (19932)

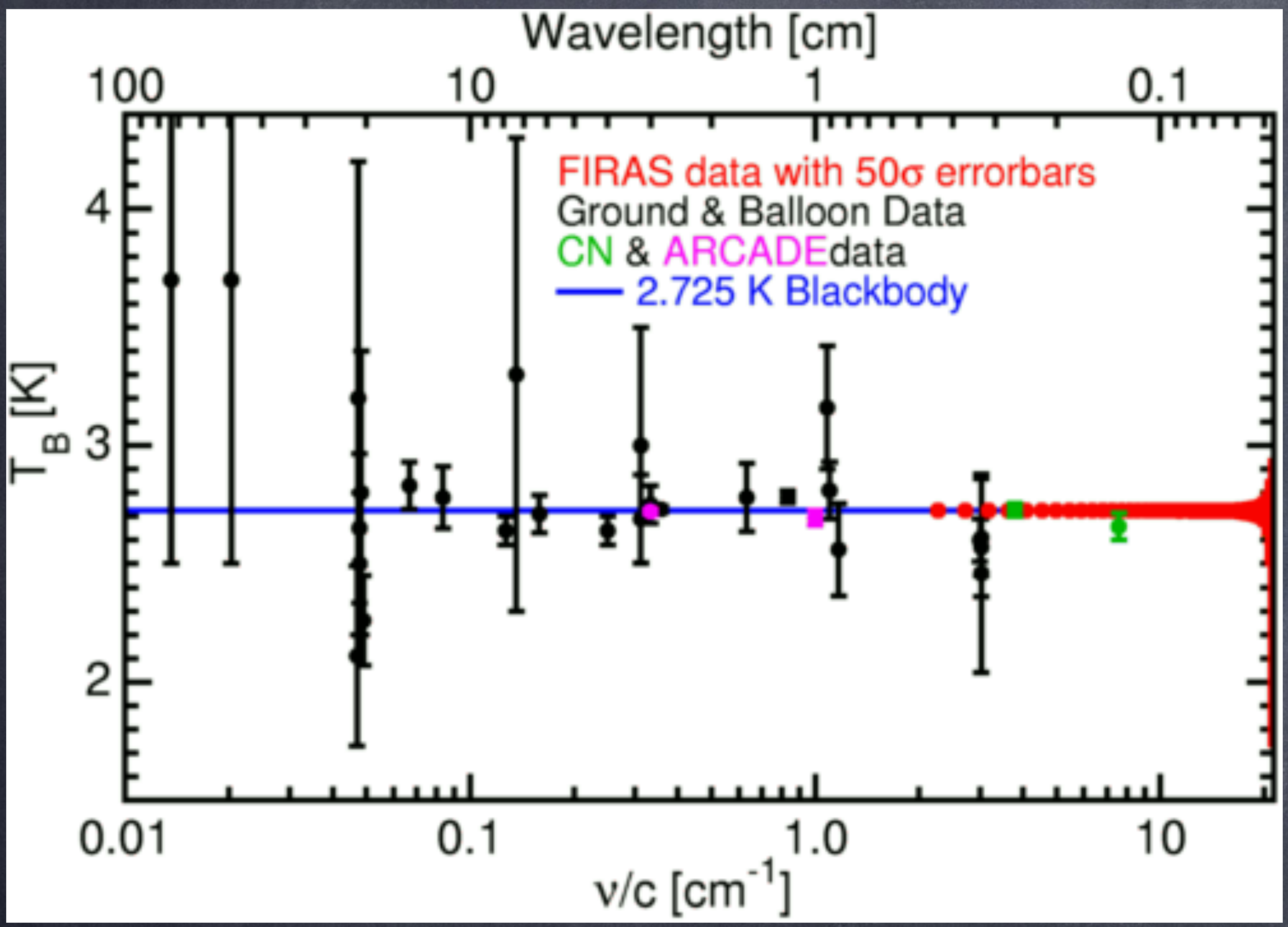
THE CMB BLACKBODY SPECTRUM

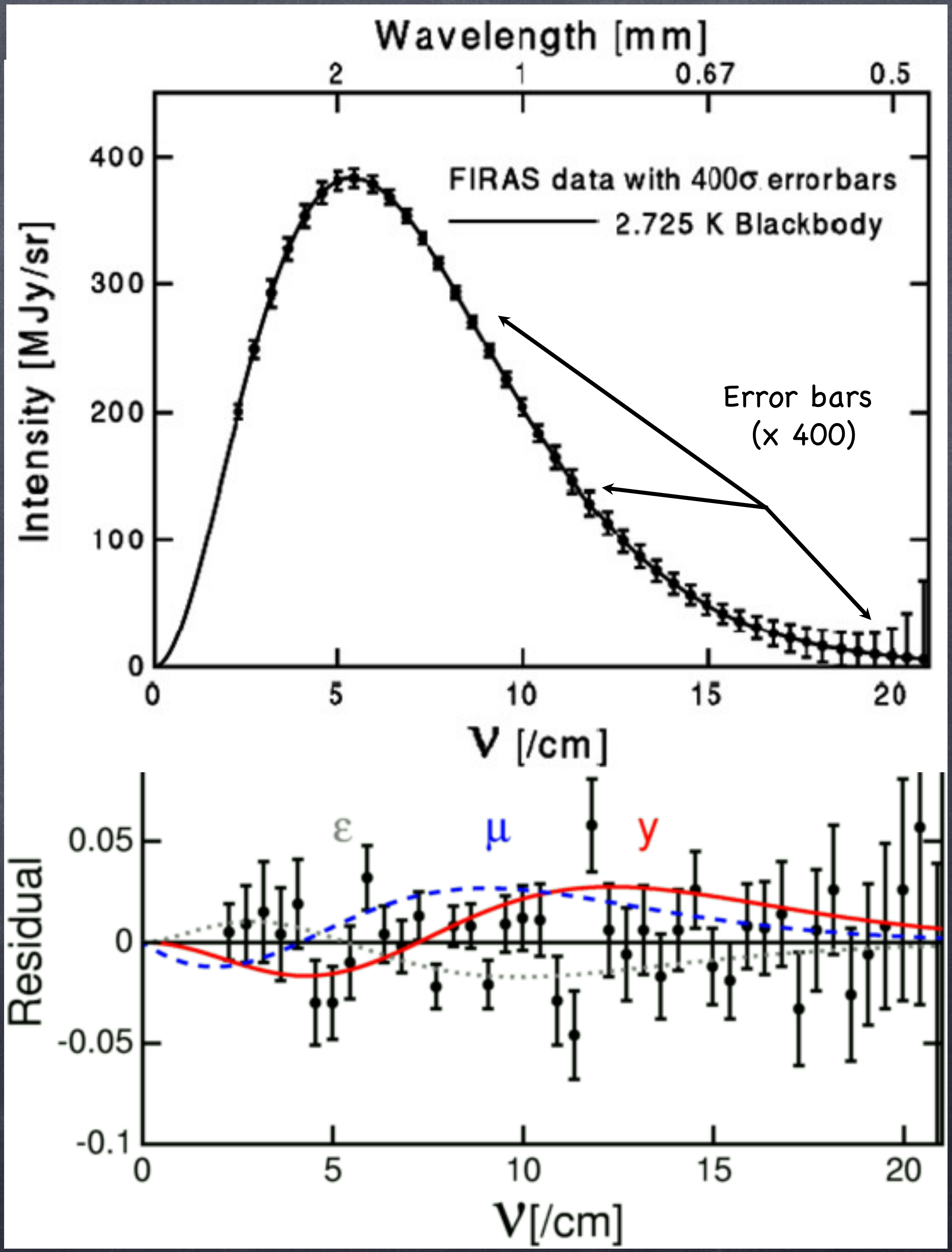
The CMB spectrum



The blackbody spectrum: energetics!!!

Distortions caused by
- Phase transition (Theories of Unification)
- Relic particle decay (Dark Matter)
- Reionization (first stars)





From Ned Wright, @ http://www.astro.ucla.edu/~wright/CMB.html

CMB Black body and cosmology

A blackbody with T=2.725K consists of ~ 414 γ/cm^3

This is ~ $\mathbf{10^9}$ higher than the average density of matter in the universe, so CMB photons are the most abundant particles in the universe

The **Black Body nature of the CMB is a direct confirmation** that the universe underwent a hot early phase (no mention about the beginning!!!!)

The primordial hot phase is the way to produce such a perfect blackbody spectrum, filling the sky with a rdiation field which is isotropic in 1 part in 10^5

What can we learn from the CMB spectrum?

- Spectrum measurements can tell us about
  - Reionization
  - Departures from thermodynamical equilibrium

- Some assumptions
  - Matter-radiation coupling: $e^+ + e^- \Leftrightarrow 2\gamma$
  - Coulomb scattering
  - Interaction of the radiation field with e^- and baryons

What can we learn from the CMB spectrum?

- Photon creation or energy change can be accomplished through
  - Thermal Bremsstrahlung (e^-, p)
  - Compton scattering
  - Double Compton scattering, where a 2nd photon is produced in ($e-,\gamma$) collision

The Planckian function

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/\kappa T} - 1}$$

$$B_\nu(T) = 2h\nu\frac{\nu^2}{c^2}\frac{1}{e^{h\nu/\kappa T} - 1}$$

Polarization states

Occupation number

Rayleigh-Jeans limit (x << 1)

$$B_\nu(T) \sim 2kT\frac{\nu^2}{c^2}$$

Wien limit (x >> 1)

$$B_\nu(T) \sim \frac{2h\nu^3}{c^2}e^{-x} \qquad x = \frac{h\nu}{\kappa T_{CMB}}$$

A black body in an expanding Universe...

- Specific energy density of a black body:

$$u_\nu = \frac{dE}{d\nu} = \frac{8\pi h\nu^3}{c^3}\frac{1}{e^{h\nu/\kappa T}-1}$$

$$u_\lambda = \frac{dE}{d\lambda} = \frac{dE}{d\nu}\frac{\nu}{\lambda} = u_\nu\frac{\nu}{\lambda} = \frac{8\pi hc}{\lambda^5}\frac{1}{e^{hc/\lambda\kappa T}-1}$$

- The energy density is:

$$u_\lambda d\lambda = \frac{8\pi hc}{\lambda^5}\frac{d\lambda}{e^{hc/\lambda\kappa T}-1}$$

Due to expansion and the redshift: $$\frac{\lambda}{\lambda_0} = \frac{a}{a_0}; \quad \frac{u_\lambda d\lambda}{u_{\lambda_0} d\lambda_0} = \left[\frac{a}{a_0}\right]^4$$

How does a black body evolve in an expanding Universe?

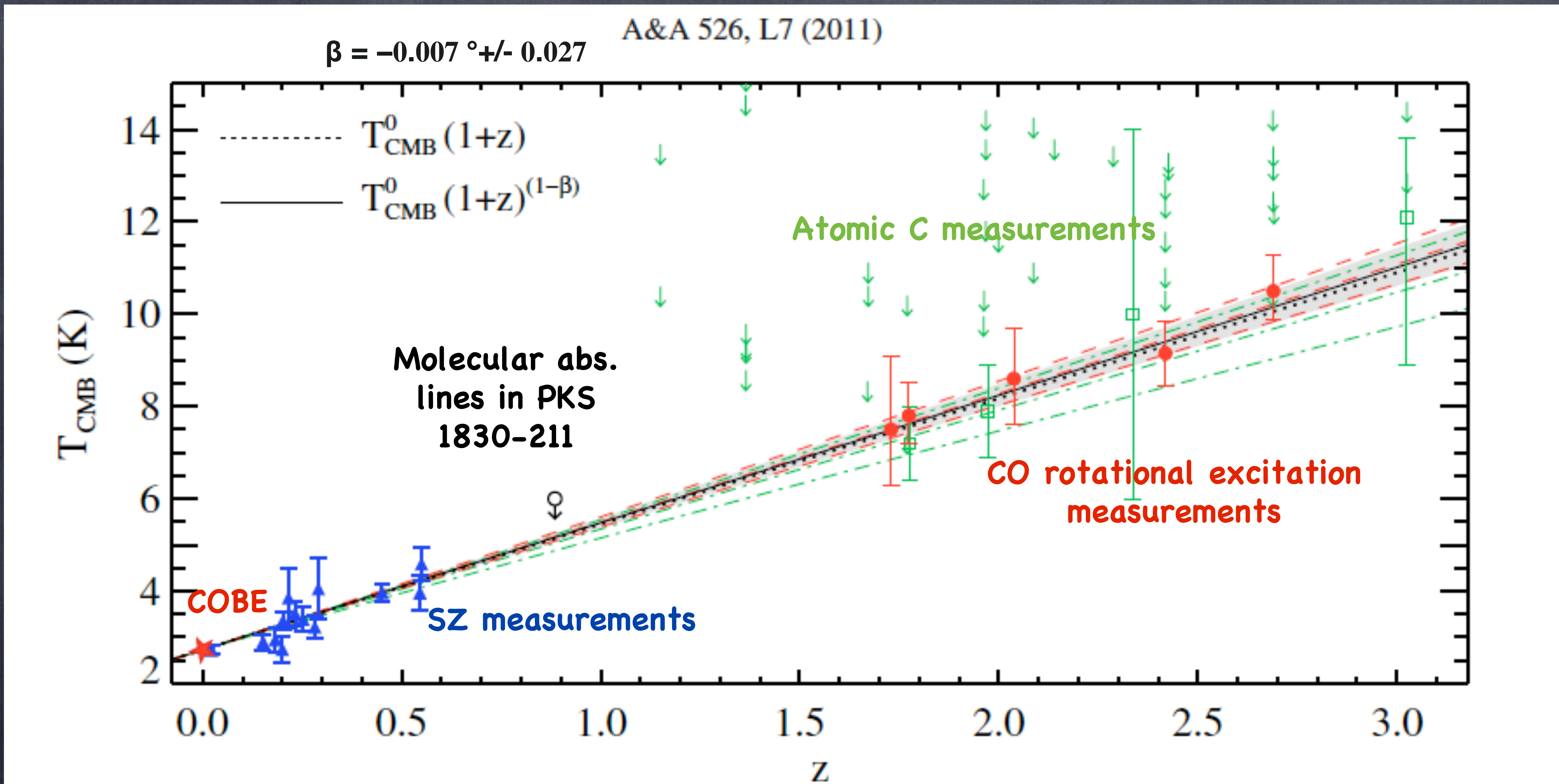
$$u_{\lambda_0} d\lambda_0 = [\frac{a}{a_0}]^4 u_\lambda d\lambda = [\frac{a}{a_0}]^4 \frac{8\pi hc}{\lambda_0^5 [\frac{a}{a_0}]^5 \left(e^{hc/\lambda_0 [a/a_0] \kappa T} - 1\right)} d\lambda_0 [\frac{a}{a_0}]$$

$$\Rightarrow u_\lambda d\lambda = \frac{8\pi hc}{\lambda_0^5 \left(e^{hc/\lambda_0 [a/a_0] \kappa T} - 1\right)} d\lambda_0$$

$$\Rightarrow u_\lambda d\lambda = \frac{8\pi hc}{\lambda_0^5 \left(e^{hc/\lambda_0 \kappa T_0} - 1\right)} d\lambda_0$$

$$\boxed{T = T_0 \frac{a_0}{a}}$$

- So, the Universe evolves and cools down, and the black body still remains the same
- Photons from primordial hot phases should still be around, but with lower energy (as a low-T black body)



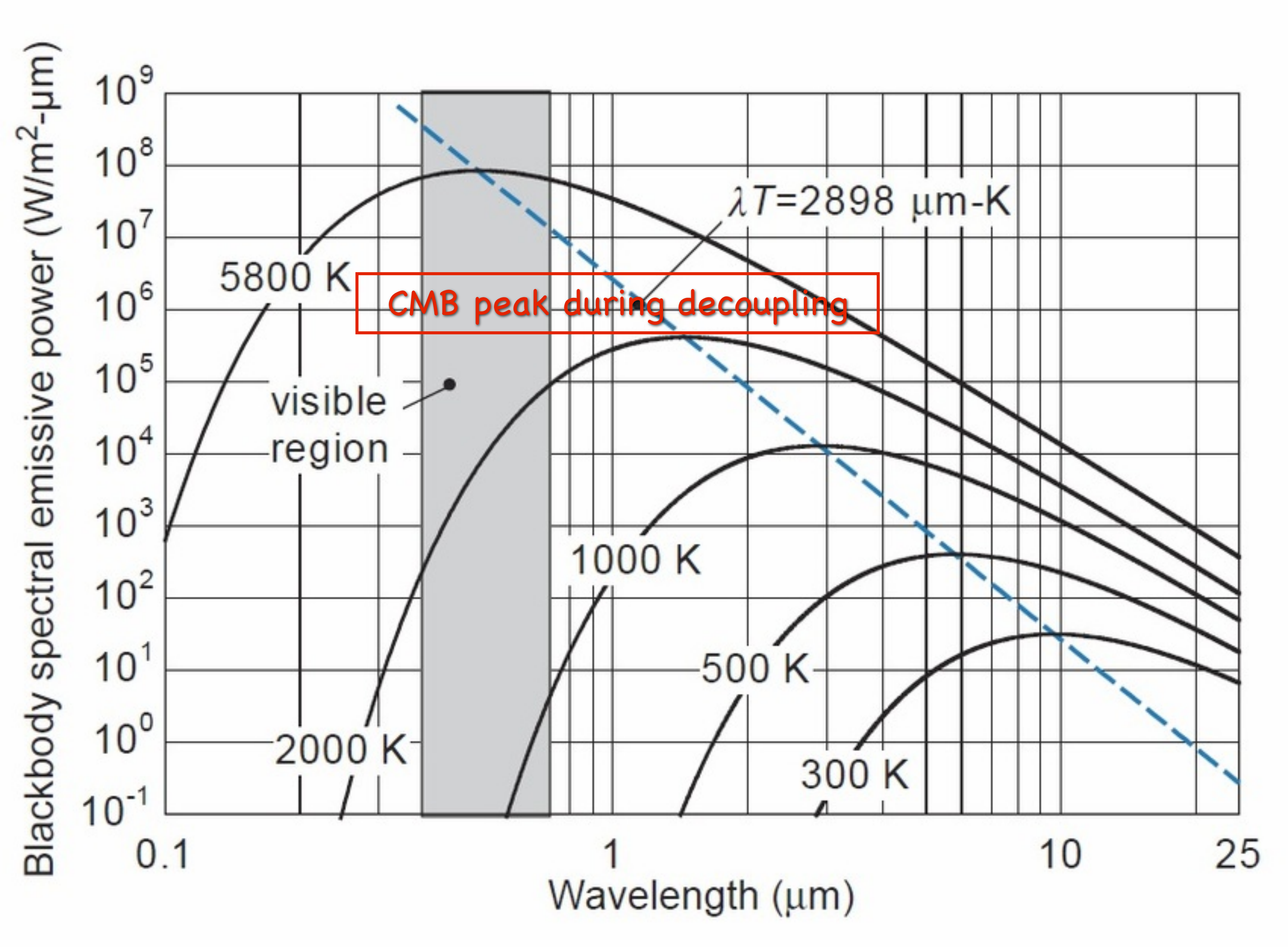
Noterdaeme et al. (2011)

What else can we learn from the CMB spectrum?

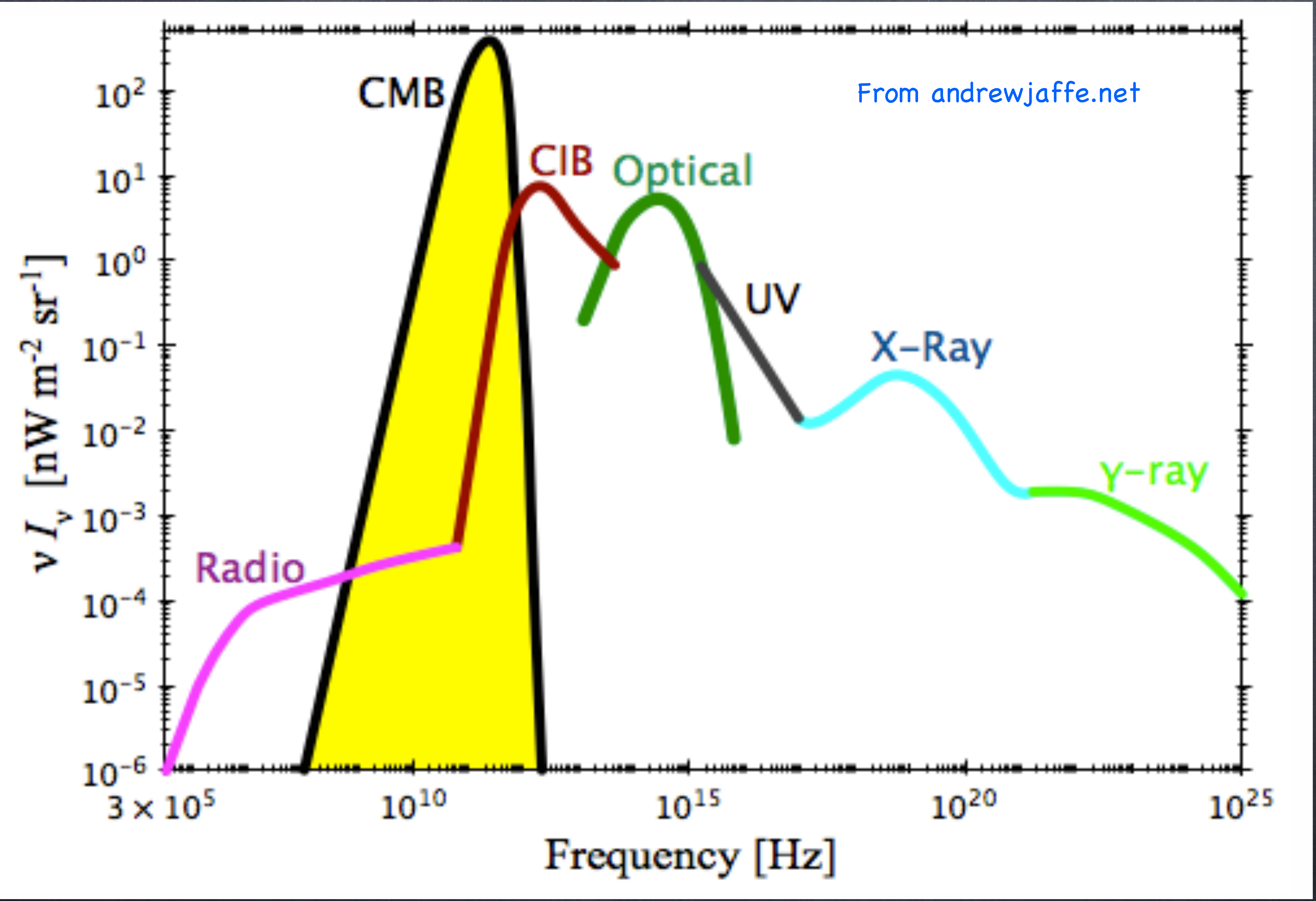
- Neutral atoms seldom interact with microwave photons
  - Ions and e- in the primordial plasma interact via Thomson scattering → changes direction but not photon frequency
  - **Thomson scattering does not produce a thermal spectrum!!**

What can we arrive to a black body spectrum?

- Under which conditions a radiation field, initially non-Planckian, relax towards a Planckian shape? Two conditions are necessary:
  - A mechanism to create photons and/or redistribute its energy
  - The interaction rate of these mechanisms MUST BE LARGER than the expansion rate of the Universe.
- In the primordial Universe, matter and radiation in thermal equilibrium create a Planckian spectrum AND expansion **DOES NOT CHANGE** its Planckian character



Blackbody spectral emissive power (W/m2-µm)
Wavelength (µm)
λT=2898 µm-K
CMB peak during decoupling
5800 K
visible region
2000 K
1000 K
500 K
300 K
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
0.1
1
10
25


CMB
CIB
Optical
UV
X–Ray
γ–ray
Radio
From andrewjaffe.net
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
νI_ν [nW m^{-2} sr^{-1}]
3×10^5
10^{10}
10^{15}
10^{20}
10^{25}
Frequency [Hz]

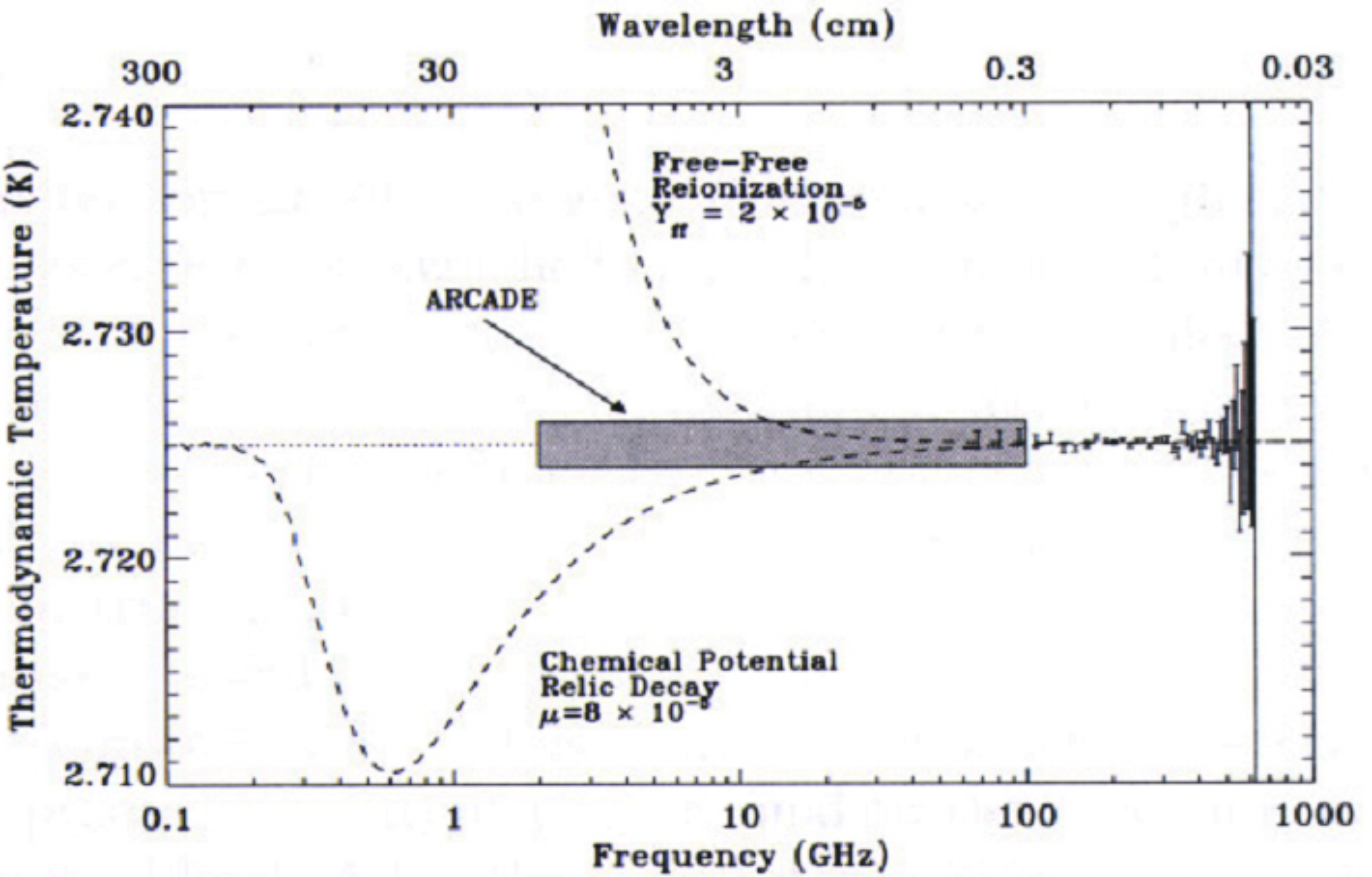
Distortions in the black body spectrum

- The blackbody spectrum of CMB was created in the blackbody photosphere at redshifts $z > 2 \times 10^6$.
- Universe dense and hot enough ⇒ **complete thermal equilibrium;** any perturbation away from the blackbody spectrum was suppressed exponentially.
- New physics (e.g., annihilation and decay of dark matter) can add energy and photons to CMB at redshifts $z \sim 10^5$ and result in a Bose-Einstein spectrum with a non-zero chemical potential (μ) ⇒ **DISTORTION**
- Processes: double Compton process, comptonization and bremsstrahlung
- Triple degeneracy in standard cosmology, i.e., the μ and y distortions from adiabatic cooling of baryons and electrons, Silk damping and annihilation of thermally produced WIMP dark matter are of similar order of magnitude ($\sim 10^{-8} - 10^{-10}$).

Kathri & Sunyaev, arvix:1203.2601

Blackbody distortions

Kogut and ARCADE collaboration (2006)



What causes the distortio[...] the black body spect[...]

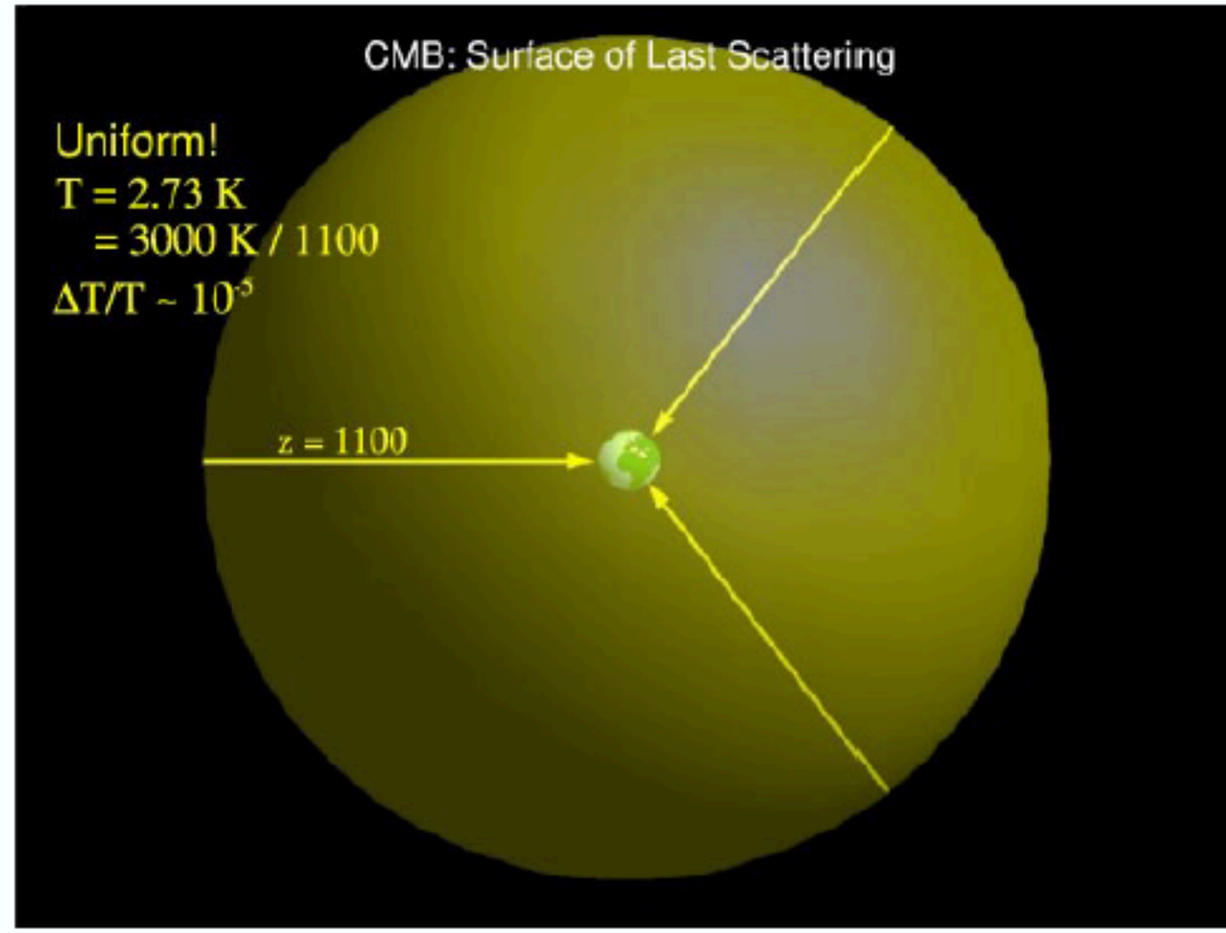
- μ-type: changes in the chemical pot[...]e CMB photons; caused by an injection [...] the CMB field; the photon number is n[...]d. | μ | < 10^{-8} (95% C.L.)

- y-type: Comptonizati[...]o the former Bose-Einstein spectrum [...]ecome a black body if the expansion rate [...]han the Compton scattering rate

Comptonization: redistribution of photons over the entire spectrum due to Compton scattering

$$y = \int \frac{\kappa_B T_e}{m_e c^2} \sigma_T n_e dl = \int d\tau_e \frac{\kappa_B T_e}{m_e c^2}$$

RECOMBINATION AND DECOUPLING



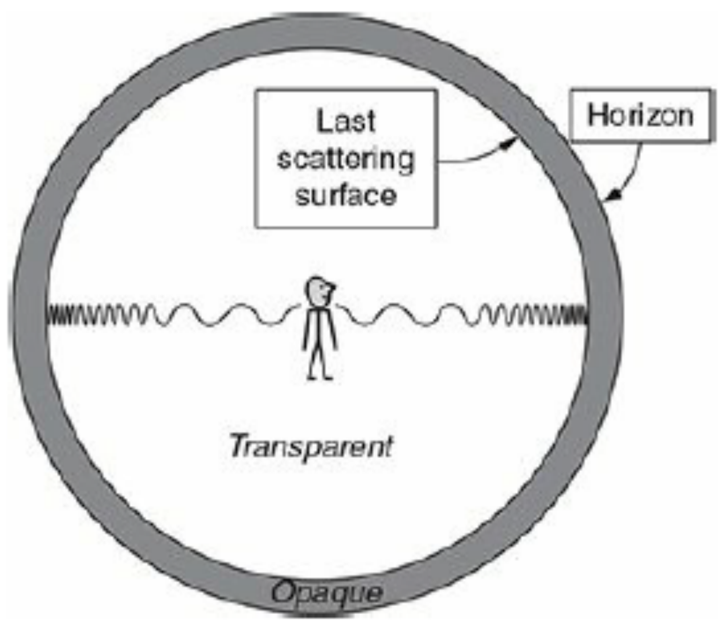


Figure 8.4 An observer is surrounded by a spherical last scattering surface. The photons of the CMB travel straight to us from the last scattering surface, being continuously redshifted.

The sequence

- CMB photons are the original photons that were coupled to the matter since after inflation.
- Matter, in this case, start from quarks & gluons, at a very early time, and became later neutrons & protons
- Photons and matter interacted closely due to Thomson scattering of e^- and γ
- Recombination (in fact, COMBINATION...) happened when temperature was low enough to allow electrons and protons to COMBINE into a hydrogen atom
- Recombination happens (formally) when $n_{ions} = n_{neutral}$

- Photon decoupling happens after e^- are removed from the environment, extinguishing the primordial plasma
- The Universe becomes "transparent"; before it was "opaque"
- Formally it happens when the photon mean free path becomes larger than the radius of the Universe at that time, or when the rate at which photons interact become smaller than the Hubble expansion rate
- The above define "the last scattering surface", the hypersurface where a photon last interacts with an e^-
- Since recombination does not happen instantaneously, the "surface" is actually a shell... Recombination starts, decoupling takes place and the beginning and end of these events define the shell

- B. Ryden's treatment includes H only, for simplification, but the formalism is exactly if we consider the real world, where He, D and Li are presente.
- X is the fraction of protons versus neutral H and protons; electrons quick in due to the neutrality requirement!

$$X = \frac{n_p}{n_p + n_H} = \frac{n_p}{n_{bar}} = \frac{n_e}{n_{bar}}$$

- For H, the relevant energy scale is the ionization energy E=13.6 eV, which affects the reaction rate below

$$H + \gamma \rightleftarrows p + e^-$$

- X depends on the balance of the above equation

- During early times, when the Universe was much smaller than today, its temperature was much higher. If we consider the time when a(t) = 10^{-5}, $T \sim 3\times10^5 K \approx 60\ eV, t \sim 10^2 yr$
- This is more than enough a temperature to keep the whole environment in an ionized state. In this case, typical scattering reactions such as

$$e^- + \gamma \rightleftarrows \gamma + e^-$$

- These reactions were responsible for sharing the energy among all components at the time
- Interaction rate at the time was $\Gamma = 5\times10^{-6}/s$, or about one scattering/week. This was much slower than the expansion rate at the time (10^{-10}/s), making photons and electrons coupled.

The physics of recombination

- Recombination temperature T=60000K... But <E> = 2.7 kT is not a very good approximation, since the blackbody distribution is A DISTRIBUTION, not an average.
- So we can have a small number of photons with E >> 2.7 KT in this distribution. Ryden quotes 1/500 with E > 10 kT, $1/3\text{x}10^6$ with E > 20 kT and $1/3\text{x}10^{10}$ with E > 30 kT
- Since there are ~ 10^9 photons for each baryon or electron, the chance of an atom being quickly ionized at early times is enormous.
- The calculation of the reaction rate for $H + \gamma \rightleftarrows p + e^-$ depends upon T and the photon/baryon ratio!!!

- The process of computing the fractional ionization state of the Universe as a function of temperature and the available species at the time uses the Saha equation and some statistical mechanics.
- For photons: $$n_\gamma = \frac{2.4041}{\pi^2}\left(\frac{kT}{hc}\right)^3 = 0.2436\left(\frac{kT}{hc}\right)^3$$
- For electrons and protons (with appropriate considerations for statistical weights, masses and energies:

$$\frac{n_H}{n_p n_{e^-}} = \frac{g_H}{g_p g_e}\left(\frac{m_H}{mpm_e}\right)^{3/2}\left(\frac{kT}{2\pi h^2}\right)^{-3/2} exp\left(\frac{[m_p + m_e - m_H]c^2}{kT}\right)$$

$$= \left(\frac{m_e kT}{2\pi h^2}\right)^{-3/2} exp\left(\frac{Q}{kT}\right)$$

- Preparing the above results to be used in the Saha equation, and considering the photon/baryon relation to the number of free protons, we obtain:

$$\frac{1-X}{X} = n_p \left(\frac{m_e kT}{2\pi h^2}\right)^{-3/2} \left(\frac{Q}{kT}\right), \quad \eta = \frac{n_p}{X n_\gamma}$$

- We can put the equation above in the form of a quadratic equation. Solving it for X, we get:

$$S(T,\eta) = 3.84\eta \left(\frac{kT}{m_e c^2}\right)^{3/2} \left(\frac{Q}{kT}\right)$$

- Considering X=1/2, and $\eta \sim 6\times10^{-10}$, corresponding to;
  - T_{rec} = 3760 K, z_{rec} = 1380, t_{rec} = 250.000 years

- B. Ryden discusses the non-instantaneous process that makes the last scattering surface actually a shell. Nevertheless, since the drop in the number of free protons is very fast, decopling happpens almost immediately after recombination.

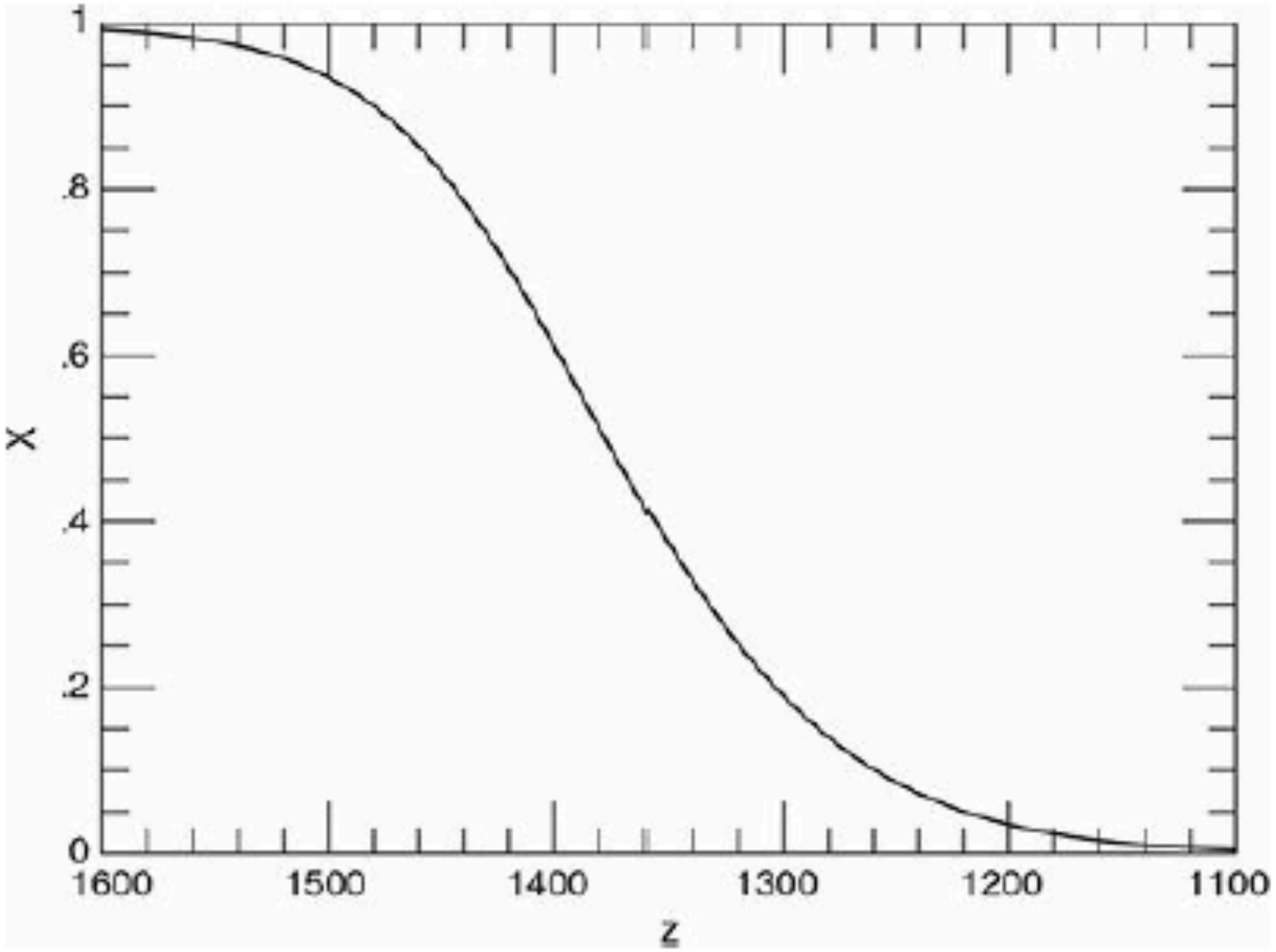
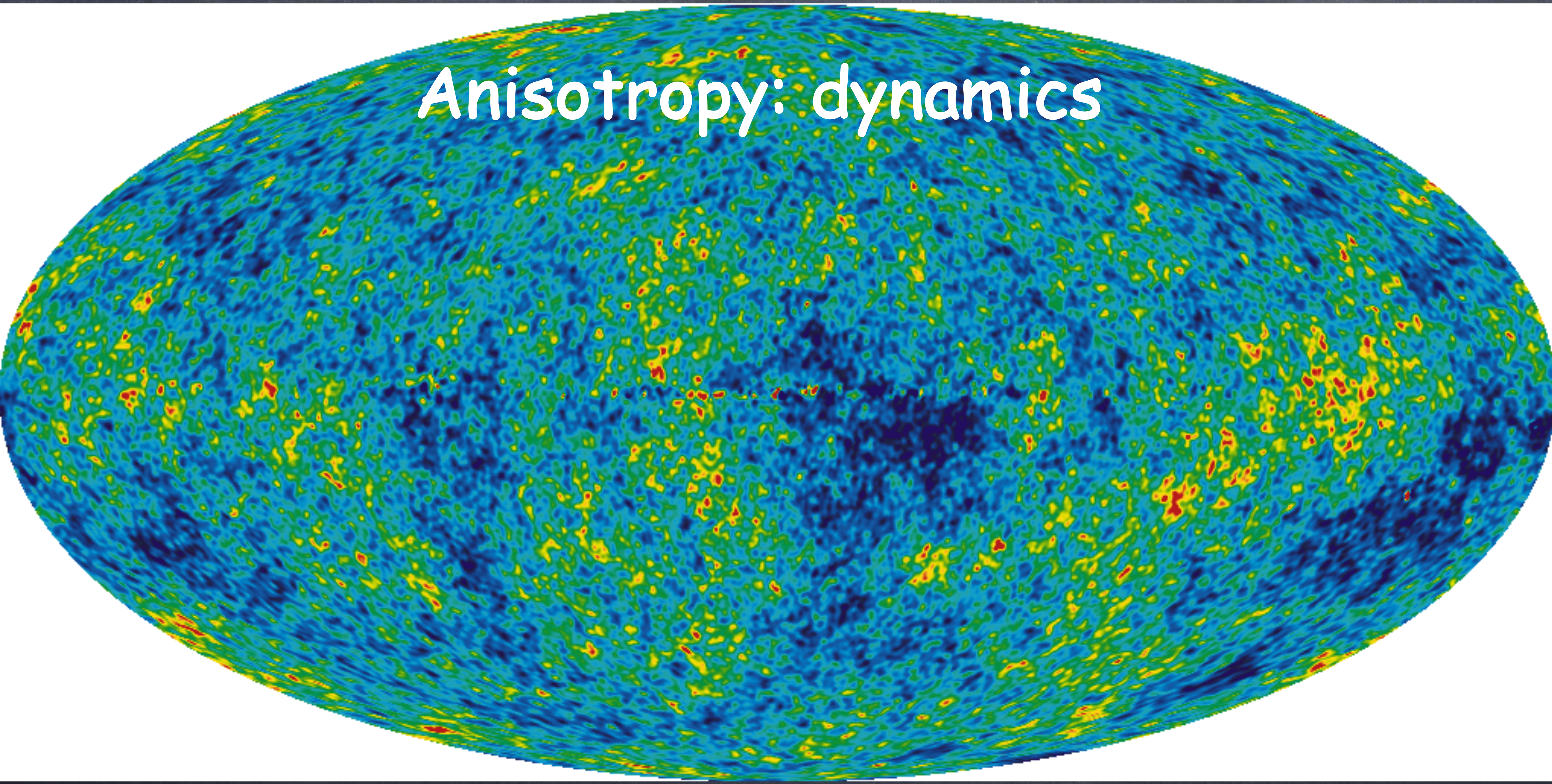


Figure 8.5 Fractional ionization X as a function of redshift during the epoch of recombination. A baryon-to-photon ratio $\eta = 6.1\times10^{-10}$ is assumed. Redshift decreases, and thus time increases, from left to right.

THE CMB TEMPERATURE FLUCTUATIONS

CMB anisotropies



Distribution of density fluctuations
Global cosmological parameters
Inflation physics

What can we learn from CMB anisotropies?

- **Initial conditions:** What types of perturbations, power spectra, distribution function (Gaussian?); => learn about inflation or alternatives. (distribution of ΔT; power as function of scale; polarization and correlation)

- **What and how much stuff:** Matter densities (Ω_b, Ω_{cdm});; neutrino mass (details of peak shapes, amount of small scale damping)

- **Geometry and topology:** global curvature Ω_K of universe; topology (angular size of perturbations; repeated patterns in the sky)

- **Evolution:** Expansion rate as function of time; reionization, Hubble constant H_0; dark energy evolution w = pressure/density (angular size of perturbations; l < 50 large scale power; polarization)

- **Astrophysics:** S-Z effect (clusters), foregrounds, etc.

Adapted from A. Lewys talk at CITA

Simple classification

- **Origin**:
  - **Intrinsec** (pre-decoupling)
    - gravitational potential (SW), local Doppler effects, primordial perturbations
  - **Extrinsec or secondary** (pos-decoupling)
    - Gravitational: Ostriker-Vishniac, Rees-Sciama, lensing, ISW
    - Scattering: SZ effect, reionization

- **Angular contributions**
  - **Large** scale ($\theta \geq 1^o$) - Sachs-Wolfe, mostly gravitational
  - **Intermediate** scales ($1' \leq \theta \leq 1^o$) - mainly from photon dynamics
  - **Small** scales ($\theta \leq 1'$) - dissipation of primary anisotropies

CMB anisotropies are given by

linear regime: contributions from gravity and scattering

$$\frac{\Delta T}{T} = \frac{1}{4}\frac{\Delta\rho_\gamma}{\rho_\gamma} + \frac{1}{3}\frac{\Delta\phi}{c^2} + \frac{v}{c}$$

radiation density fluctuations

gravitational redshift (Sachs-Wolfe effect + integrated SW)

scattering against moving e-

Combined in the Boltzmann equation

$$\begin{aligned}\frac{d}{d\eta}[e^{-\tau}(\Theta+\Psi)] &= e^{-\tau}(\dot\phi+\dot\psi)\\ &- \dot\tau e^{-\tau}\left(\Psi + \vec{e}\bullet\vec{v}_b + \frac{3}{16\pi}\int d\hat{m}\Theta(\epsilon,\hat{m})[1+(\vec{e}\bullet\hat{m})^2]\right)\end{aligned}$$

$$\boxed{+\frac{\Delta T}{T}_{sec}}$$

polarization, secondary scattering and, for pos-recombination, mainly SZ effect and lensing, will be discussed later...

Solutions

$$T(\vec{\kappa},\mu,\eta) = T_0(\eta)[1+\Theta(\vec{\kappa},\mu,\eta)]$$

temperature perturbation

$$\Theta_l = \frac{i^l}{2}\int_{-1}^{1} P(\mu)\Theta(\mu)d\mu \Leftrightarrow$$

$$\Theta(\mu) = \sum_{l=0}^{\infty}\frac{2l+1}{i^l}P_l(\mu)\Theta_l$$

$$\mu = \frac{\vec{\kappa}.\vec{p}}{\kappa p}$$

Spherical harmonics give the temperature coefficients.

How do we compute the CMB power spectrum?

- $\Delta T/T$ computed from the integration (in conformal time) of Einstein and Boltzmann eqs. along the line-of-sight photon cone
  - Geometric term: radial eigenfunctions, model-independent
  - Source terms: photon, baryon and metric perturbations
- Polarization spectrum: comes from rotation due to Stokes parameters' determination. It is weaker, includes scalar, vector and tensor components

How do we compute the CMB power spectrum?

$$\frac{\Delta T(\theta,\phi)}{T_{CMB}} = \sum_{l=0}^{\infty}\sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta,\phi)$$

spatial distribution of the amplitudes of the fluctuations

encodes the physical processes imprinted in the radiation produced in the LSS

$$Y_{lm}(\theta,\phi) = \sqrt{\frac{2l+1}{4\pi}\frac{|l-m|!}{|l+m|!}} P_l^m(cos\theta) e^{im\phi}$$

$$a^*_{lm} = (-1)^m a_{l-m}$$

since the temperature is a real quantity...

How do we compute the... CMB power spectru

Now, let's get to the more formal details...

- Theory: Linear physics + Gaussian primo uctuations

$$\boxed{C_l = \frac{1}{2l+1}\sum_{-m}^{+m} a_{lm}a^{*}_{lm}}$$

$$\sigma_{CMB} \quad = \frac{\Delta C_l}{C_l} = \sqrt{\frac{2}{2l+1}}$$

- va erage over all possible sky realizations)
stical isotropy implies independent of m

- In practice, things the following way:

Initial conditi
+ cosmolo
para

linearized GR
+ Boltzmann equations

$\longrightarrow$

C_l , a.k.a. the CMB power spectrum

CMBFAST: cmbfast.org
CAMB: camb.info
CMBEASY: cmbeasy.org
COSMICS, etc..

Callin, astro-ph:0606683

Boltzmann eqs. for all species

P subscript - polarization
. - conformal time derivative

Photons

$$\dot{\Theta} + i\kappa\mu\Theta = -\dot{\Phi} - i\kappa\mu\Psi - \dot{\tau}\left[\Theta_0 - \Theta + \mu v_b - \frac{1}{2}P_2(\mu)\Pi\right]$$

$$\Pi = \Theta_2 + \Theta_{P_2} + \Theta_{P_0}$$

$$\dot{\Theta}_P + i\kappa\mu\Theta_P = -\dot{\tau}\left[-\Theta_P + \frac{1}{2}(1 - P_2(\mu))\Pi\right]$$

Dark matter

$$\dot{\delta} + i\kappa v = -3\dot{\Phi}, \qquad \dot{v} + \frac{\dot{a}}{a}v = -i\kappa\Psi$$

Baryons

$$\dot{\delta}_b + i\kappa v_b = -3\dot{\Phi}, \qquad \dot{v}_b + \frac{\dot{a}}{a}v_b = -i\kappa\Psi + \frac{\dot{\tau}}{R}\left[v_b + 3i\Theta_1\right]$$

Neutrinos

$$\dot{N} + i\kappa\mu N = -\dot{\Phi} - i\kappa\mu\Psi$$

$$\Theta_l \equiv \frac{1}{(-i)^l}\int_{-1}^{1}\frac{d\mu}{2}P_l(\mu)\Theta(\mu)$$

$$\dot{\tau} = n_e\sigma_T a$$

$$\mu = \hat{p} \bullet \hat{k}$$

- If we compute the previous set of equations up to the angular scale of interest ($l \sim 3000$ and up, in 2020)...
- Huge number of coupled equations (may take days to solve by brute force on the fastest computers)
- Strategies were developed to solve them...
  - Initial code (COSMICS): Bertschinger (1995)
  - Breakthrough (CMBFAST): Seljak & Zaldarriaga (1996)
  - The present (CAMB and CMBEASY): Lewis and Challinor (1999), Doran, Robbes and Müller (2003)
  - A coupled pipeline (COSMOMC): Lewis and Bridle (2002)
  - **Many other codes in the market in 2020, based in Python, but CAMB remains the latest reference for all of them**

Line-of-sight integration

- Instead of expanding the set of equations in multipoles and integrating them, solve equation for dΘ/dt and do the multipole expansion at the end!
- Order of magnitude gain in time processing
- Solution for Θ

$$\Theta(\kappa, \mu, \eta_0) \quad = \quad \int_0^{\eta_0} \left\{ -\dot{\Phi} - i\kappa\mu\Psi - \dot{\tau}\left[\Theta_0 + i\mu v_b - \frac{1}{2}P_2(\mu)\Pi\right\} \times e^{i\kappa\mu(\eta-\eta_0)^{-\tau}} d\eta$$

μ disappears, being absorbed by the spherical Bessel function j_l

$$\Theta_l(\kappa,\eta_0) = \int_0^{\eta_0} S(\kappa,\eta) j_l[\kappa(\eta-\eta_0)]d\eta$$

$$S(\kappa,\eta) = g\Big[\Theta_0 + \Psi + \frac{1}{4}\Pi\Big] + e^{-\tau}\Big[\dot{\Psi} - \dot{\Phi}\Big] - \frac{1}{\kappa}\frac{d}{d\eta}(gv_b) + \frac{3}{4\kappa^2}\frac{d^2}{d\eta^2}(g\Pi)$$

- C_l are, essentially, $\Theta_l^2(x)$, with the contribution of the spectrum, defined by the initial conditions

Harrison-Zeldovich spectrum, predicted by inflation...

- Generally speaking (not including normalizations for the amplitude of the fluctuations):

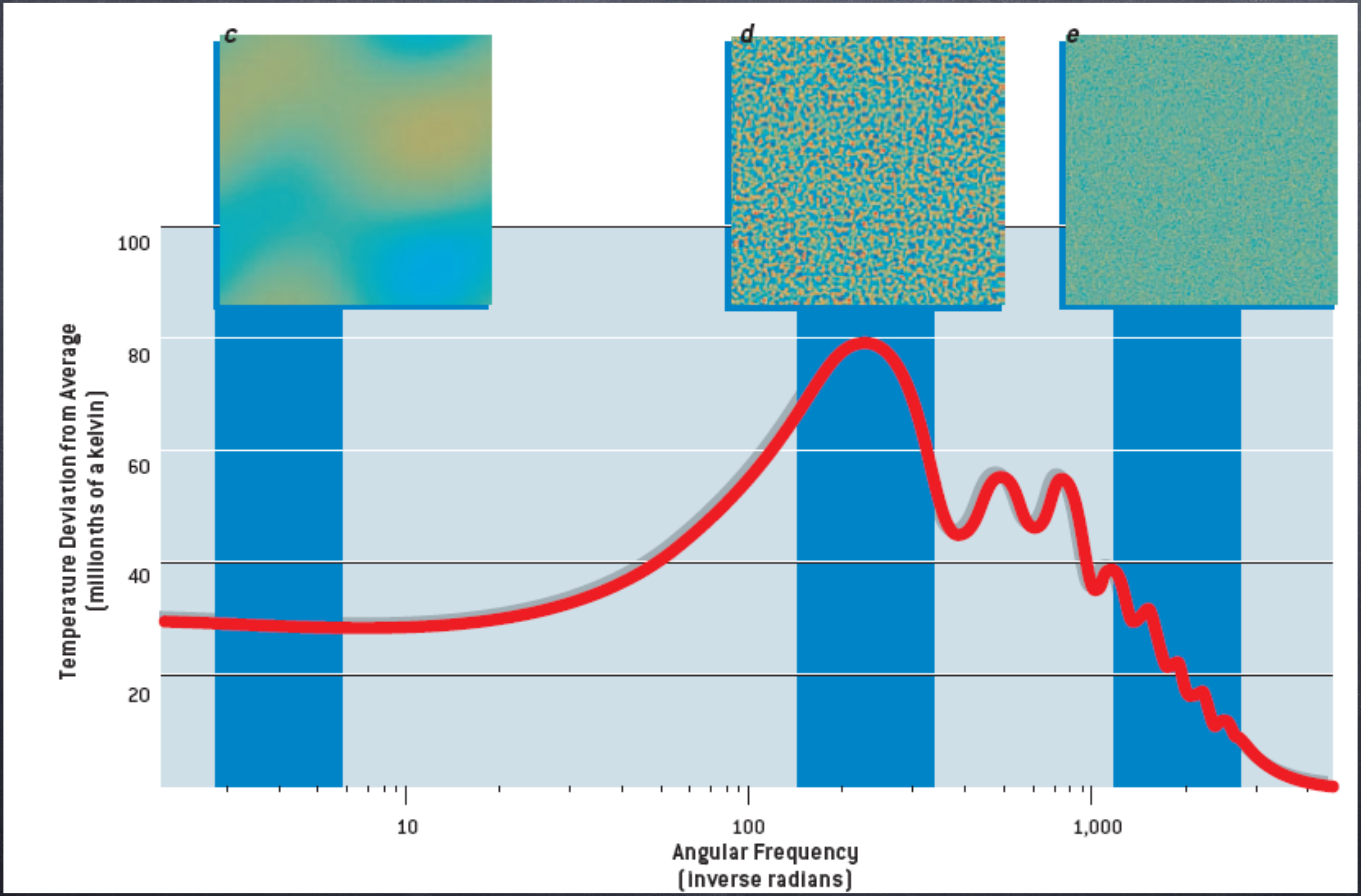
$$C_l = \int \frac{d^3\kappa}{2\pi^2} P(\kappa)\Theta_l^2(\kappa)$$

$$\frac{\kappa^3}{2\pi^2}P(\kappa) = \left(\frac{\kappa}{H_0}\right)^{n-1}, \quad \text{so}$$

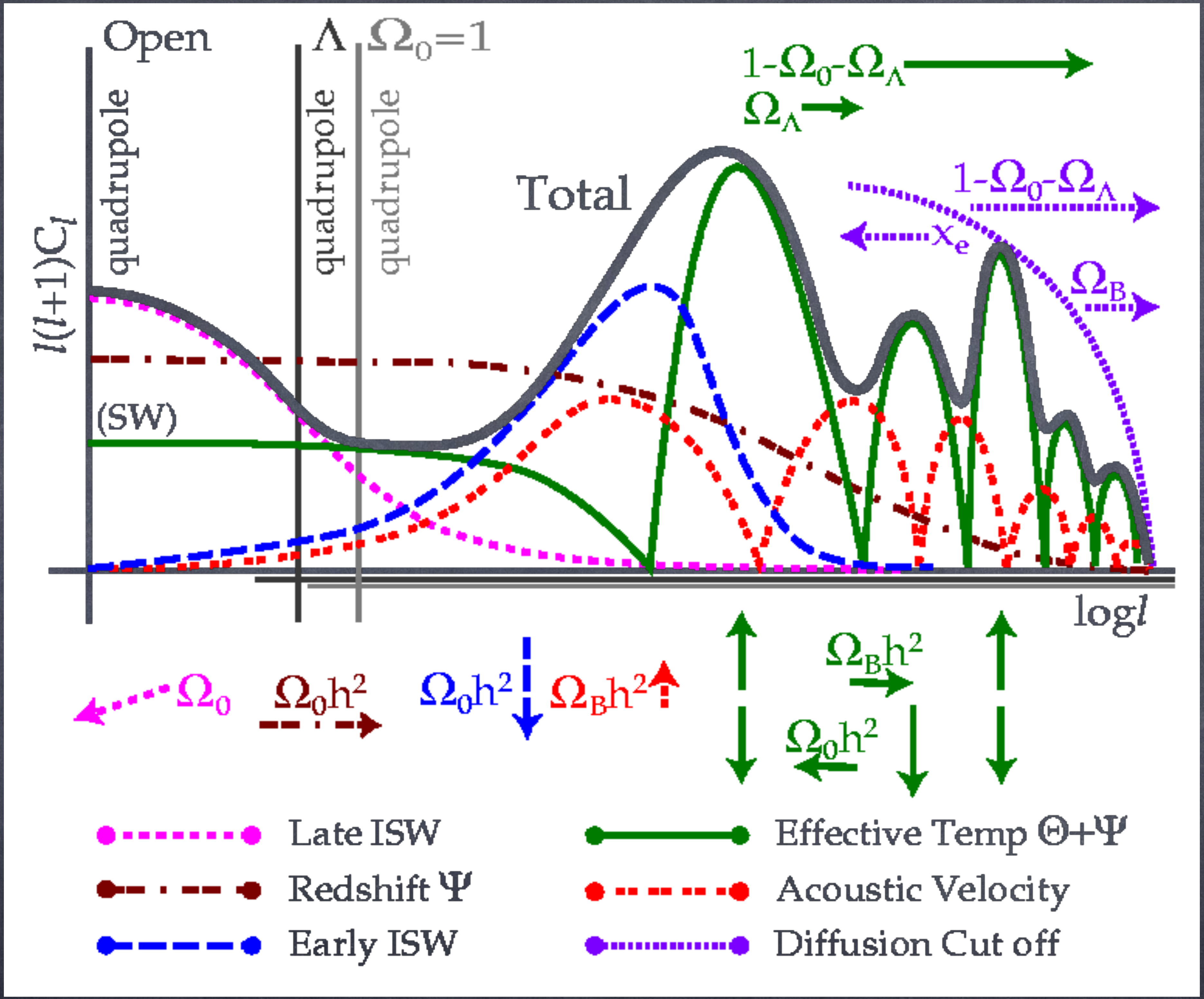
$$C_l = \int_0^\infty \left(\frac{\kappa}{H_0}\right)^{n-1}\Theta_l^2(\kappa)\frac{d\kappa}{\kappa}$$

The CMB power spectrum

Primordial perturbations + later physics

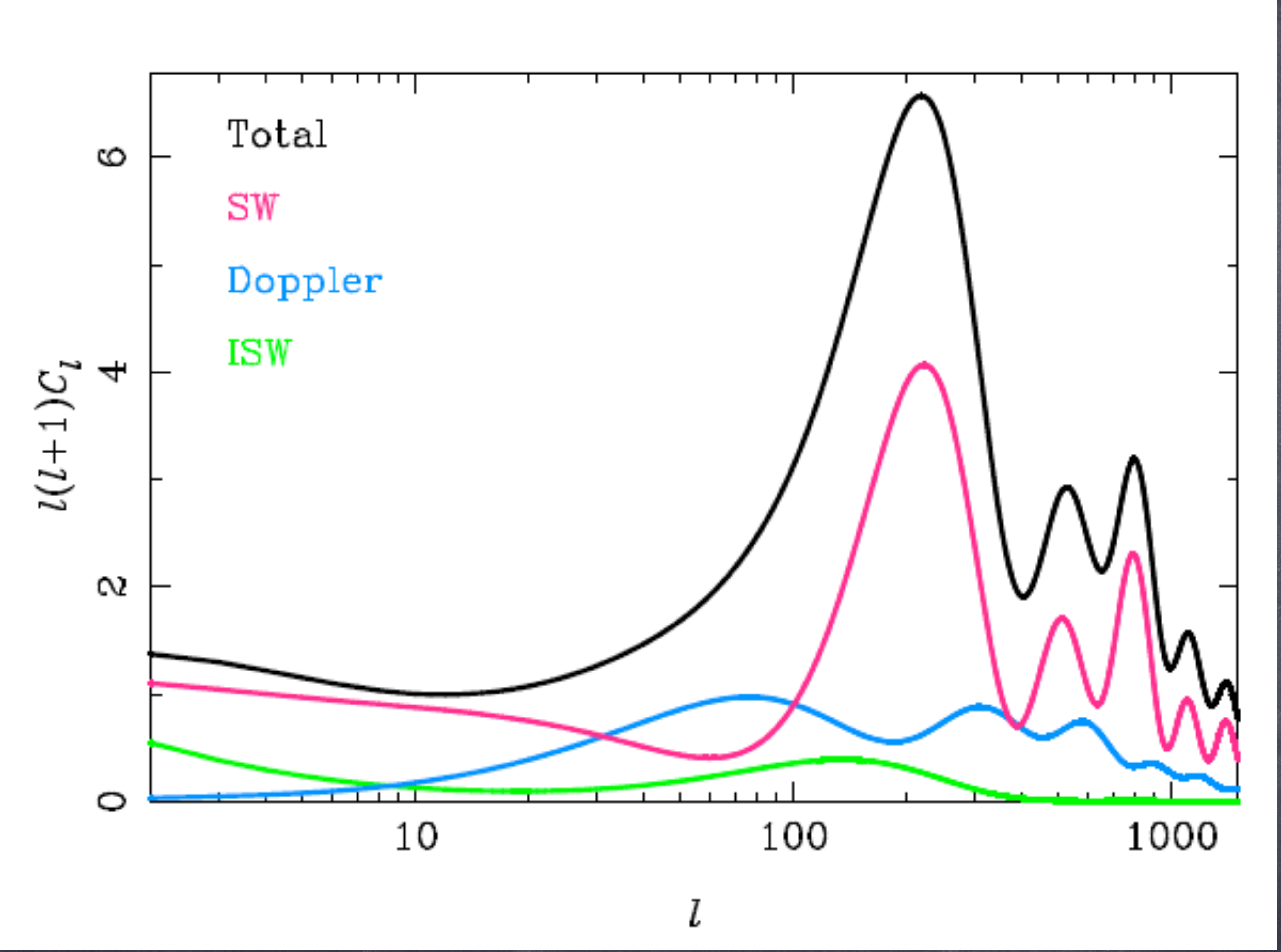


Hu & White, Sci. Am., 290 44 (2004)



From Paul Steinhardt (1995)

Speaking of acoustic waves...



$$\frac{d}{d\eta}[e^{-\tau}(\Theta+\Psi)] \quad = \quad e^{-\tau}(\dot{\phi}+\dot{\psi})$$

$$- \quad \dot{\tau}e^{-\tau}\left(\Psi + \vec{e}\bullet\vec{v}_b + \frac{3}{16\pi}\int d\hat{m}\Theta(\epsilon,\hat{m})[1+(\vec{e}\bullet\hat{m})^2]\right)$$

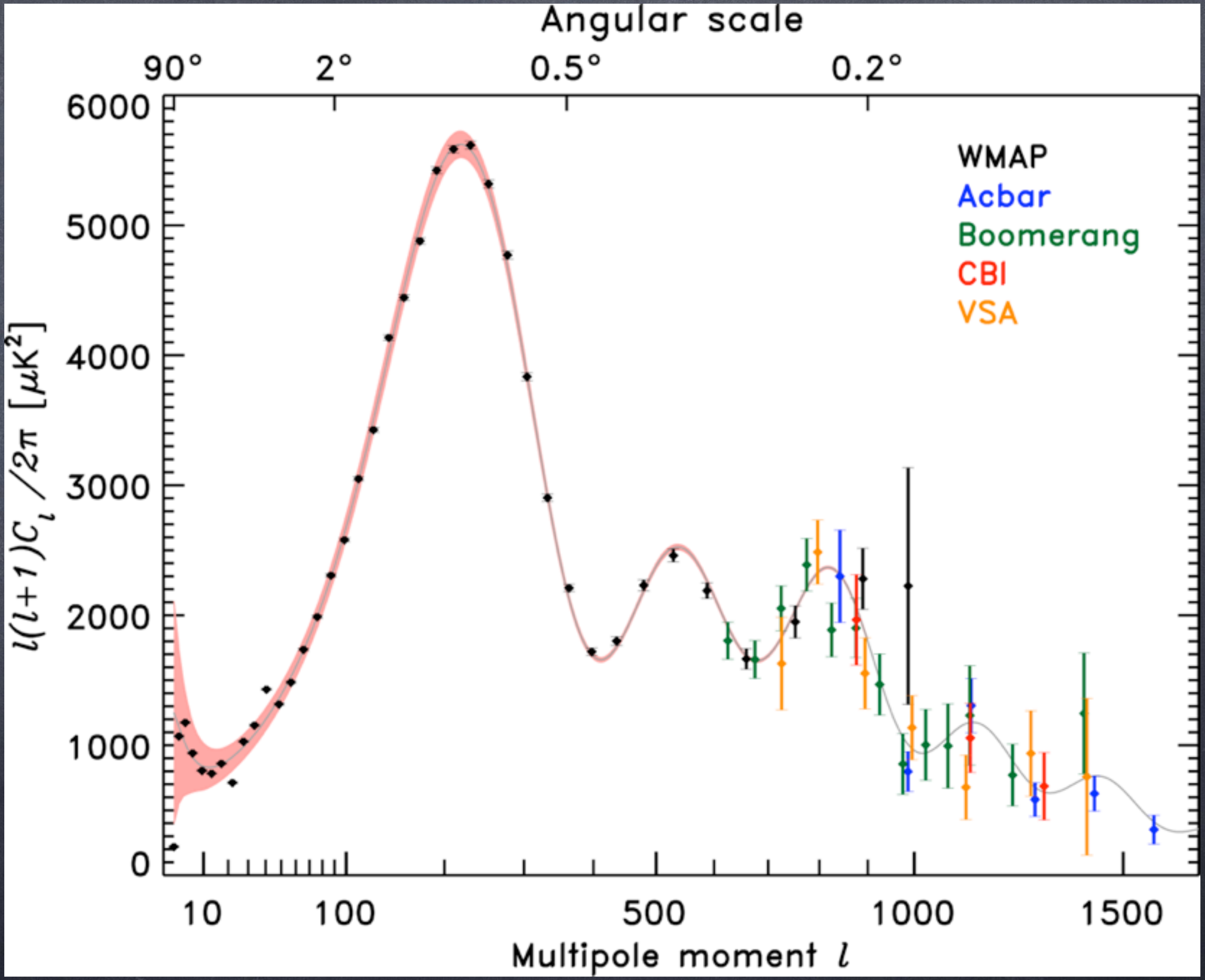
scattering by moving e-

radiation density fluctuations

integrated Sachs-Wolfe

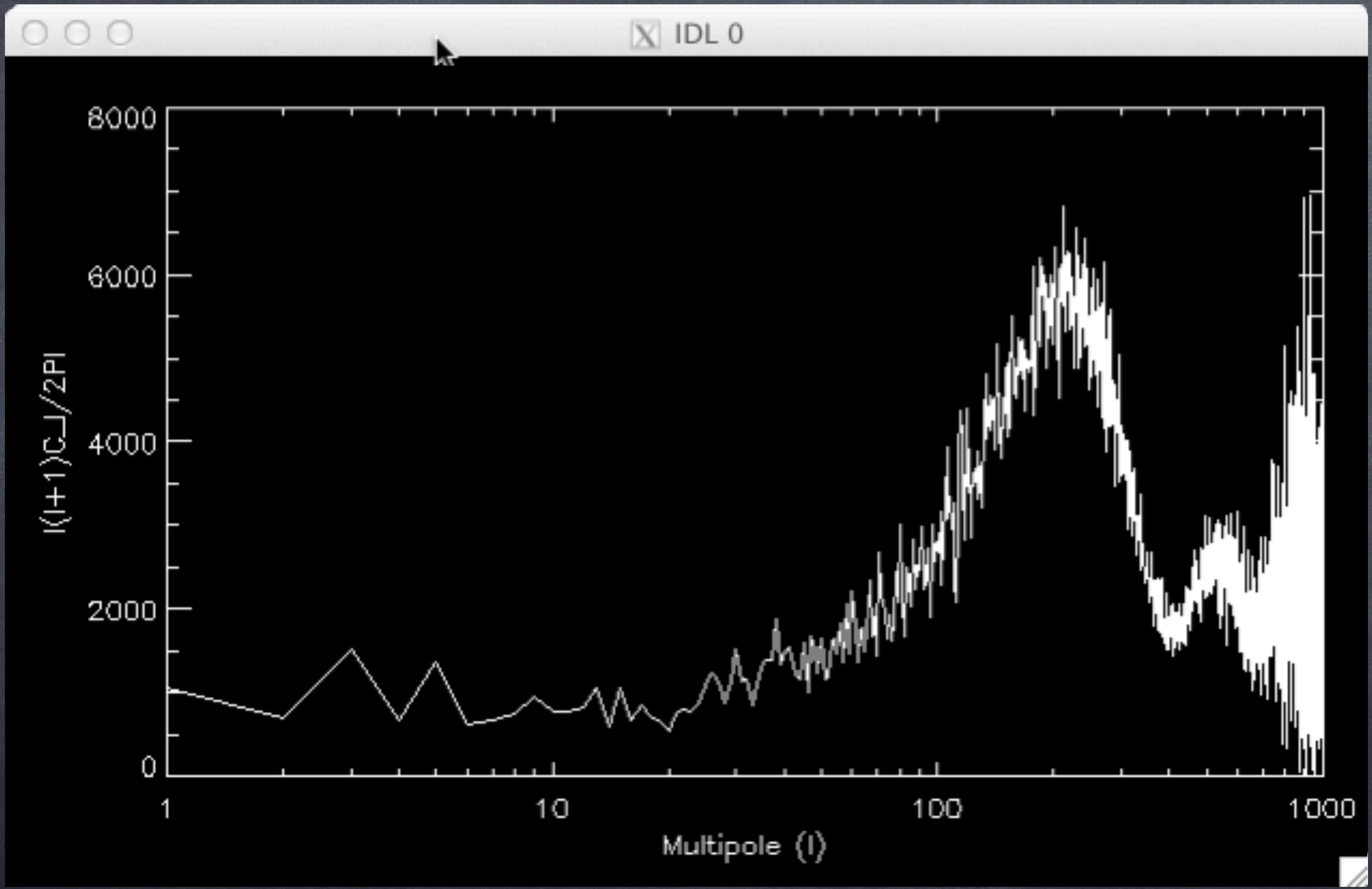
+ Sachs-Wolfe

(l+1) - accounts for the real contribution of the alm to the power spectrum (lost when the average is taken <>)



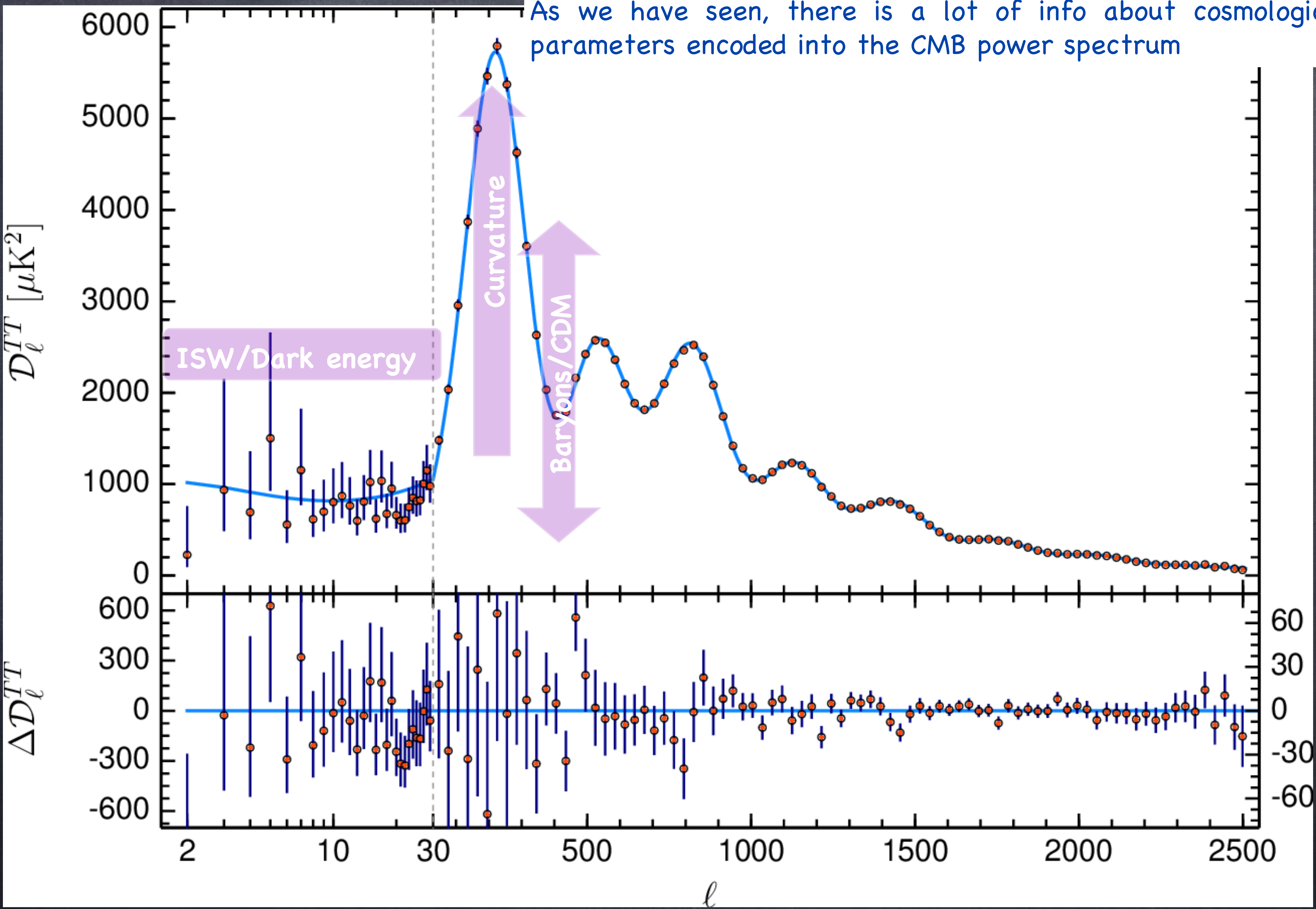
l - accounts for the decreasing power in smaller scales

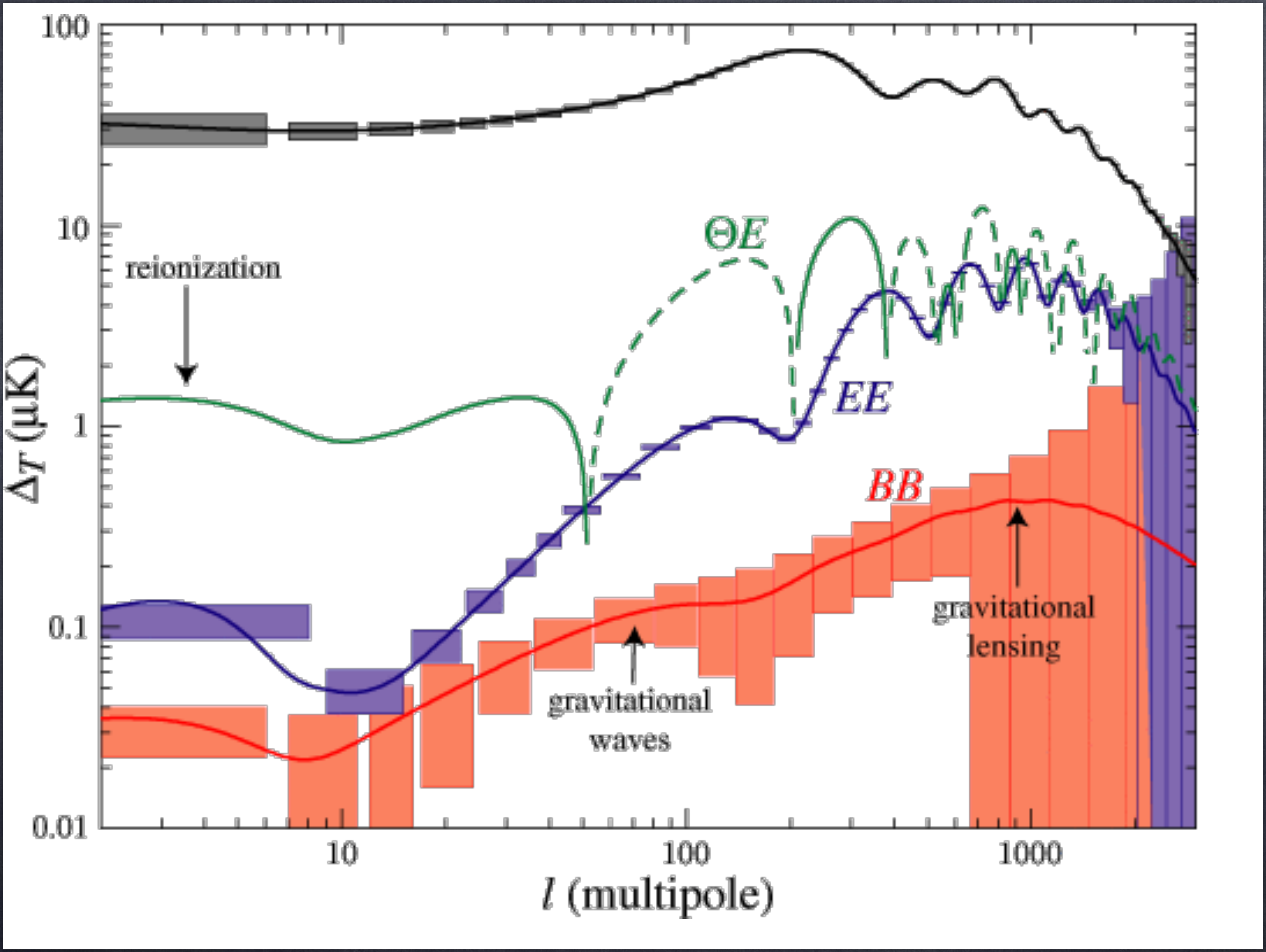
WMAP 7-year power spectrum (Jarosik et al 2011)


IDL 0
8000
6000
4000
2000
0
l(l+1)C_l/2PI
1
10
100
1000
Multipole (l)

Aghanim et al. Planck 2018 results. VI. Cosmological parameters (A&A 2020)

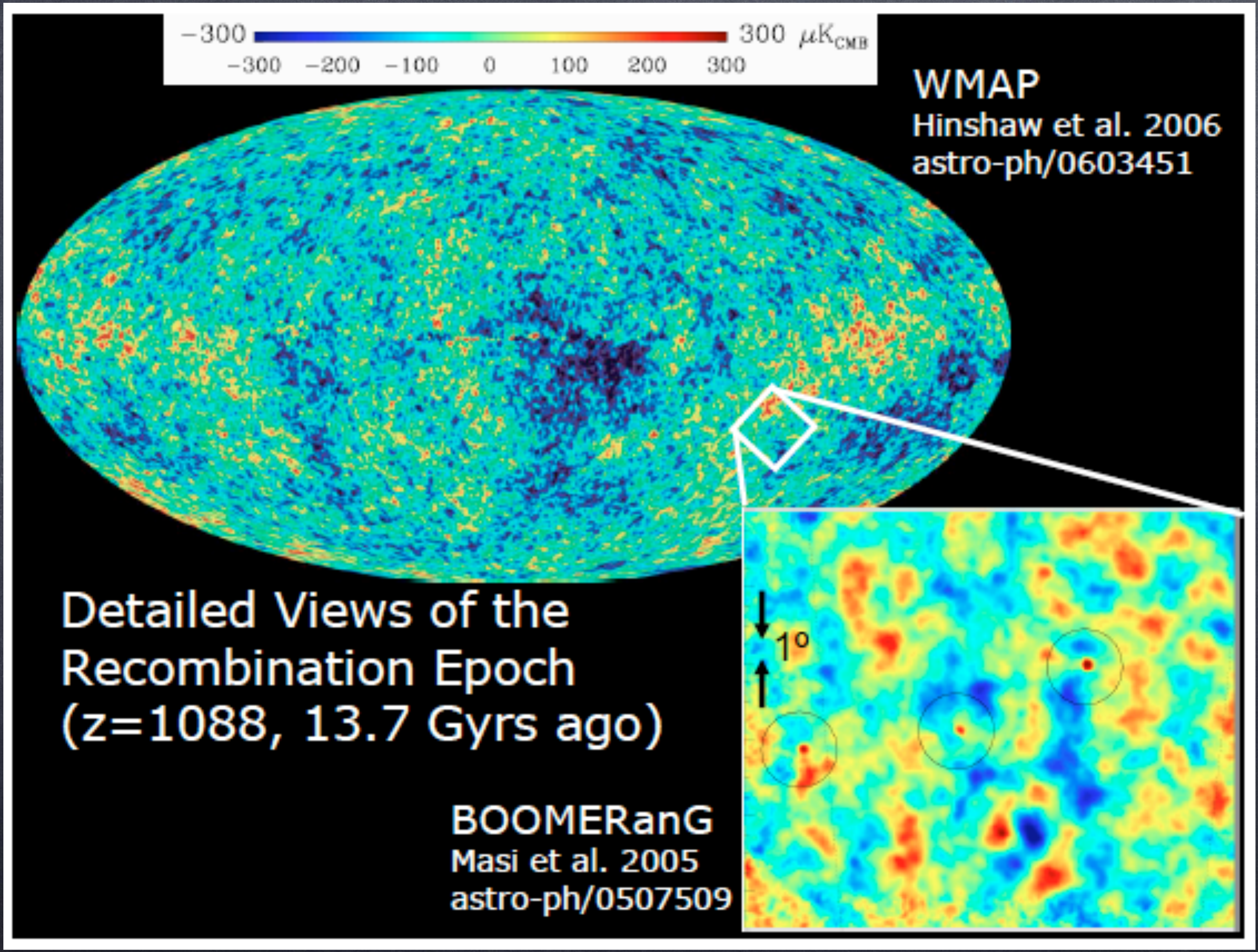
As we have seen, there is a lot of info about cosmological parameters encoded into the CMB power spectrum



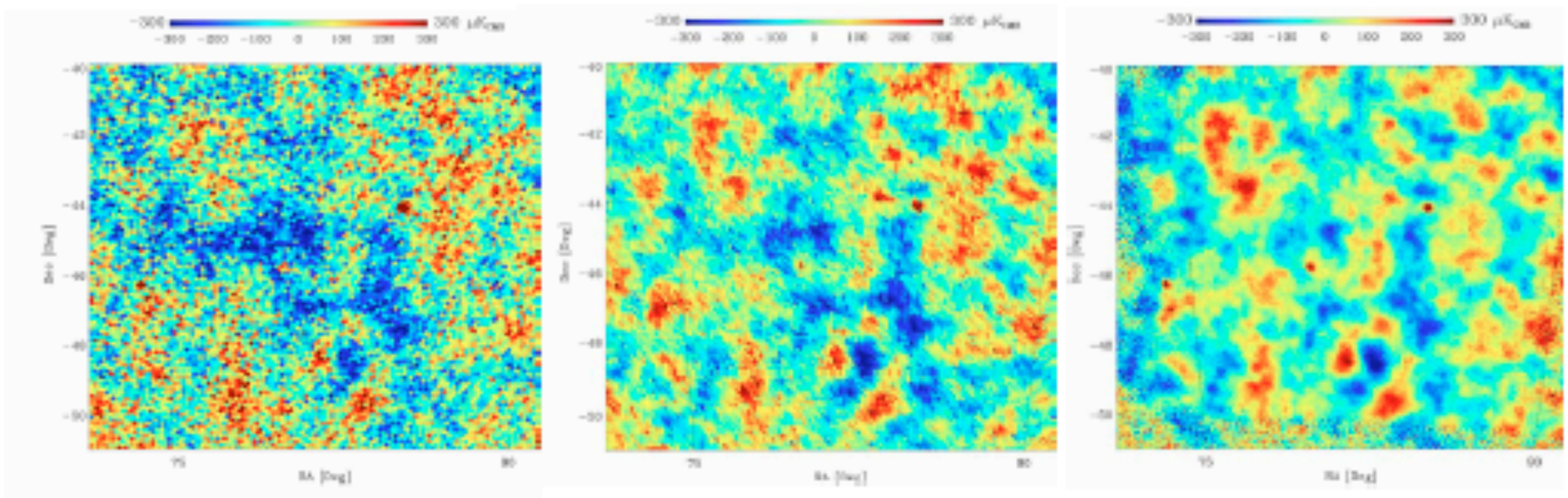


From Wayne Hu @ http://background.uchicago.edu/~whu/araa/node4.html

Consistency tests



From Paolo de Bernardis (lecture @ INPE's IV Advanced School)



WMAP 3 years
23-94 GHz

BOOMERanG-98
145 GHz

BOOMERanG-03
145 GHz

The consistency of the maps from three *independent* experiments, working at very different frequencies and with very different mesurement methods, is the best evidence that the faint structure observed

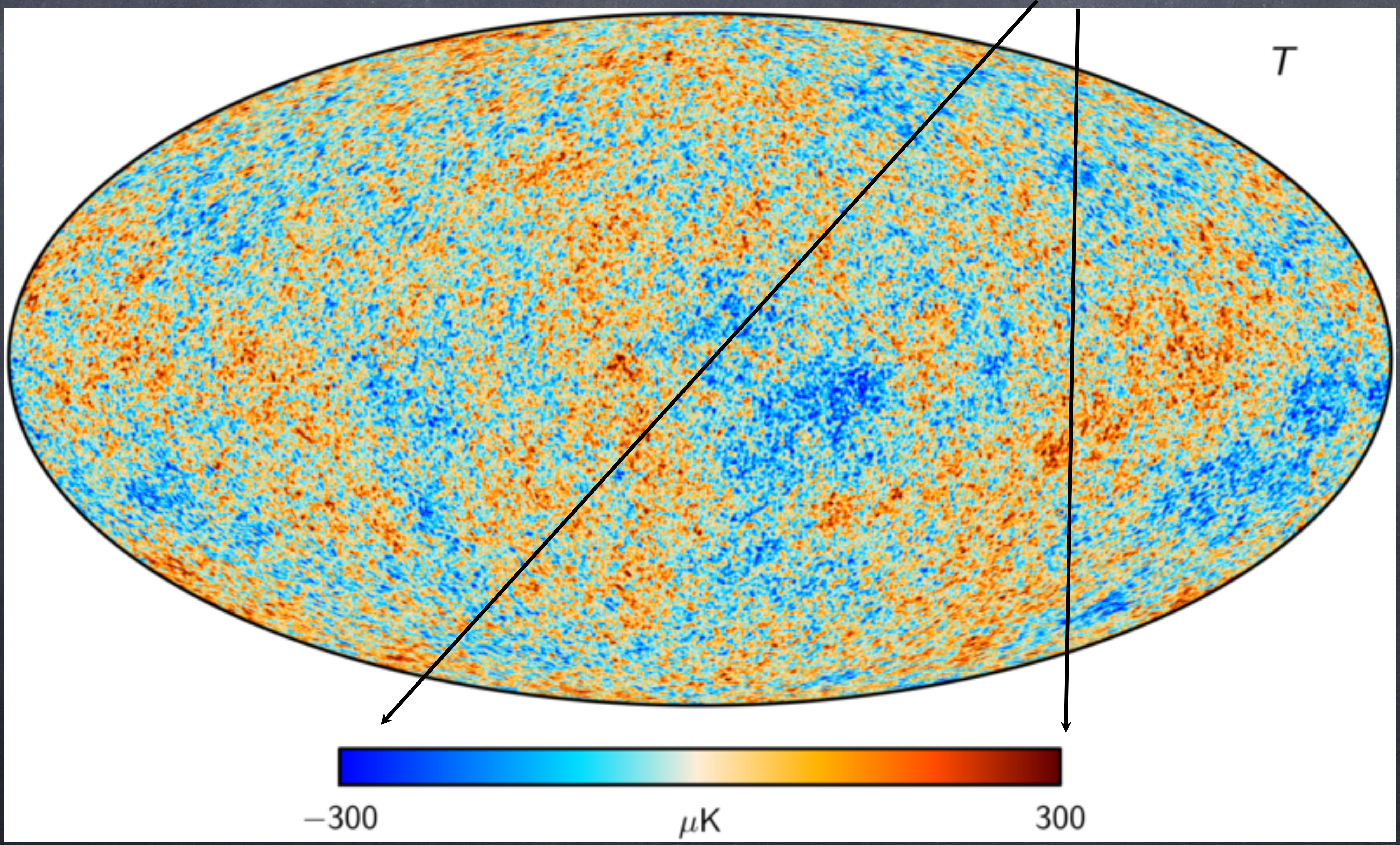
- *is not due to instrumental artifacts*
- *has exactly the spectrum of CMB anisotropy, so it is not due to foreground emission*
- The comparison also shows the *extreme sensitivity of cryogenic bolometers* operated at balloon altitude (the B03 map is the result of 5 days of observation)

From Paolo de Bernardis (lecture @ INPE's IV Advanced School)

Just for your curiosity...

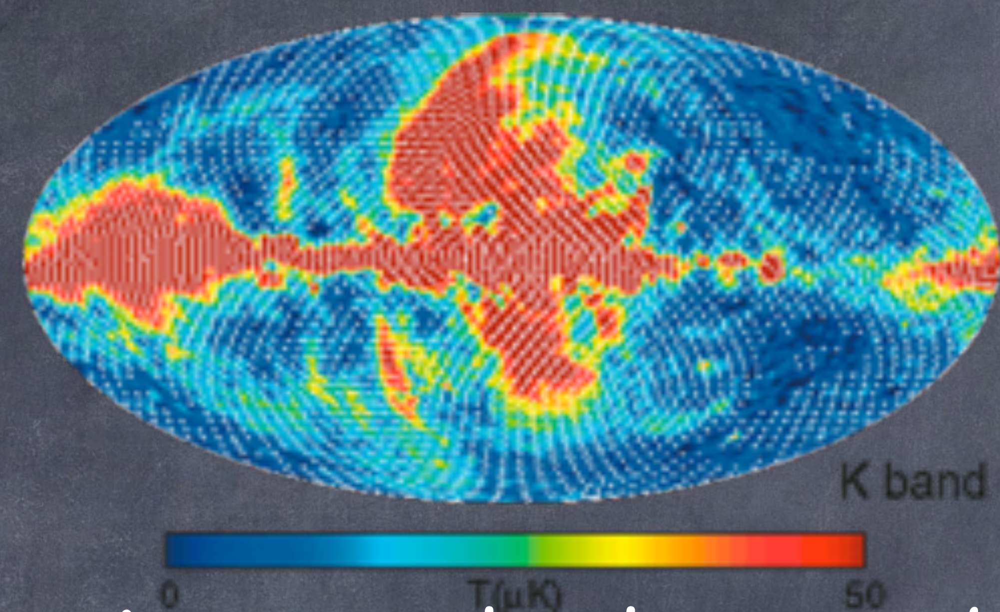
- Best determination of CMB temperature: T_{CMB} = 2.7255 +/- **0.0006** K (Fixsen et al., ApJ 2009)

- Temperature interval of a CMB anisotropy map: +/- **0.0003** K



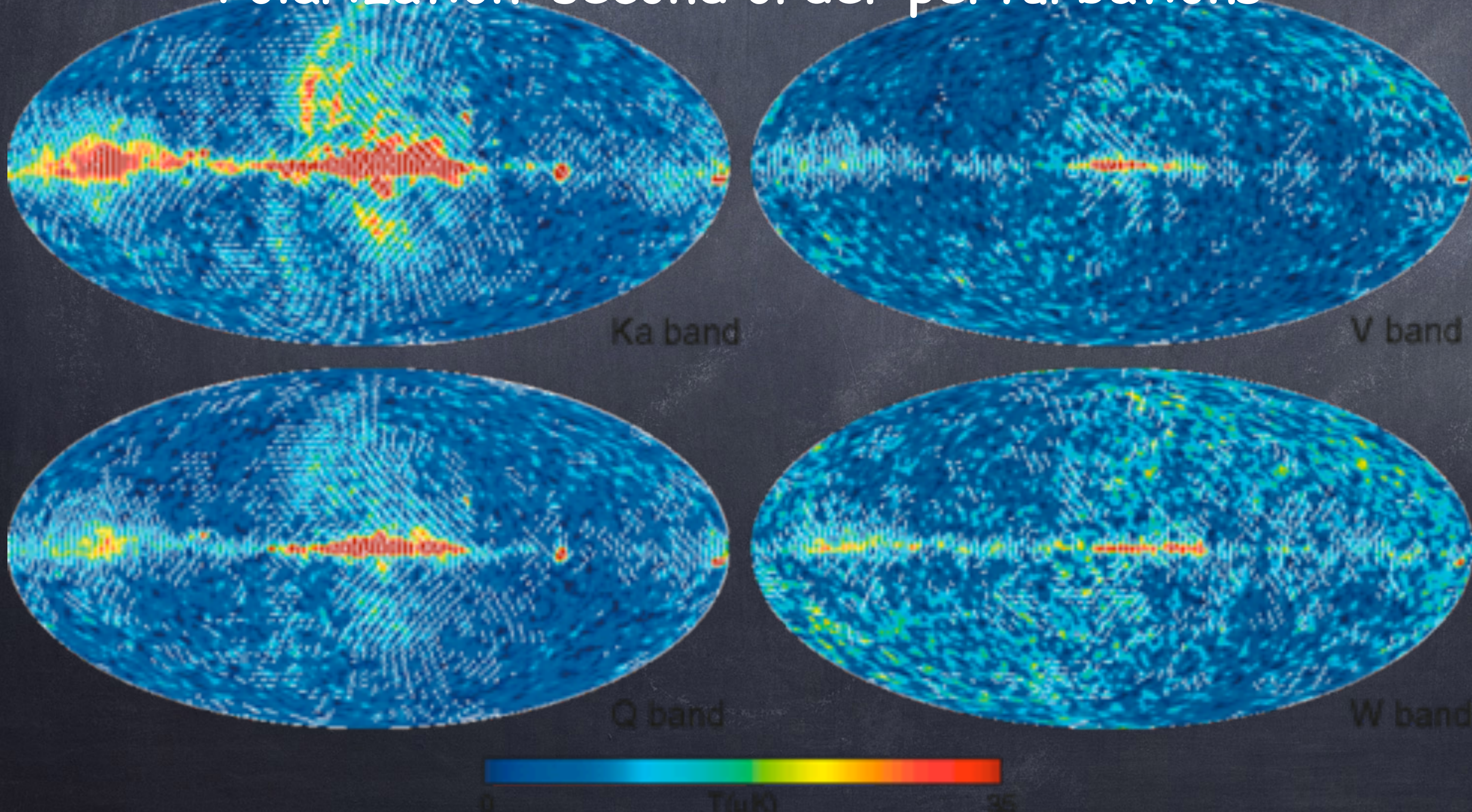
Source: https://wiki.cosmos.esa.int/planck-legacy-archive

CMB polarization



- Reionization
- Matter distribution in the LSS
- Primordial gravitational waves

Polarization: second order perturbations



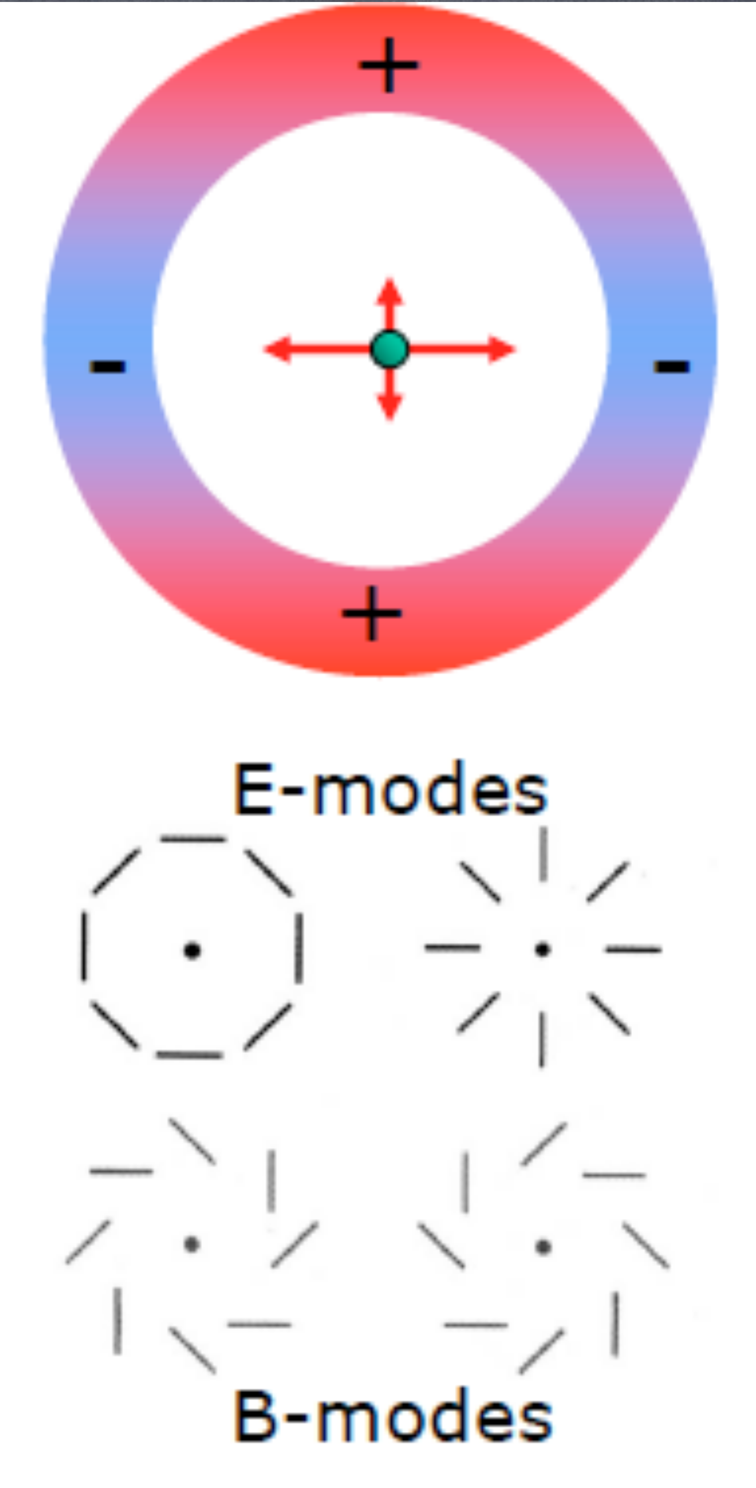
SCATTERING!!!!!

Why CMB polarization?

- An **inflation phase** at $E=10^{16}-10^{15}$ GeV ($t=10^{-36}-10^{-33}$ s) is currently the most popular scenario to explain
  - The origin of our universe
  - The geometry of our universe
  - The origin and morphology of structures in our universe
  - The lack of defects, and the smoothness of the CMB at super-horizon scales.
- Inflation is a **predictive** theory:
  1. Any initial curvature is flattened by the huge expansion: we expect an Euclidean universe.
  2. Adiabatic, gaussian density perturbations are produced from quantum fluctuations. This is the physical origin for structures in the Universe.
  3. The power spectrum of scalar perturbations is approximately scale invariant, $P(k)=Akn^{-1}$ with n slightly less than 1.
  4. Tensor perturbations produce a background of primordial gravitational waves (PGW)
- 4. can be tested measuring CMB polarization
- 1.,2.,3. have been confirmed already by measurements of CMB anisotropy

Why CMB polarization?

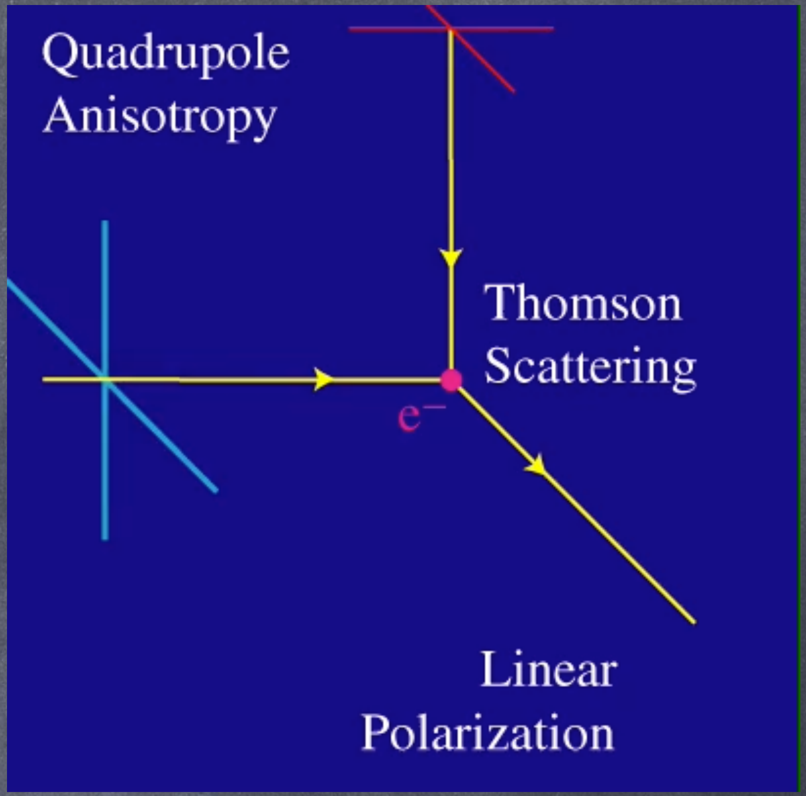
- Linear Polarization of CMB photons is induced via Thomson scattering by quadrupole anisotropy at recombination ($z=1100$, $t=1.2\times10^{13}$s).
- In turn, quadrupole anisotropy is induced by
  - Density perturbations (scalar relics of inflation) producing a curl-free polarization vectors field (**E-modes**)
  - Gravitational waves (tensor relics of inflation) producing both curl-free and curl polarization fields (**B-modes**)
- No other sources for a curl polarization field of the CMB at large angular scales:
- **B-modes are a clear signature of inflation.**



From Paolo de Bernardis (lecture @ INPE's IV Advanced School)

What can we learn from the CMB polarization?

- Polarization measurements
  - Thomson scattering produces LINEAR polarization
  - After scattering, only the quadrupolar component remains



- Different polarization modes produced by distinct processes
  - scalar → density perturbations
  - Vector → Vorticity in the primordial plasma (not observed in the standard model)
  - Tensor → primordial gravitational waves deform the potential wells

THESE ARE DEPENDENT ON THE CHOICE OF GAUGE

Polarization information not contained in the CMB data

- Direct evidence of primordial gravitational waves ⇒ B mode, r>0.01, a detection through polarization will be possible
- Reionization and star formation ⇒ large angular scales, $\theta \gtrsim 180/z_{reio} \sim 7^o$ (E mode only)
- CMB quadrupole when its photons crossed galaxy clusters ⇒ $a_{22}(z_{clust})$ (E-mde only) (Kamionkowksi & Loeb, PRL 1997)
- Hints of cosmic magnetic fields ⇒ circular polarization, V
- Mixing of E and B modes through weak lensing (parity break) ⇒ limits in neutrino masses (Kaplinghat et al., PRL 2003)

THE CMB SECONDARY FLUCTUATIONS

The Sunyaev-Zeldovich Effect

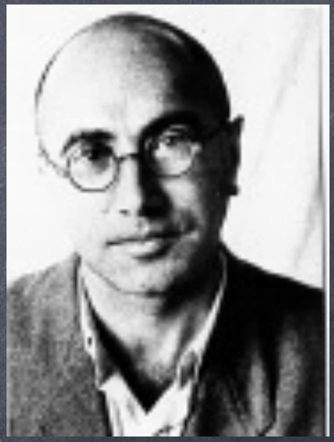
- It occurs when Cosmic Microwave Background (CMB) photons pass through intracluster regions where the gas reaches temperatures T ~ 10^7 – 10^8 K.

- There is no reduction in photon number during the cluster crossing, but a shift to higher energies.

- 1 in 100 CMB photons is scattered by electrons in the hot intracluster gas, via inverse Compton scattering.

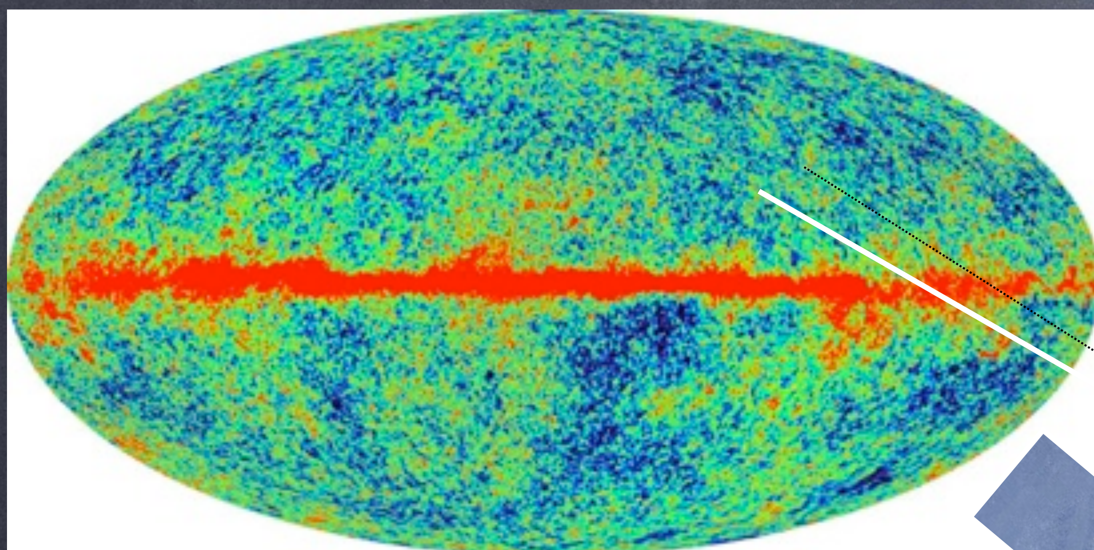
- Scattering distorts the CMB blackbody spectrum and is independent from the distance to the cluster.

Rachid SUNYAEV

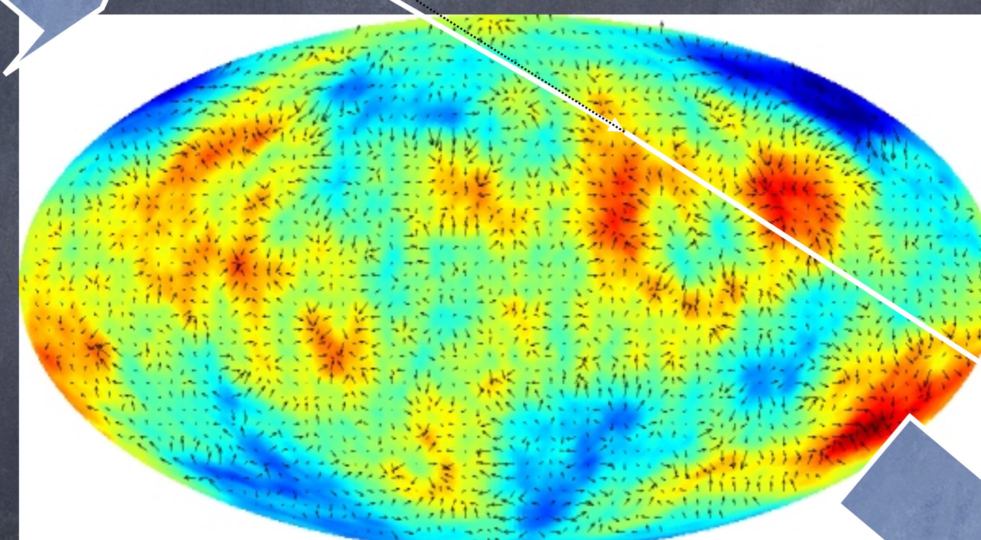


Yakob B. ZEL'DOVICH

Weak lensing of the CMB



Last scattering surface



Inhomogeneous universe
 - photons deflected

Observer

Slide from A. Lewis

Why is lensing important ?

- Act as a CMB contaminant, mainly changing primordial polarization
- Can also account for:
  - non-gaussianity (introduced by lensing distribution) ⇒ higher order statistics
  - statistical anisotropy (introduced by fixed distribution of lenses) ⇒ off-diagonal elements in the covariance matrix
  - **Change the CMB power spectrum at large l!!!**
- Useful to break parameter degeneracies and place better constraints on ω and ν energy budget

CMB Anomalies

- Inadequate statistical intepretation, according to WMAP team (Bennett et al., ApJ 2011)

- Anomalies were reported as REAL EFFECTS, according to the rest of the communityr (Bernui, Abramo, Andrade, Wuensche, Vielva, Luminet, Eriksen, Huterer, Paselski, Land, Magueijo...)

- Anomalies are real effects, but to a very small level of statistical significance (Planck 2018 papers)

- Interpretation of an "a priori likelihood", specially when the detection of a given event is optimized by the choice of analysis method is not "unbiased". **Recurring, complicated and hard to quantify (check Planck 2018 papers:**
  - **VII. Isotropy and statistics of the CMB**
  - **IX. Constraints on primordial non-Gaussianity**

Non-gaussianity

- ΛCDM does not predict NG effects
- WMAP estimator: the bispectrum

$$< \Phi_{k_1}, \Phi_{k_2}, \Phi_{k_3} >= (2\pi)^3 \delta^D(\vec{k}_1 + \vec{k}_2 + \vec{k}_3) F(\vec{k}_1, \vec{k}_2, \vec{k}_3)$$

- $F=F(P_\Phi, f_{NL}, k)$ are "local", "equilateral" and "orthogonal"
- WMAP result: $-306 < f_{NL} < +166$ (V+W, foreground marg.) - consistent with null hypothesis
- Planck should limit $|f_{NL}| < 3$

WMAP - Bennett et al ApJ, 2011

Planck 2018: IX. Constraints on primordial non-Gaussianity

What can still be done after Planck, SPT and ACT?

- Measure the intrinsic anisotropy to determine the high-l tail of the primary anisotropy and to search for intrinsic non-Gaussianity.

- Measure the gravitational lensing of the CMB. The CMB lensing field can be described by the detection field as $T_{obs}(n) = T_{int}(n + d)$ where T_{int} is the unlensed temperature field, n is the direction, and d is the detection field.

- Find clusters of galaxies through their SZ effect, determine the cluster redshifts with optical follow up, understand the mass selection function with a combination of SZ, optical, and X-ray measurements, and from the cluster catalog determine dN=dz or dN(> M)=dM [3].

- Correlate and compare the CMB with lower redshift cosmological measurements. In the most straightforward application, one uses the interaction of the CMB with lower redshift phenomena and from that determines the growth rate of structure.

Final remarks

- Polarization
  - large scale B-mode polarization from primordial gravitational waves:
    - energy scale of inflation
    - rule out most ekpyrotic and pure curvaton/ inhomogeneous reheating models and others
  - Small scale B-modes
    - Strong signal from any vector vorticity modes, strong magnetic fields, topological defects
- Weak lensing of CMB
  - B-modes potentially confuse primordial signals
  - Important correction to theoretical linear result
- The Sunyaev-Zeldovich Effect
  - Excellent tracer of mass distribution at high redshifts
  - Can be used to place strong constraints in Ω_M, Ω_Λ, σ_8

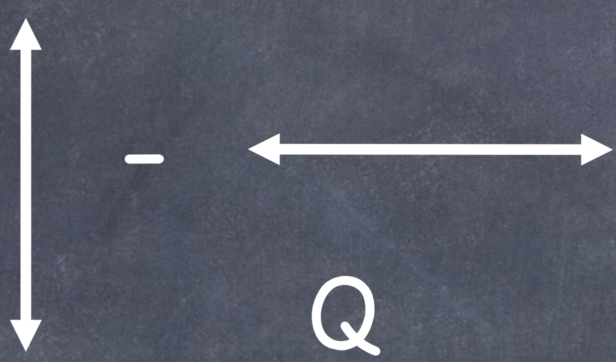
Final remarks

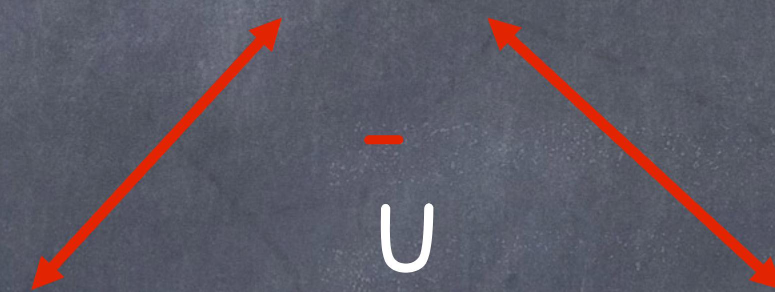
- CMB studies are one of the most interesting and rich fields of study to probe the early Universe. Precision cosmology: a CMB highlight, constraining many cosmological parameters and primordial perturbations
- **Deviations from gaussianity: small deviations** from standard, near scale-invariant, adiabatic primordial spectrum.
  - **Anomalies and power asymmetries are present** in the current CMB (space, balloon and ground-based) data
- **Polarization: E-mode and T-E cross-correlation** optical depth, constrain reionization and isocurvature modes
  - B-modes potentially confuse primordial signals
  - Important correction to theoretical linear results

- **B-mode polarization is the target for this decade, with ground instruments ongoing and under construction (BICEP, ACT, SPT, Simons Array, Simons Observatory) and a new ESA CoP for a new space mission. CMBPol/COrE is the main candidate**

End of Lecture 8

Polarization: Stokes' Parameters





Q → -Q, U → -U under 90 degree rotation

Q → U, U → -Q under 45 degree rotation

- Note that Stokes parameters refer explicitely to a given coordinate system, so **Q**(θ,φ) and **U**(θ,φ) maps in the sky depend **upon the choice of the coordinate system**. Under a rotation around the z-axis:

$$Q' = Q\cos(2\varphi) + U\sin(2\varphi)$$

$$U' = -Q\sin(2\varphi) + U\cos(2\varphi)$$

From Q, U to E, B

$$Q_f(\hat{z}) = \frac{3\sigma_T}{16\pi}\int d\Omega \sin^2\theta \cos(2\varphi)\, I_i(\theta,\varphi)$$

$$U_f(\hat{z}) = -\frac{3\sigma_T}{16\pi}\int d\Omega \sin^2\theta \sin(2\varphi)\, I_i(\theta,\varphi)$$

$$Q - iU \sim \int d\Omega\, Y_{22}(\theta,\varphi)\, I(\theta,\varphi)$$

Polarization depends upon the quadrupole of the incident radiation. It is convenient to write U, Q in terms of the complex function P:

$$P = Q - iU = \frac{3\sigma_T}{4\pi}\sqrt{\frac{2\pi}{15}}a_{22}$$

$$\Pi = E + iB$$

NOT invariant under rotation... We need to construct a new function, through quantum lowering operators, that is **invariant under rotation!**

- ***E*** (or ***G***) is the gradient mode
  → zero rotational
  → even under reflextion

- ***B*** (or ***C***) is the rotational mode
  □ zero gradiente
  □ odd under reflexion

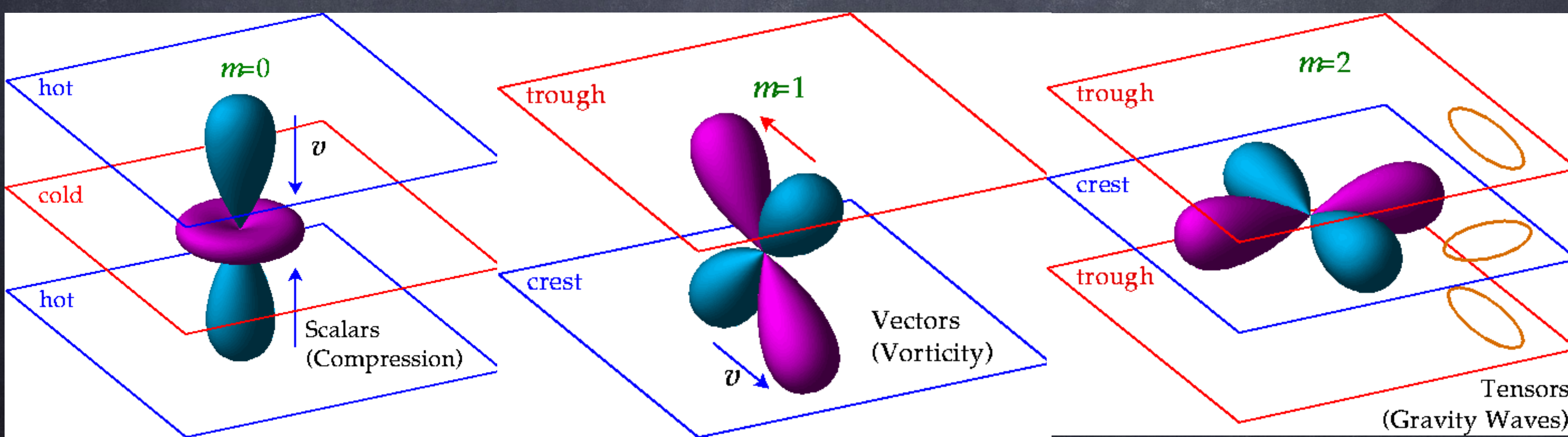
- Expand scalar P_E and P_B in spherical harmonics
- Expand P_{ab} in tensor spherical harmonics

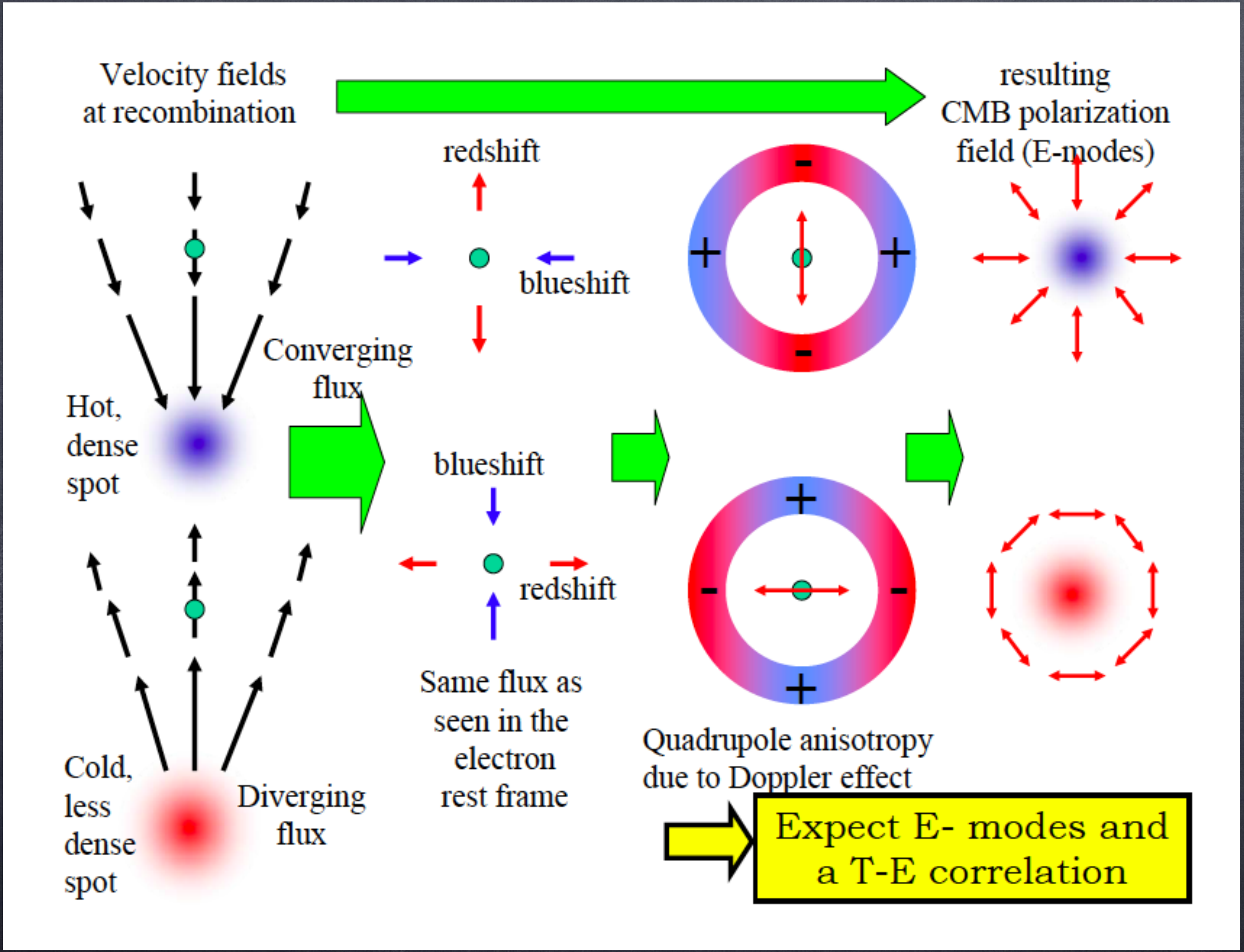
$$E_{lm} = \sqrt{2}\int_{4\pi} \mathrm{d}S\, Y^{G\,ab*}_{(lm)} \mathcal{P}_{ab}$$

$$B_{lm} = \sqrt{2}\int_{4\pi} \mathrm{d}S\, Y^{C\,ab*}_{(lm)} \mathcal{P}_{ab}$$

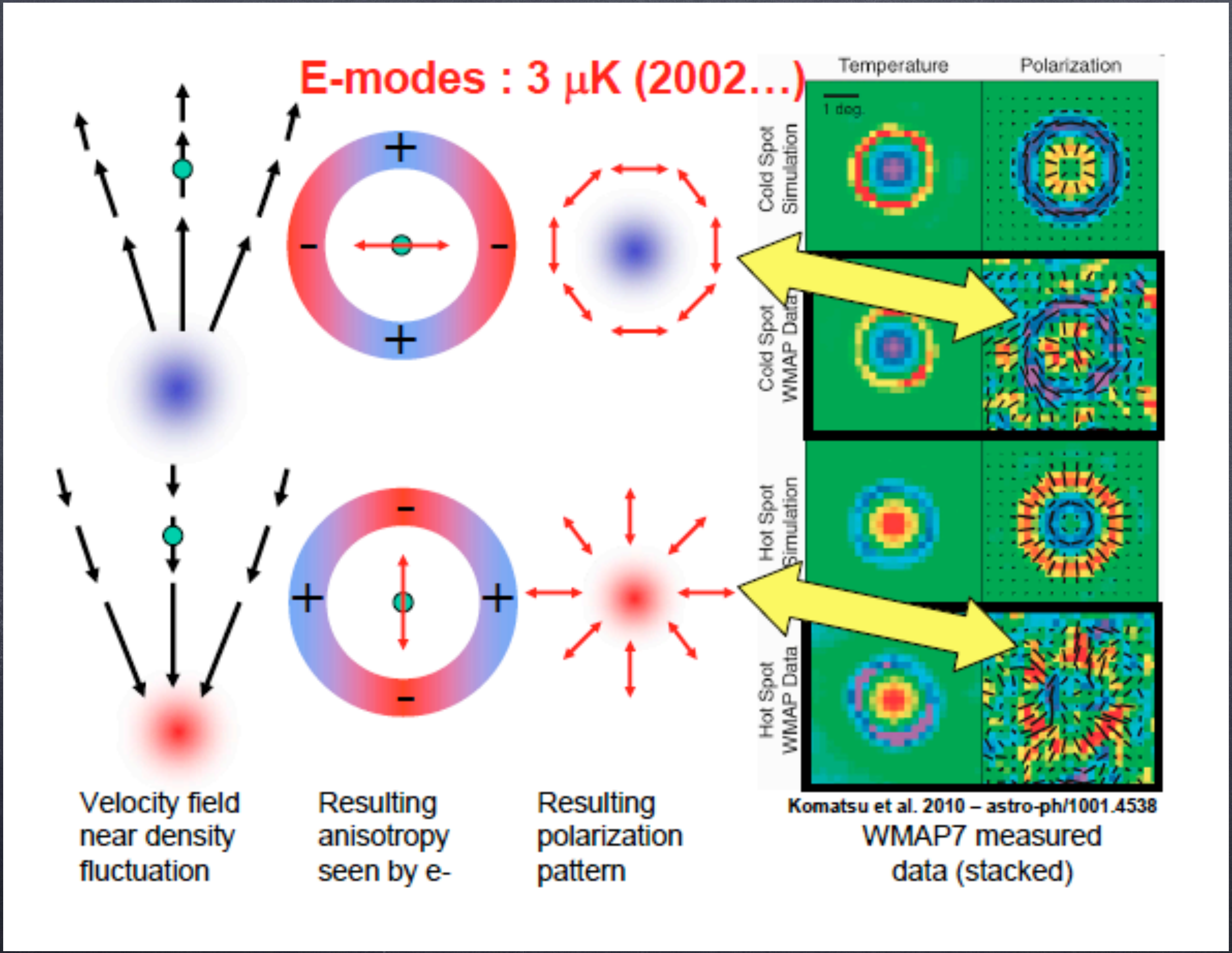
$$\mathcal{P}_{ab} = \frac{1}{\sqrt{2}} \sum_{lm} \left(E_{lm}\, Y^{G}_{(lm)ab} + B_{lm}\, Y^{C}_{(lm)ab} \right)$$

Figures by Wayne Hu
(http://background.uchicago.edu/~whu/intermediate/Polarization/





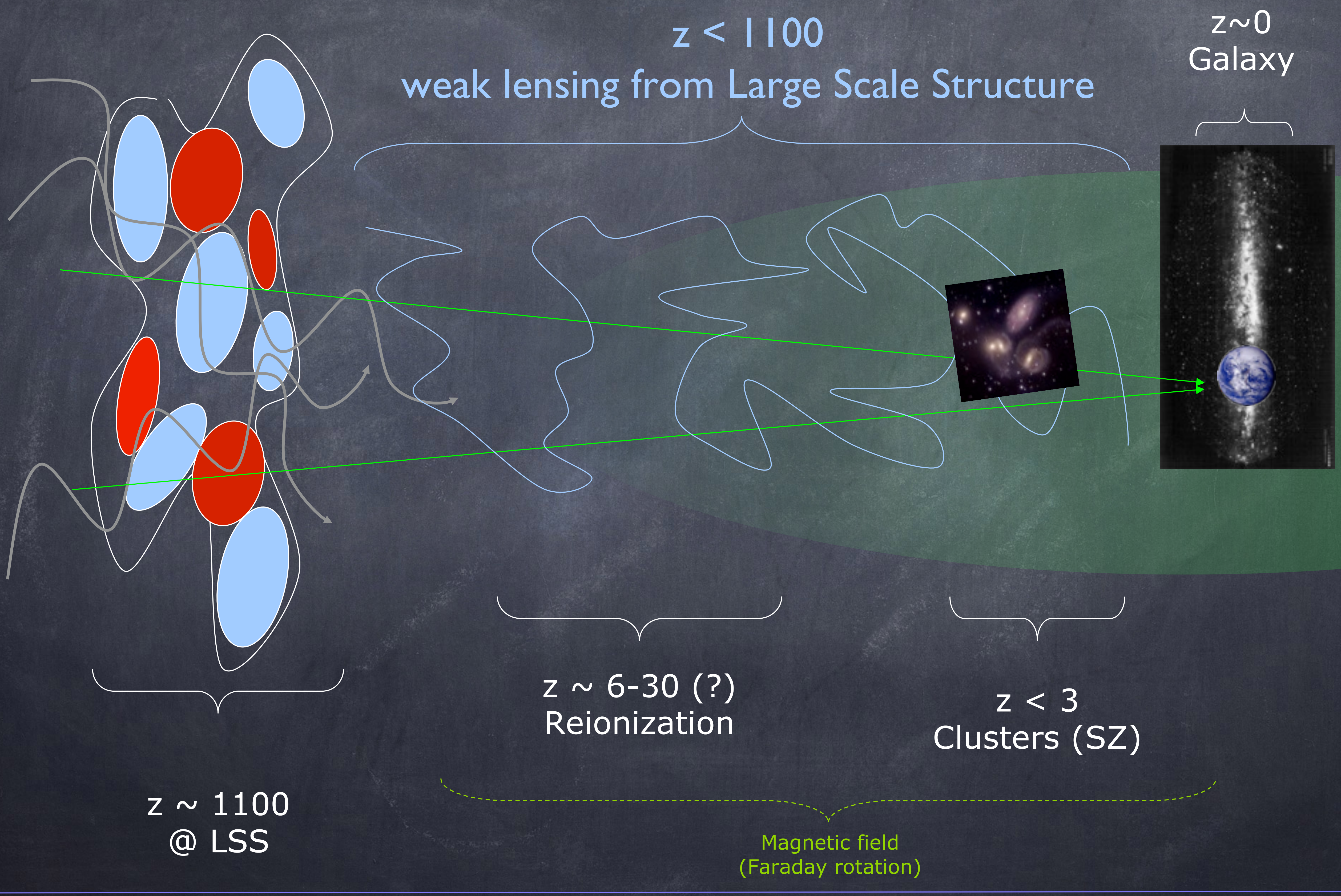
From Paolo de Bernardis (lecture @ INPE's IV Advanced School)



From Paolo de Bernardis (lecture @ INPE's IV Advanced School)

Primary/secondary sources of polarization: free e-, with a given optical depth for Thomson scattering:

$$d\tau = \sigma_T \, n_e \, d\eta$$



Slide from Raul Abramo

Primordial B modes

- The amplitude of this effect is very small, but depends on the Energy scale of inflation. In fact the amplitude of tensor modes normalized to the scalar ones is:

$$R = \left(\frac{T}{S}\right)^{1/4} \equiv \left(\frac{C_2^{GW}}{C_2^{Scalar}}\right)^{1/4} \cong \frac{V^{1/4}}{3.7\times 10^{16}\,\mathrm{GeV}}$$

Inflation potential

- and

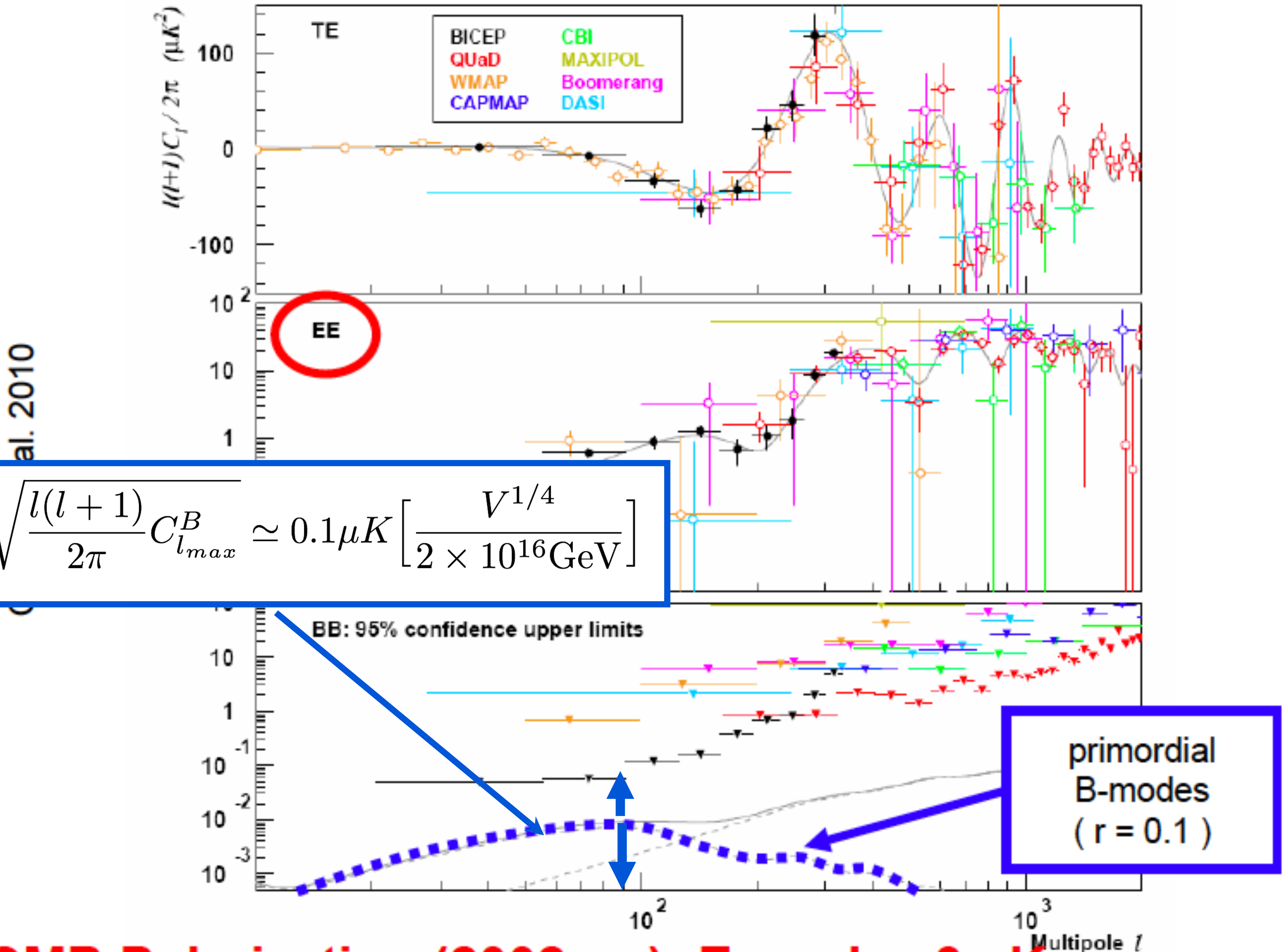
$$\sqrt{\frac{\ell(\ell+1)}{2\pi} c^{B}_{\ell\max}} \cong 0.1\mu K\left[\frac{V^{1/4}}{2\times 10^{16}\,\mathrm{GeV}}\right]$$

- There are theoretical arguments to expect that the energy scale of inflation is close to the scale of GUT i.e. around 10^{16} GeV.
- The measurement of B-modes is a good way to investigate fundamental physics at extremely high energies.

From Paolo de Bernardis (lecture @ INPE's IV Advanced School)

B-modes and lensing of E-modes

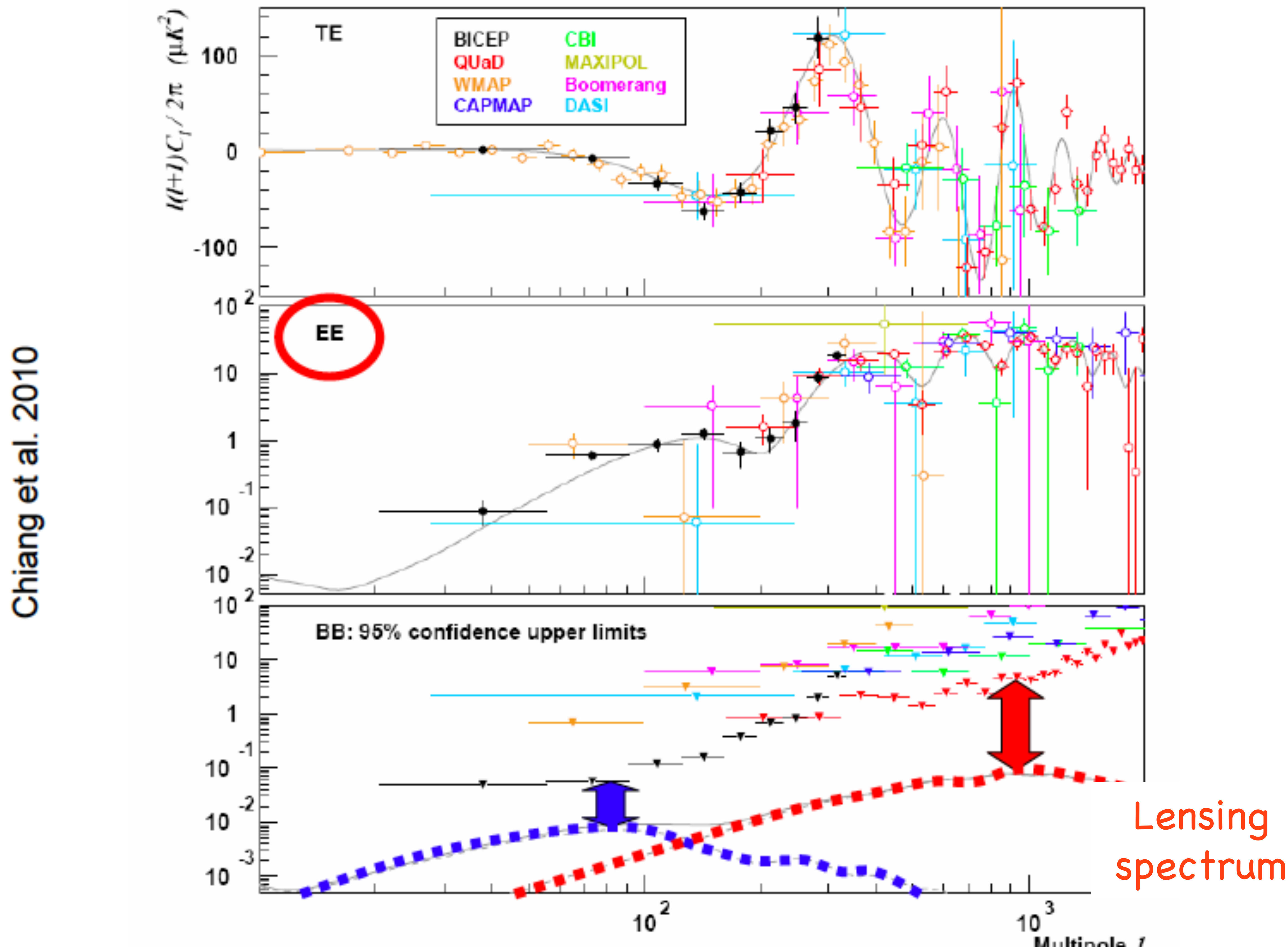
- E-modes have been measured already with good accuracy, and will be measured with exquisite accuracy by Planck and other experiments.
  - They depend on the distribution of mass (mainly dark matter) so their study can shed light on the nature of dark matter (including massive neutrinos).
- While the primordial B-mode is maximum at multipoles around 100 (θ=2°), the lensed B-mode is maximum at multipoles around 1000 (θ=0.2°), requiring high angular resolution polarization experiments



$$\sqrt{\frac{l(l+1)}{2\pi} C^B_{l_{max}}} \simeq 0.1 \mu K \left[\frac{V^{1/4}}{2 \times 10^{16} \mathrm{GeV}} \right]$$

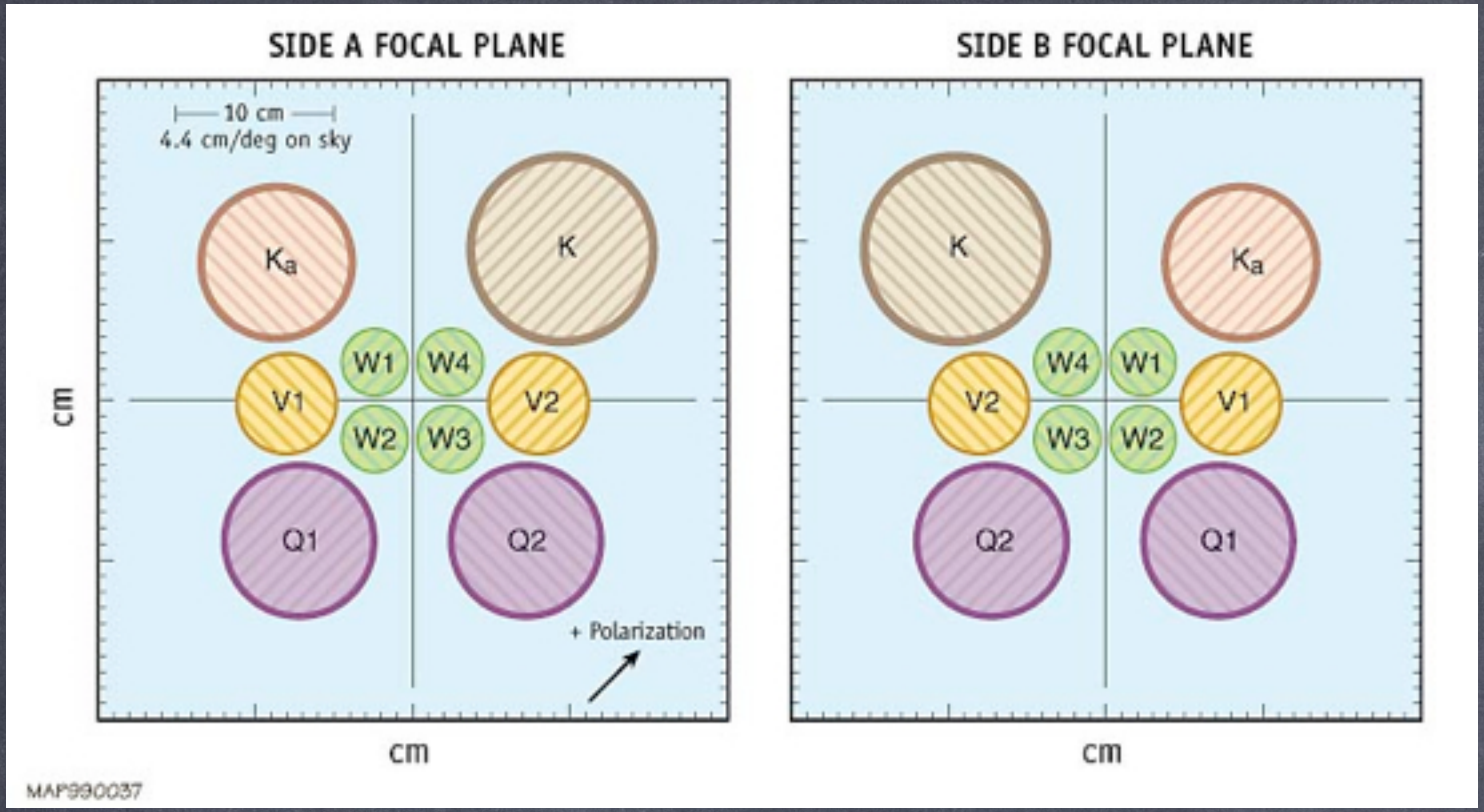
CMB Polarization (2002 …): E-modes 3 μK

From Paolo de Bernardis (lecture @ INPE's IV Advanced School)



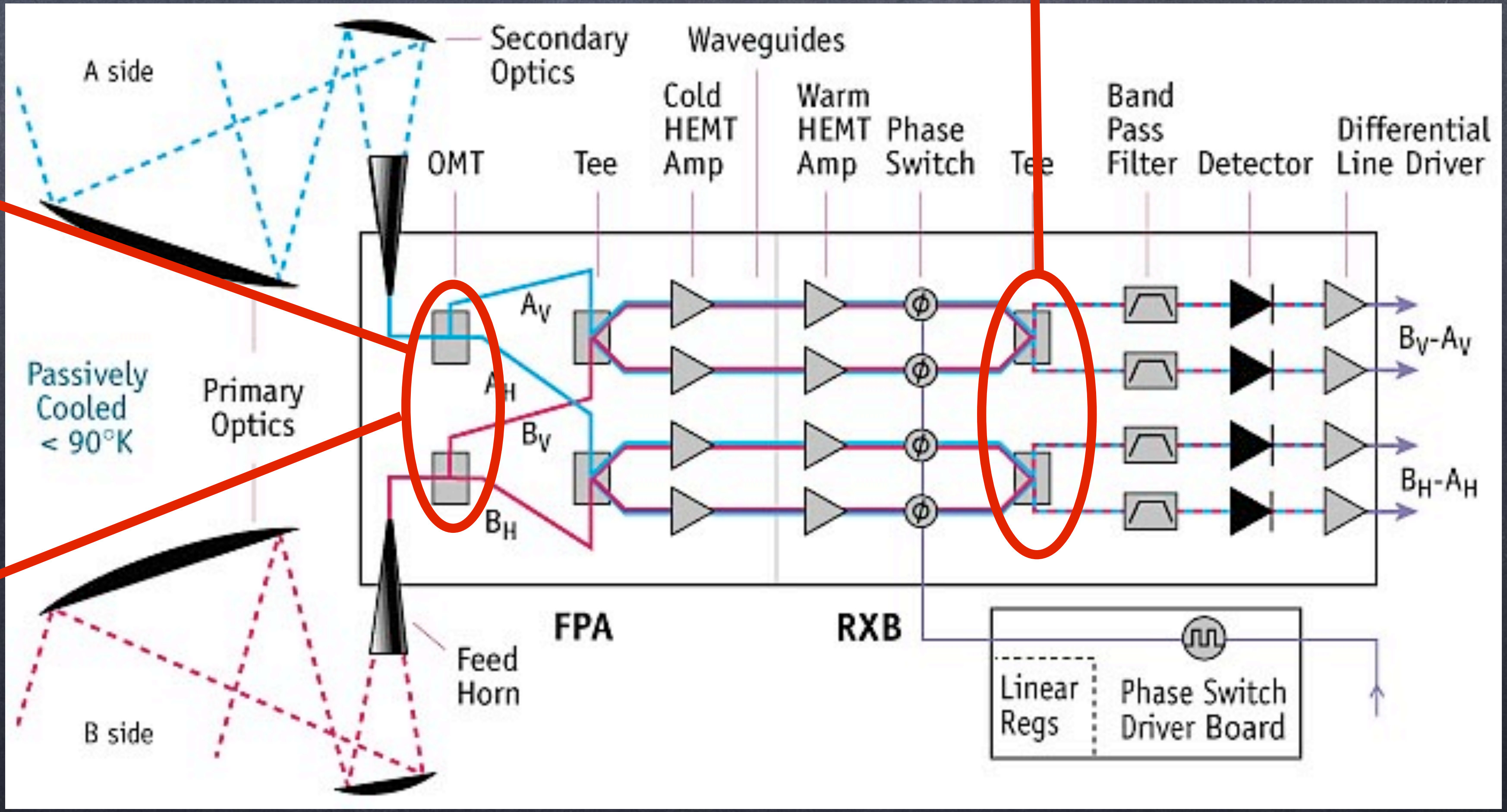
CMB Polarization (2002 …): E-modes 3 μK

From Paolo de Bernardis (lecture @ INPE's IV Advanced School)



Differencing occurs here

OMT splits the signal into 2 polarizations



A+B′/sqrt(2) and A−B′/sqrt(2)

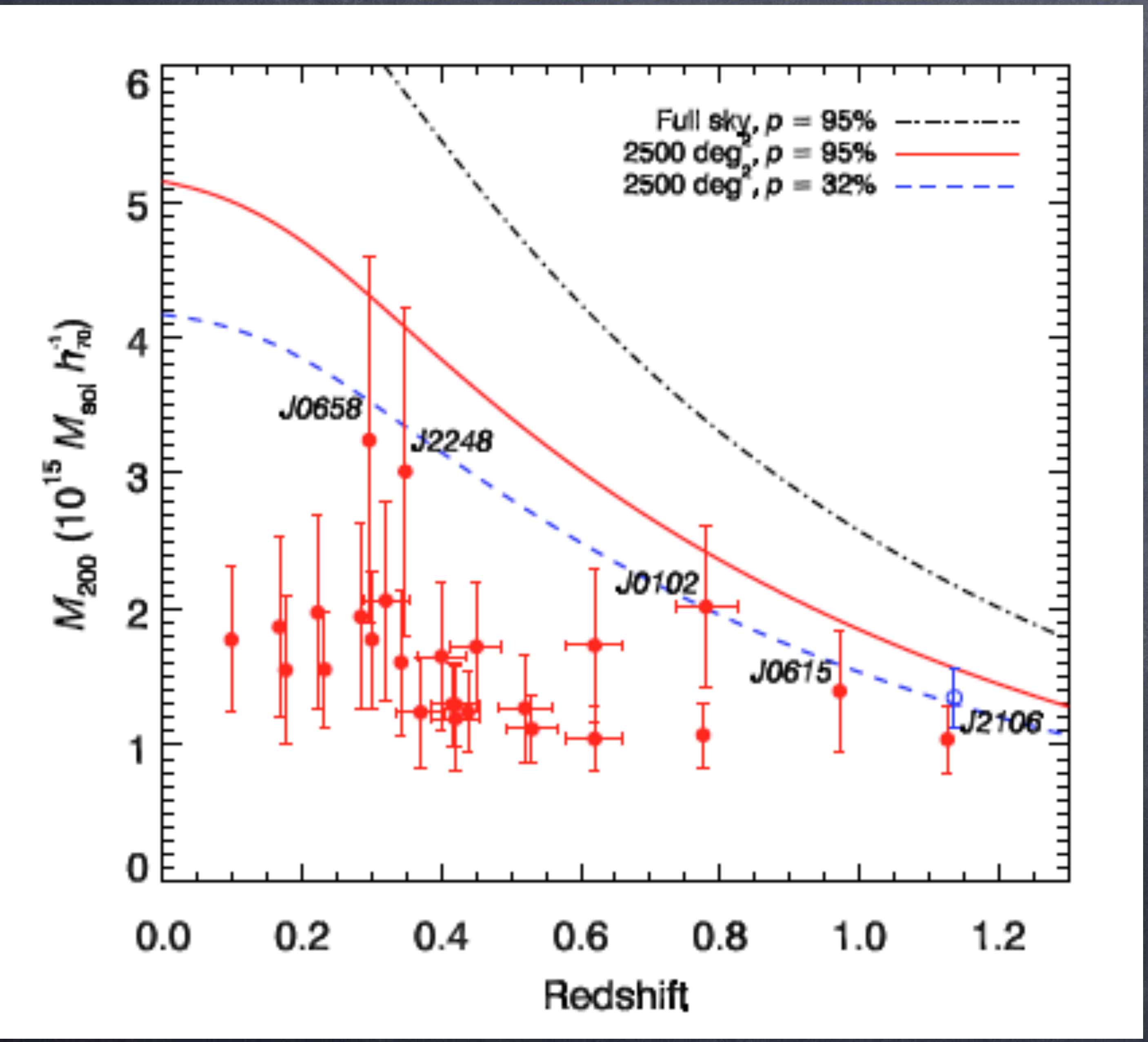
Primordial Perturbations: fluid at redshift < 10^9

- Photons
- Nearly massless neutrinos
  Free-streaming (no scattering) after neutrino decoupling at z 10^9
- Baryons + electrons

tightly coupled to photons by Thomson scattering

- Dark Matter
  Assume cold. Coupled only via gravity.
- Dark energy
  probably negligible early on

Tests of Lambda-CDM and non-gaussianity



- The 26 most significant clusters over full 2500 deg2 SPT survey.

  - Tests extreme tail of matter power spectrum (high-mass, high-redshift clusters)

  - Even a single massive cluster could indicate tension with λCDM (Mortonson, Hu, Huterer 2010).

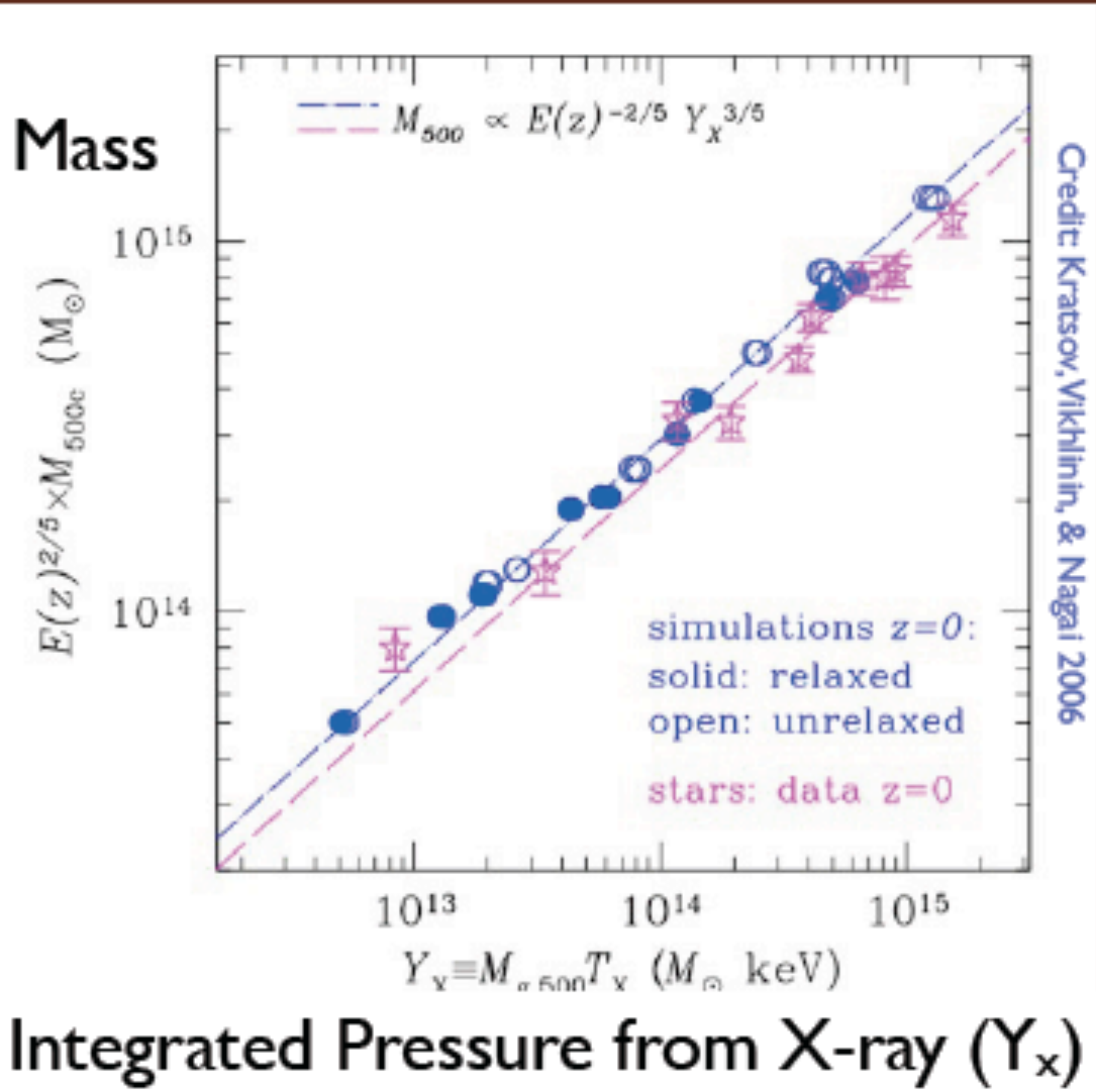
We find:

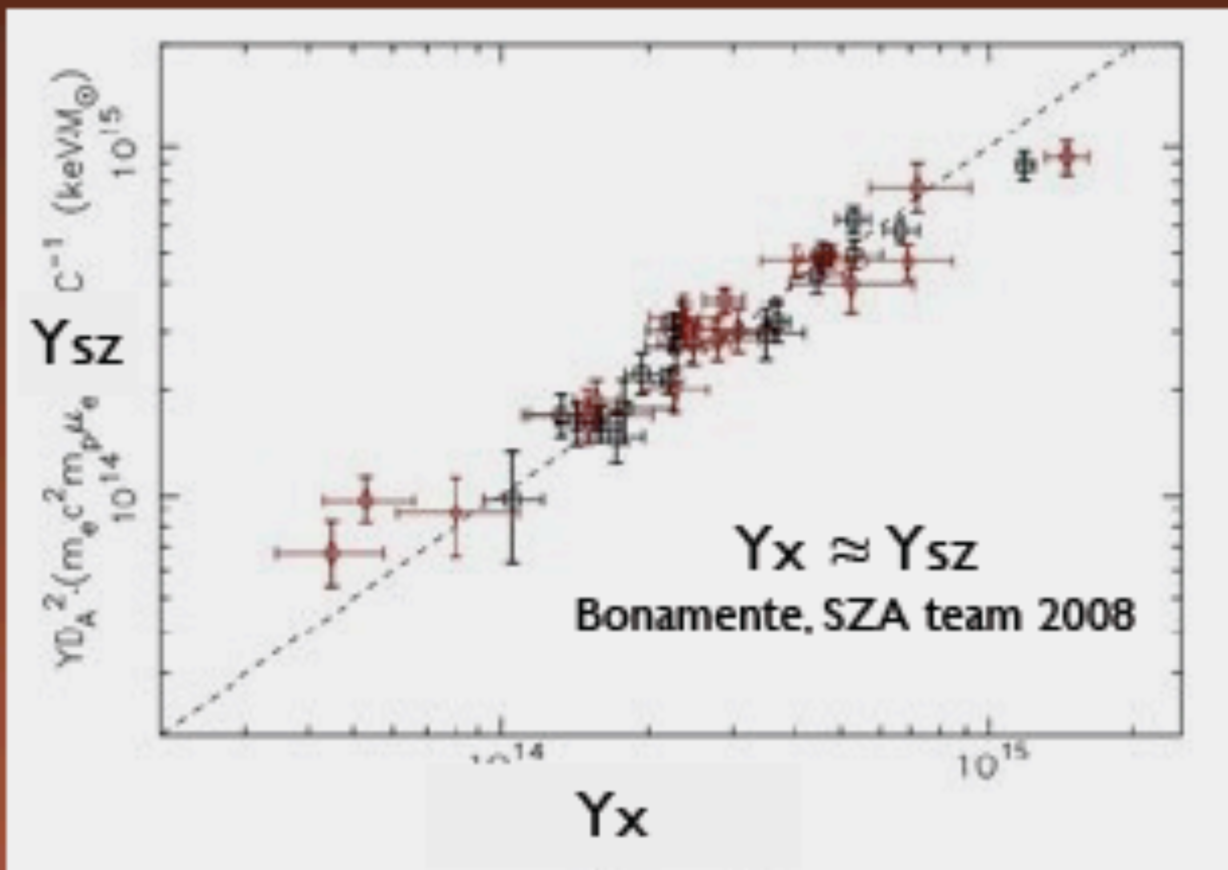
- consistent with λCDM
- consistent with initial Gaussian density fluctuations

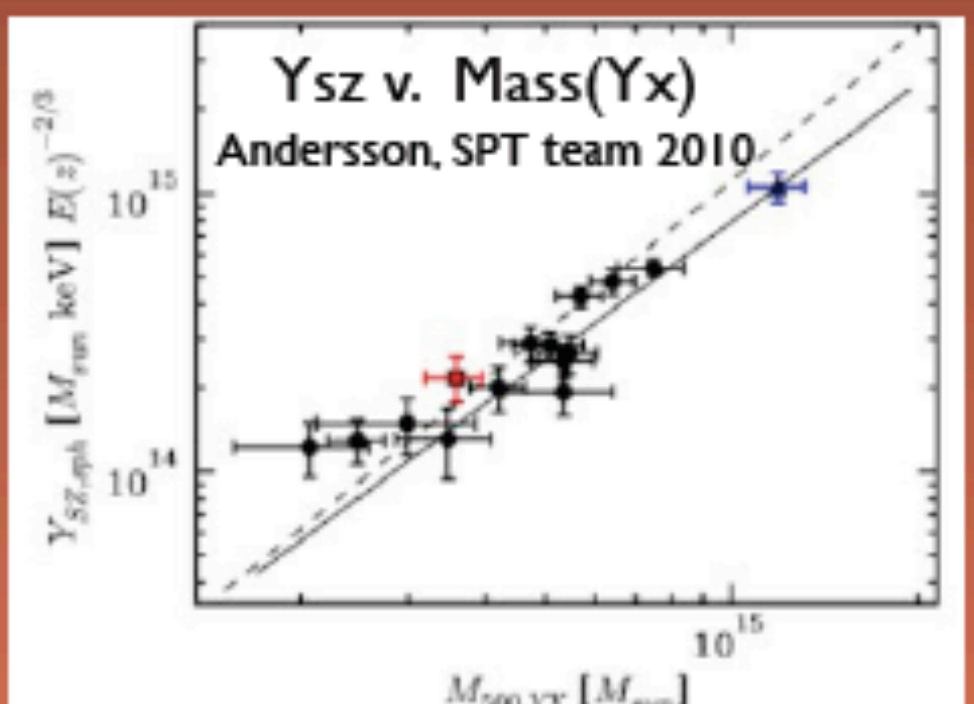
Williamson et al. ApJ 2011

slide from John Carlstrom

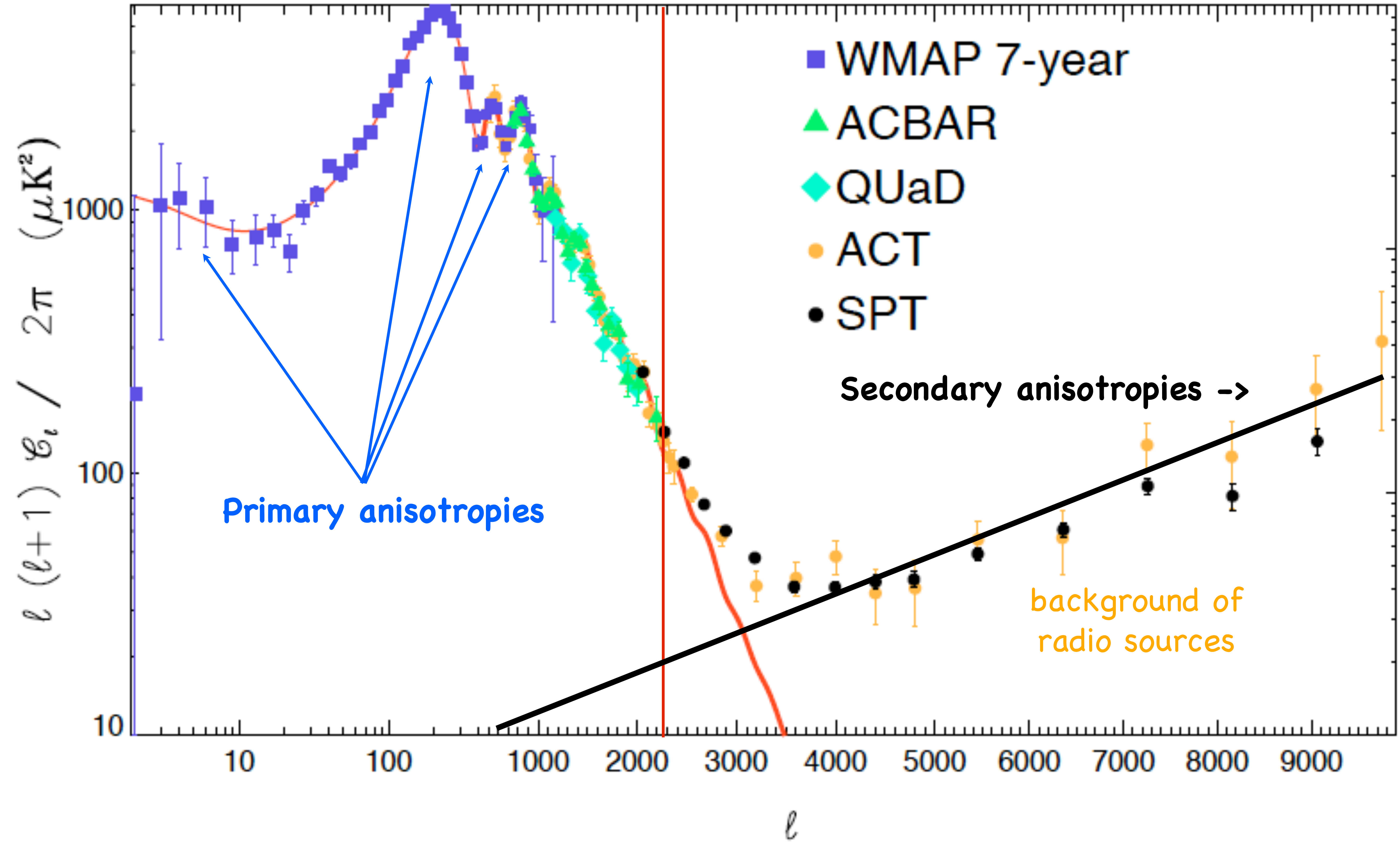
Cluster Gas Pressure is a "Clean" Mass Estimator







Simulations predict ~7 pct scatter in cluster total mass vs integrated pressure (Yx or Ysz)



WMAP 7-year
ACBAR
QUaD
ACT
SPT
Secondary anisotropies ->
Primary anisotropies
background of radio sources
1000
100
10
10
100
1000
2000
3000
4000
5000
6000
7000
8000
9000
ℓ
$\ell(\ell+1)\,\mathcal{C}_\ell\,/\,2\pi\;(\mu K^2)$

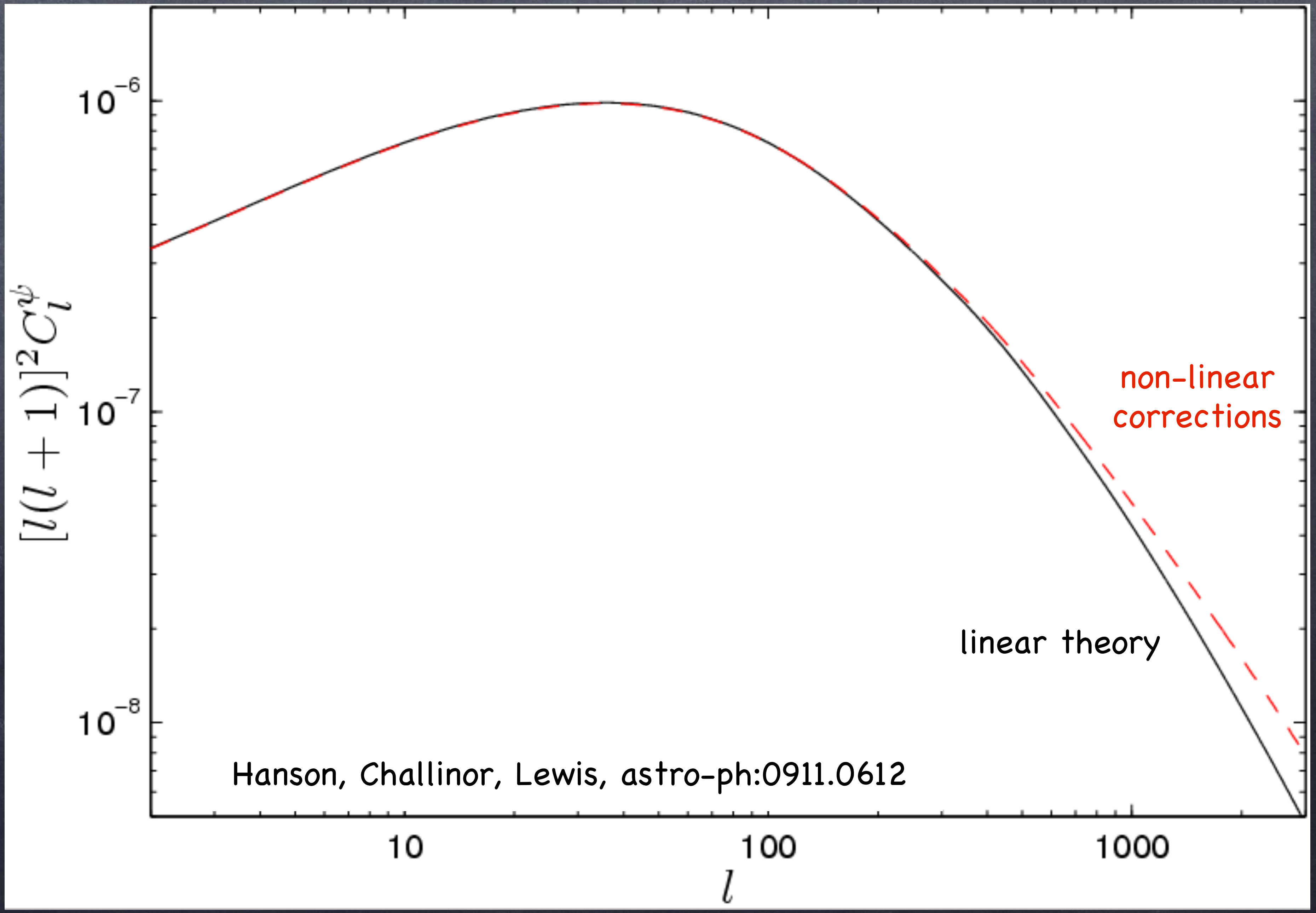
Lensing Potential

$$\tilde{T}(\vec{x}) = T(\vec{x} + \alpha(\vec{x}))$$
$$[\tilde{Q} \pm i\tilde{U}](\vec{x}) = [\tilde{Q} \pm i\tilde{U}](\vec{x} + \alpha(\vec{x}))$$

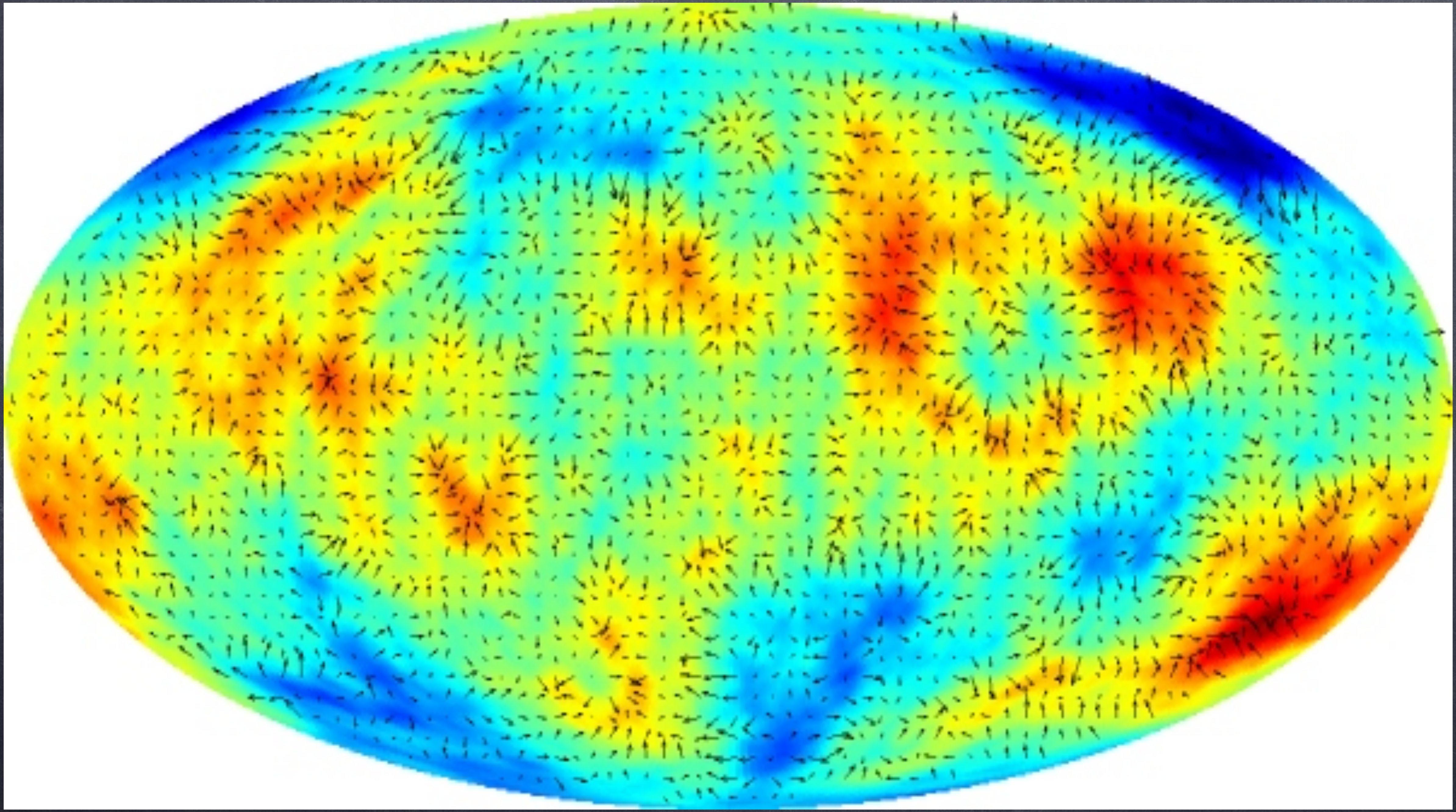
Field of deflection vectors

$$\alpha(\vec{x})) = -2\int_0^{\chi_*} d\chi \frac{\chi_* - \chi}{\chi_*} \nabla_\perp \Phi(\chi\vec{x}; \eta_0 - \chi)$$

- LSS can be thought of as a collection of potential wells acting as point sources for lensing
- Deflections $O(10^{-4})$, or 2′, but coherent on degree scales → important!

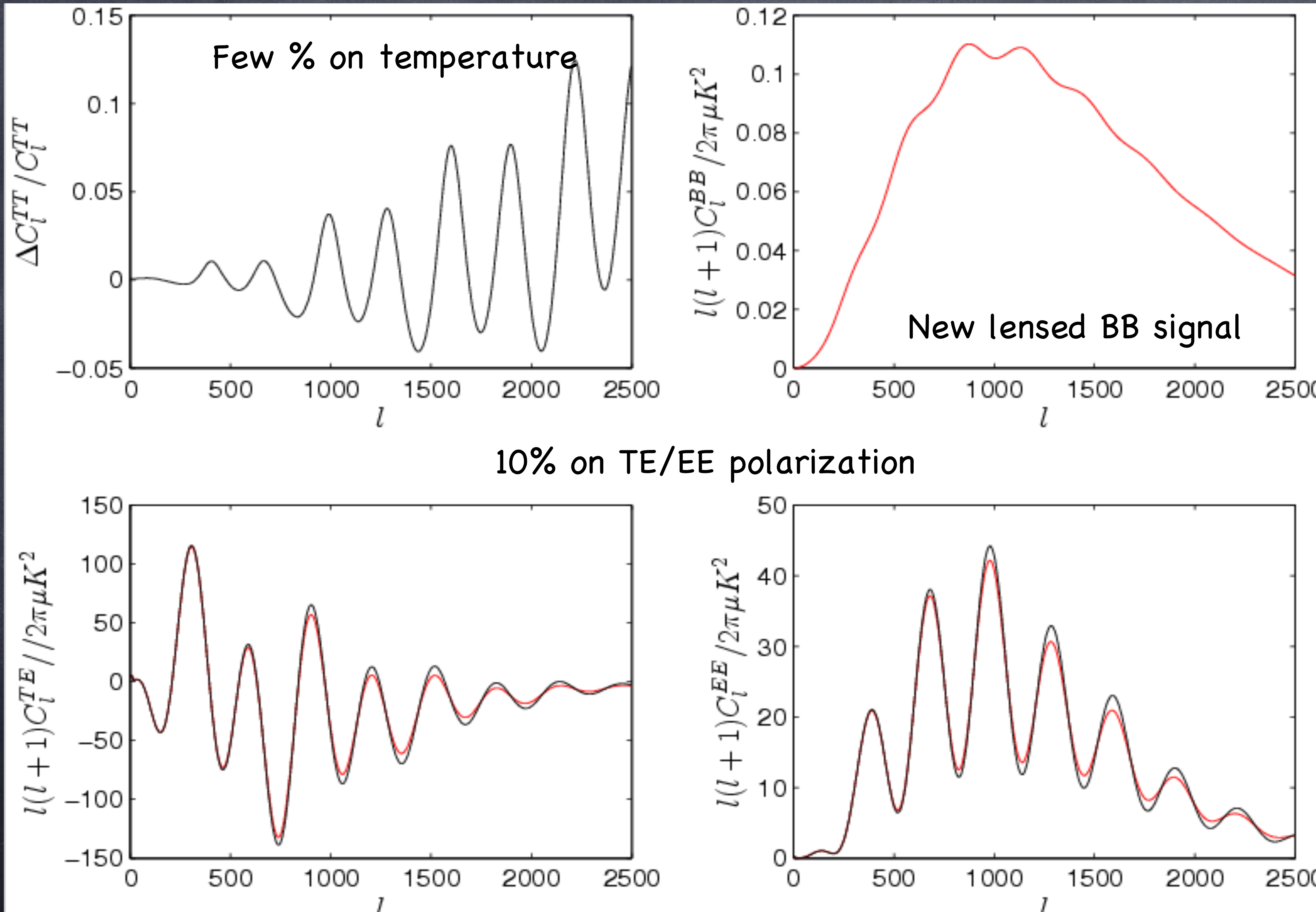


Lensing potential and deflection angles



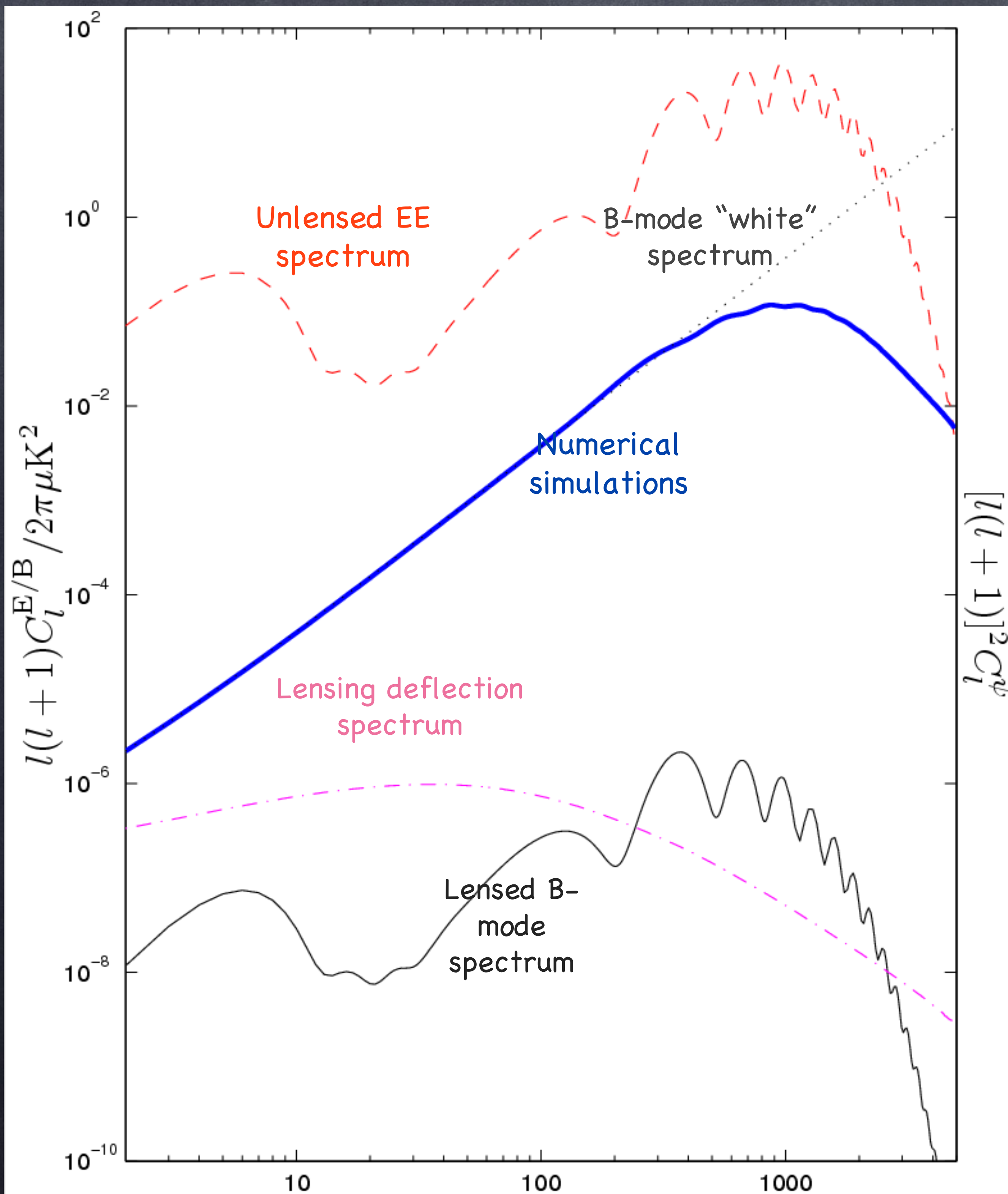
LensPix sky simulation code:
http://cosmologist.info/lenspix

Lensed CMB power spectra



Slide from A. Lewis

Lensing of CMB polarization



Hanson, Challinor, Lewis, astro-ph:0911.0612

Nearly white BB spectrum on large scales

Potential confusion with tensor modes

Leakage from E to B-modes

Lensing effect can be largely subtracted if only scalar modes + lensing present, but approximate and complicated (especially posterior statistics).

Hirata, Seljak : astro-ph/0306354
Okamoto, Hu: astro-ph/0301031

WEAK-LENSING MASS MEASUREMENTS OF FIVE GALAXY CLUSTERS IN THE SOUTH POLE TELESCOPE SURVEY USING MAGELLAN/MEGACAM

arXiV:1205.3103

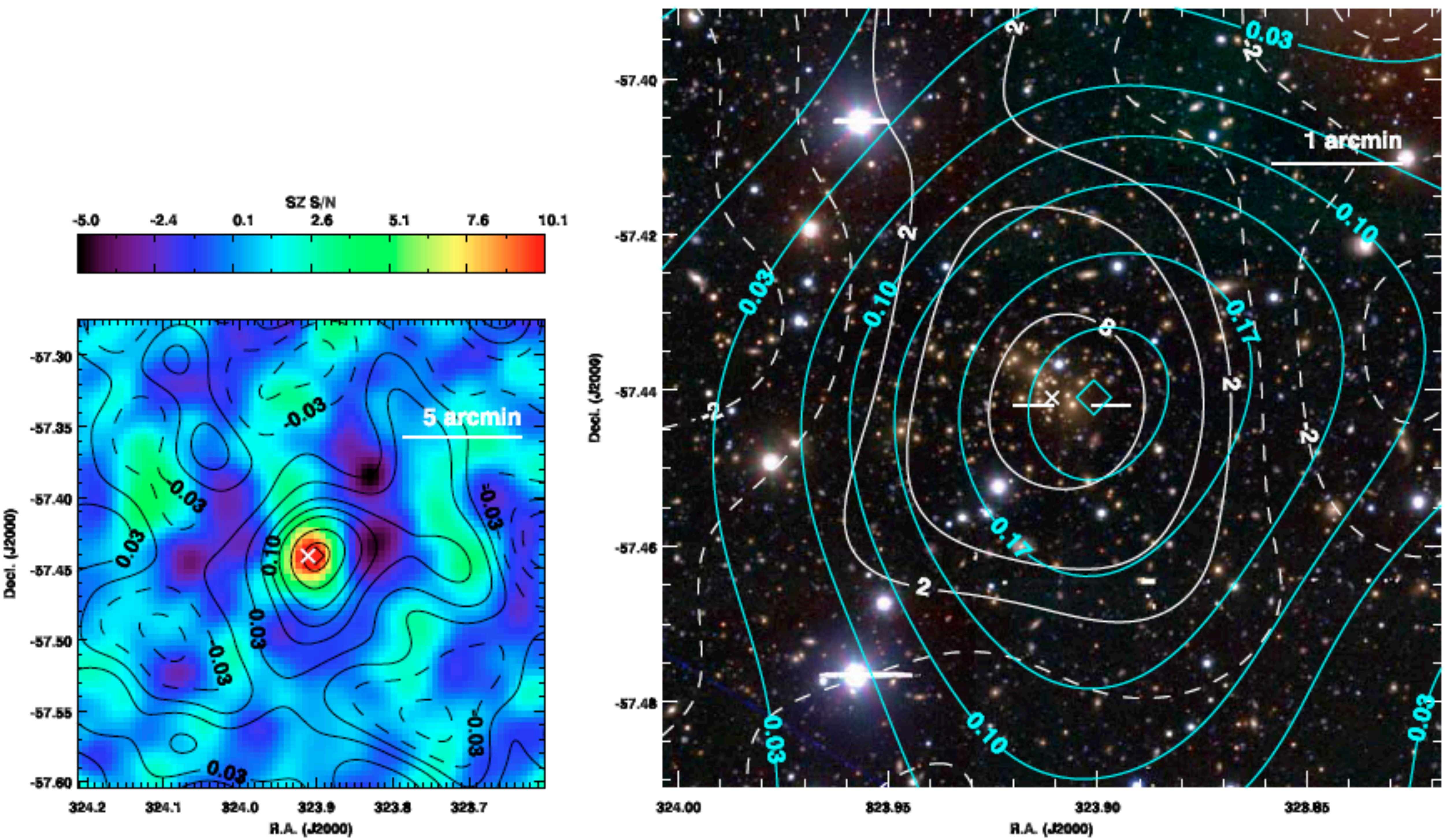
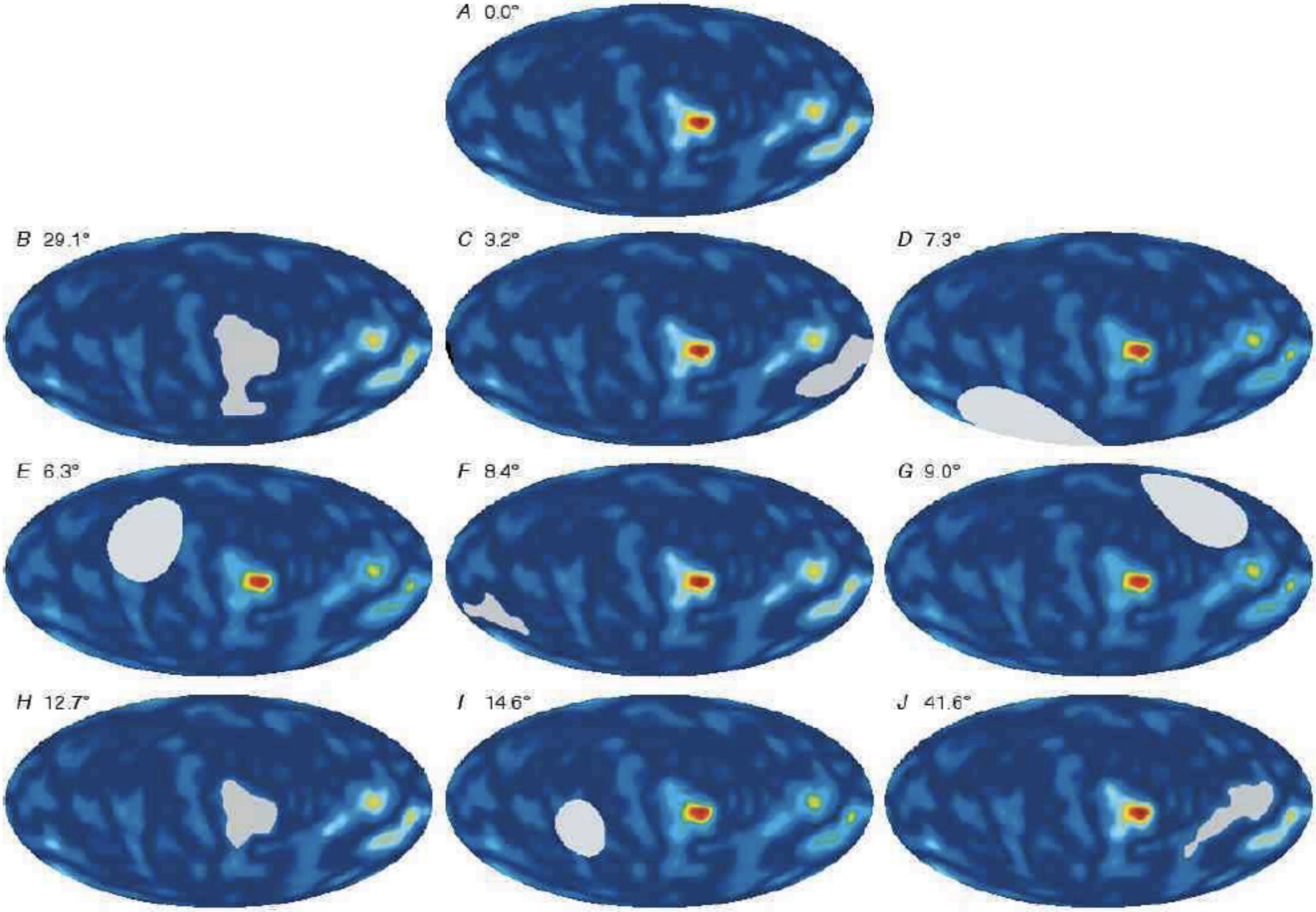


Fig. 16.— SZ, optical, and κ data for SPT-CL J2135-5726. See Section A for a description.


A 0.0°
B 29.1°
C 3.2°
D 7.3°
E 6.3°
F 8.4°
G 9.0°
H 12.7°
I 14.6°
J 41.6°

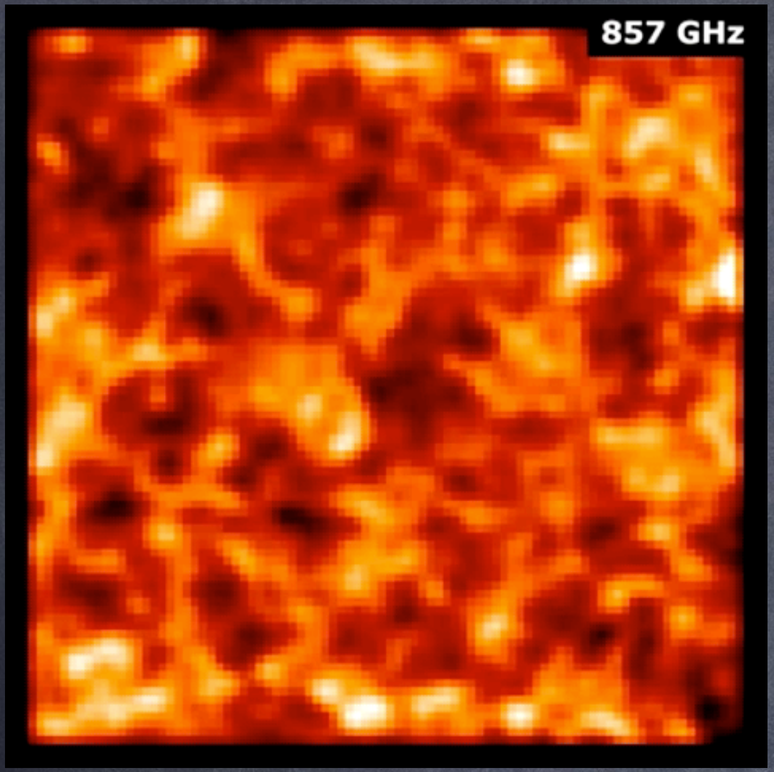
Limitations?

- Foregrounds understanding limits:
  - Polarization measurements ⇨ synchrotron and dust emission can be > 70% polarized
  - SZ measurements ⇨ limited by our ability to measure the X-ray flux of extragalactic radio sources and by distortions caused by lensing
  - CMB lensing ⇨ can be limited by SZ and the residual radio background
- CMB lensing and SZ can hamper each other measurements

Science with Planck

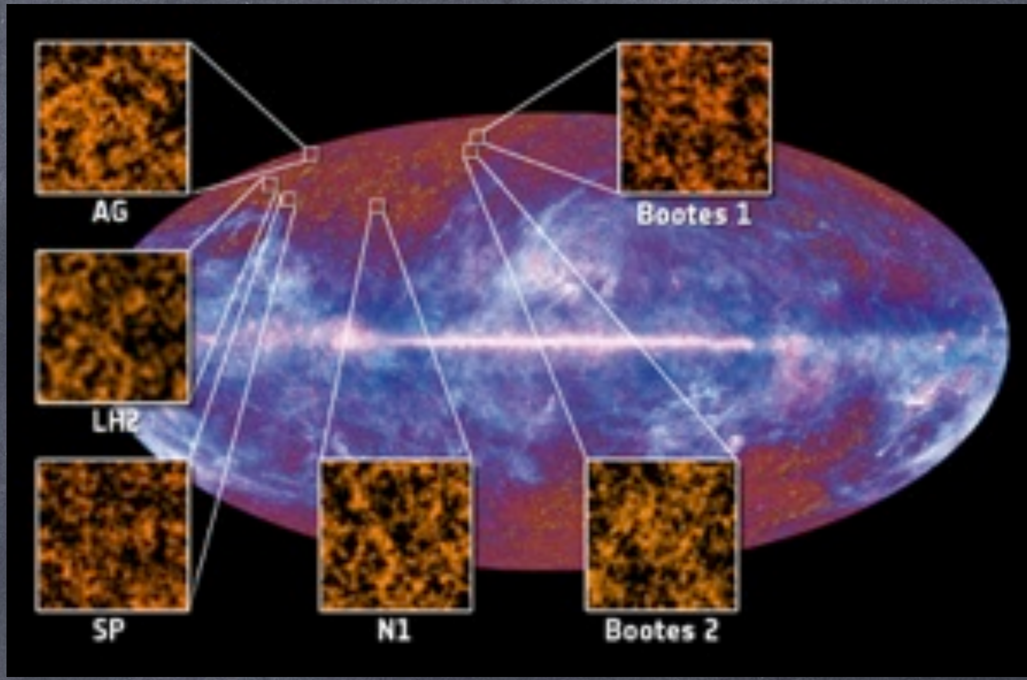
- Determine the large scale properties of the Universe with highest precision
- Test inflation and search for primordial gravitational waves
- Search for defects in the space-time and non-gaussian signatures in the otherwise Gaussian CMB distribution
- Study the origin of present-day large scale structures
- Study our Galaxy (and other galaxies) in microwave and submillimeter

Planck results (no CMB)

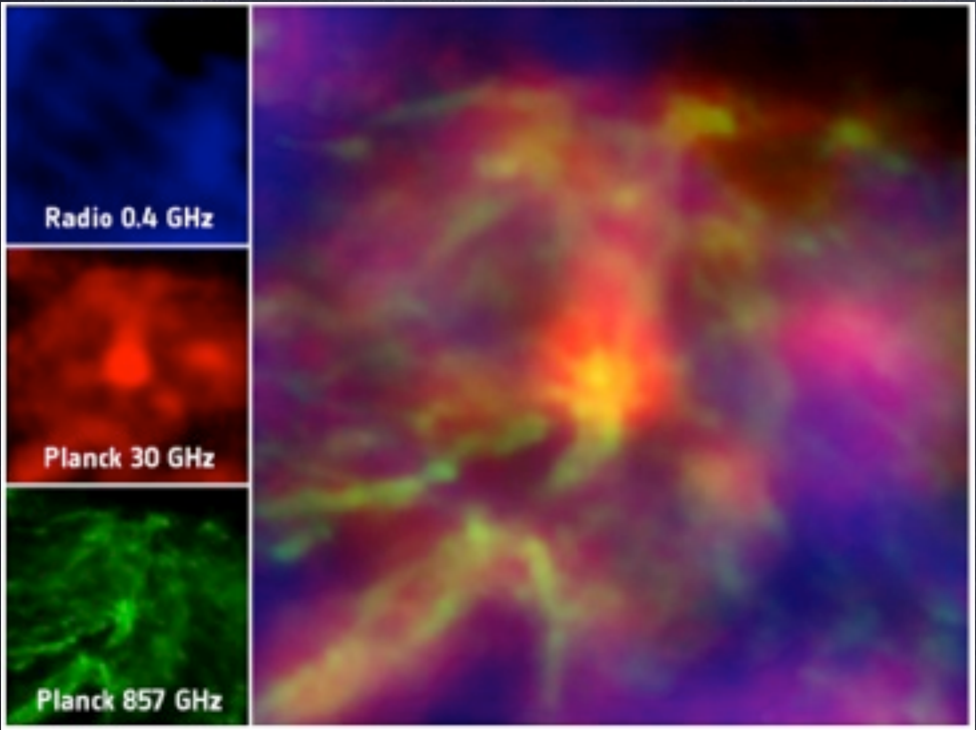


Clumps corresponding to dusty galaxies (in large scales and throughout cosmic history)

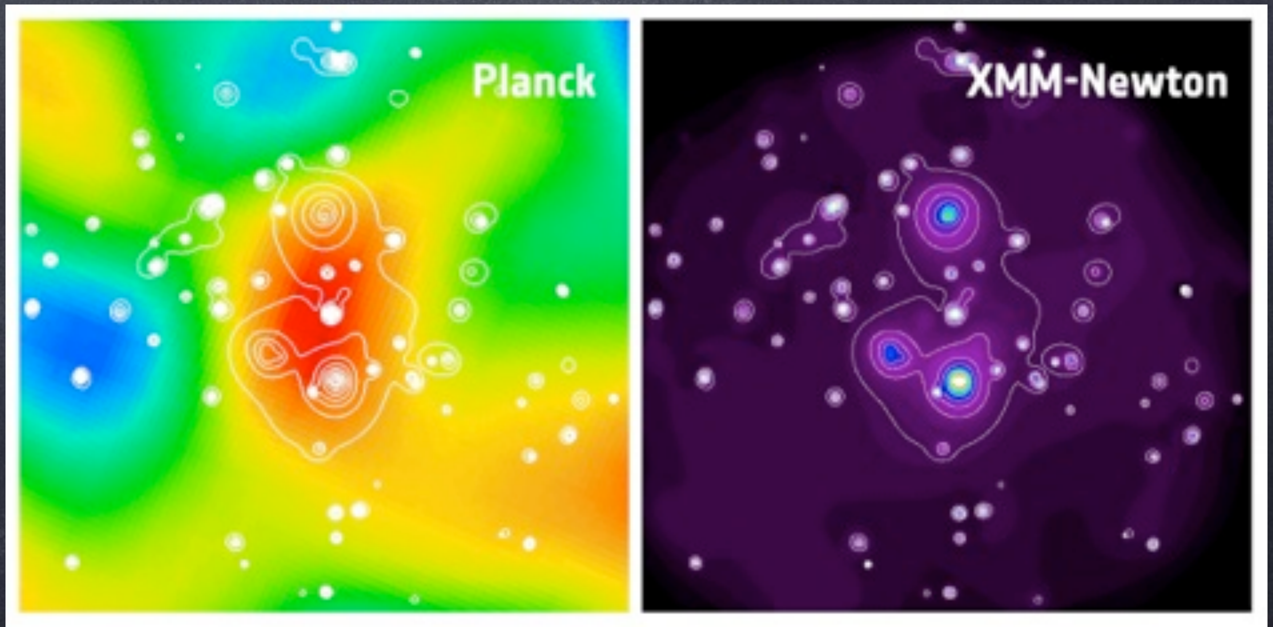
Measurements of the CIB



Measurements in Rho Ophiuchus: correlation between anomalous emission in μ-waves (30 GHz) and thermal dust emission (857 GHz)



Discovery of the first supercluster of galaxies, (PLCK G214.6+37.0) detected by Planck and confirmed by XMM-Newton.



Source: Planck collaboration