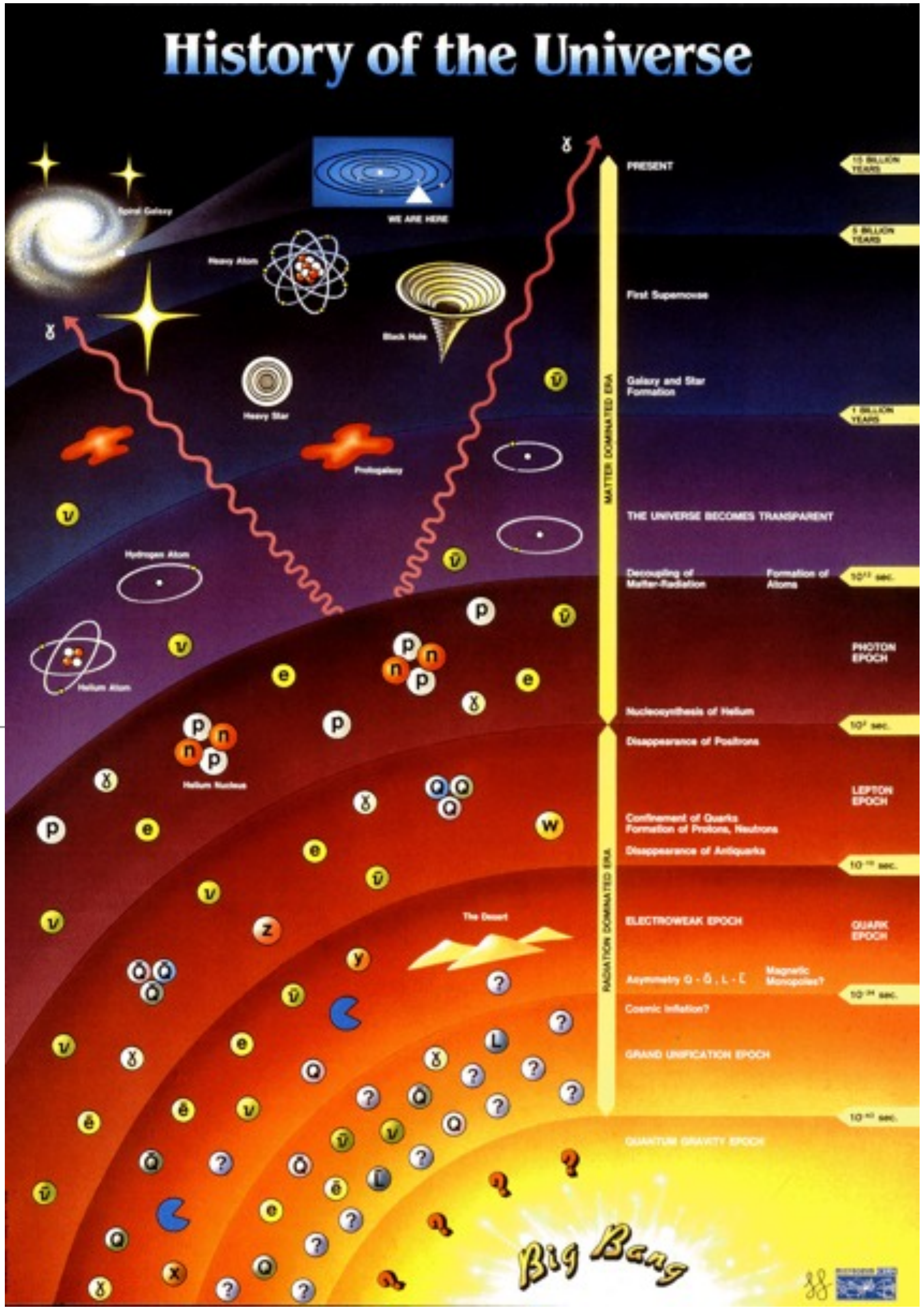
Cosmology

Kerstin Kunze

IUFFyM and Universidad de Salamanca

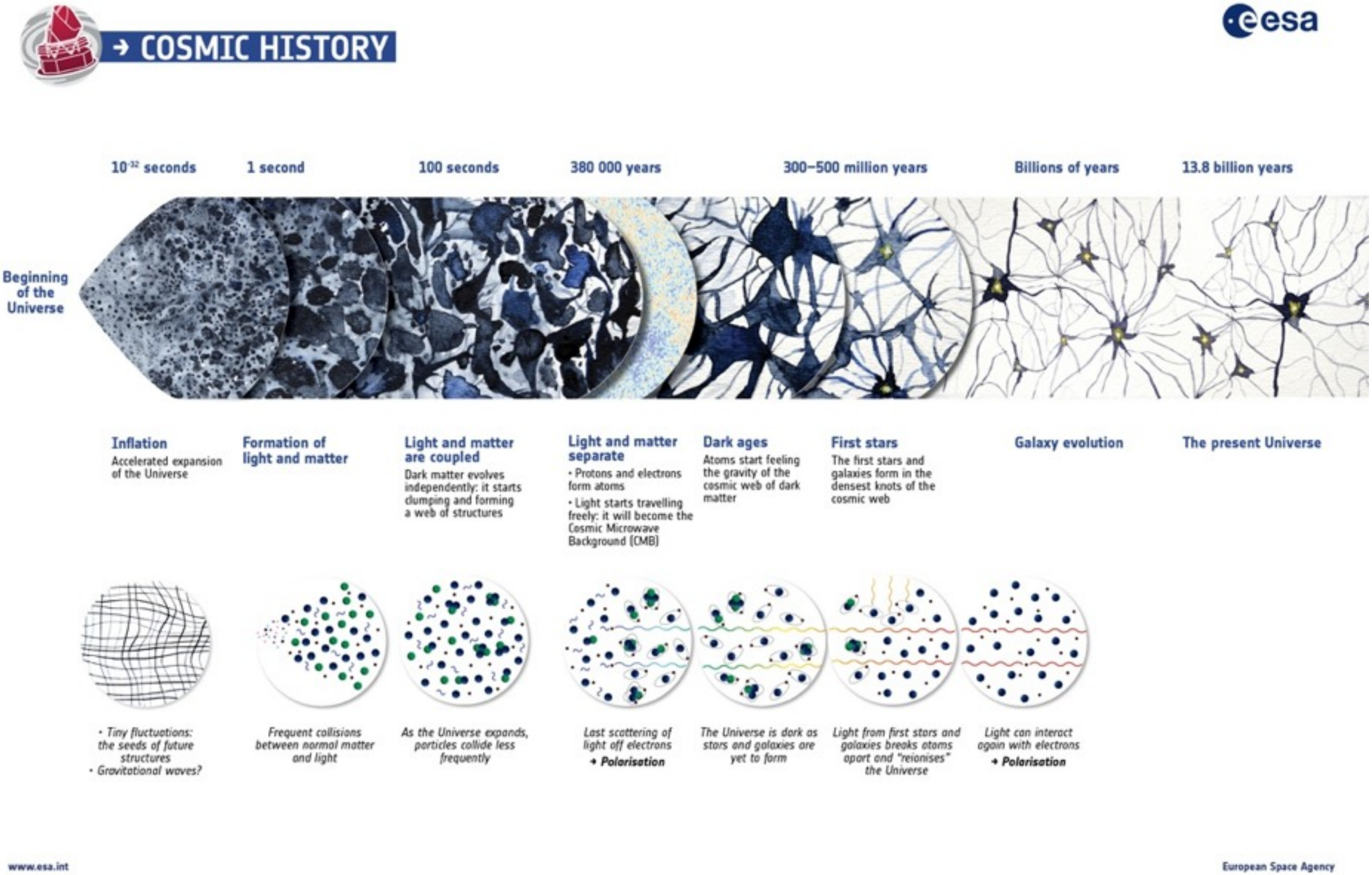


Overview

- Cosmology 1: The homogeneous universe
  - ★The expansion stages of the universe
- Cosmology 2: The inhomogeneous universe
  - ★The cosmic microwave background
  - ★Large scale structure
- Cosmology 3:
  - ★Dark matter
  - ★Dark energy

Cosmology 2

Cosmology 2



Inflation
Accelerated expansion of the Universe

Formation of light and matter

Light and matter are coupled
Dark matter evolves independently: it starts clumping and forming a web of structures

Light and matter separate
- Protons and electrons form atoms
- Light starts travelling freely: it will become the Cosmic Microwave Background (CMB)

Dark ages
Atoms start feeling the gravity of the cosmic web of dark matter

First stars
The first stars and galaxies form in the densest knots of the cosmic web

Galaxy evolution

The present Universe

• Tiny fluctuations: the seeds of future structures
• Gravitational waves?

Frequent collisions between normal matter and light

As the Universe expands, particles collide less frequently

Last scattering of light off electrons
→ Polarisation

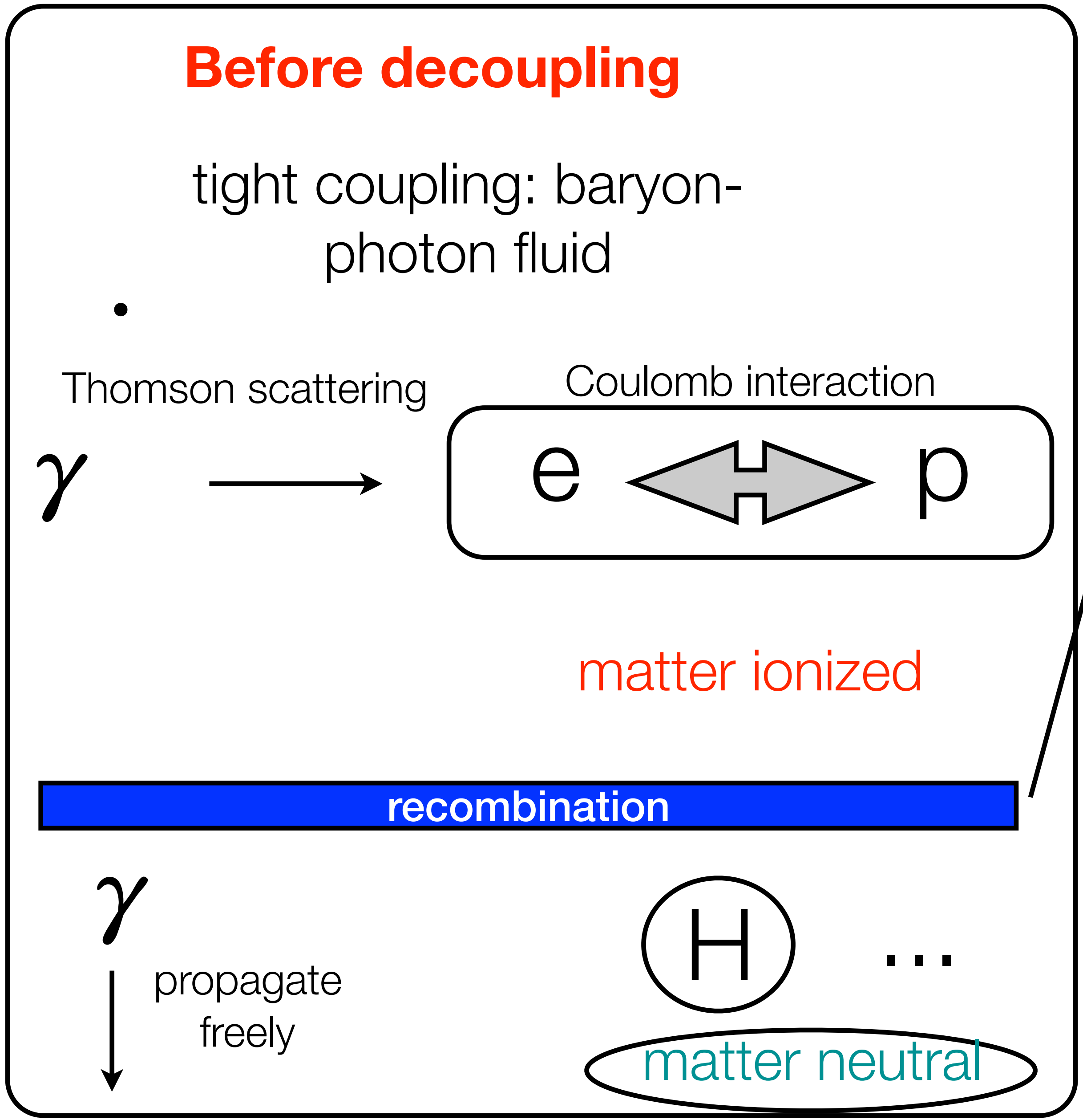
The Universe is dark as stars and galaxies are yet to form

Light from first stars and galaxies breaks atoms apart and "reionises" the Universe

Light can interact again with electrons
→ Polarisation

Cosmology 2

- ***The cosmic microwave background***



Before decoupling

tight coupling: baryon-photon fluid

Thomson scattering

Coulomb interaction

$\gamma \longrightarrow \boxed{e \Leftrightarrow p}$

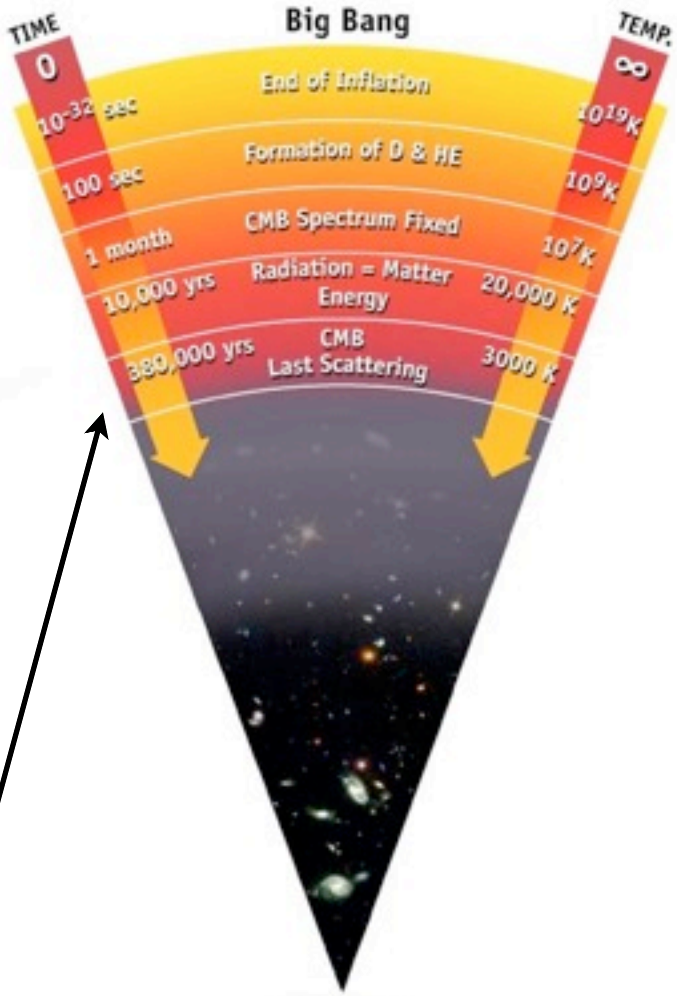
matter ionized

recombination

γ propagate freely

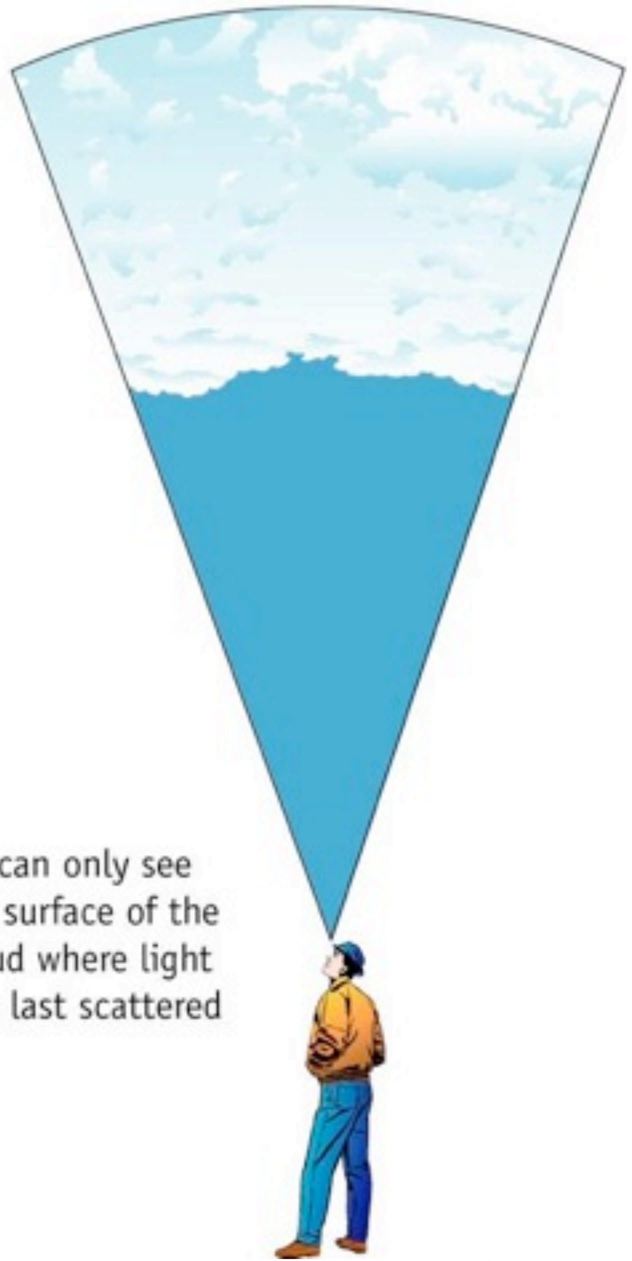
H ...

matter neutral



PRESENT
13.7 Billion Years
after the Big Bang

The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.



We can only see the surface of the cloud where light was last scattered

NASA

Cosmology 2

- Recombination would occur much earlier than about 4000K if just depended on 13.6 eV=kT → 160000 K.

- Subtleties of recombination are due to two-photon decay process and interactions drop out of Saha equilibrium.

- **Recombination**: epoch when electrons join nuclei. Define at ionization fraction Xe=0.1.
  - free electrons become rare
  - Saha equation not applicable anymore

- **Decoupling:** epoch after which photons will not scatter again.
  - residual ionization fraction of order 0.001
  - define as epoch when the duration of photon mean free path equals the age of the universe

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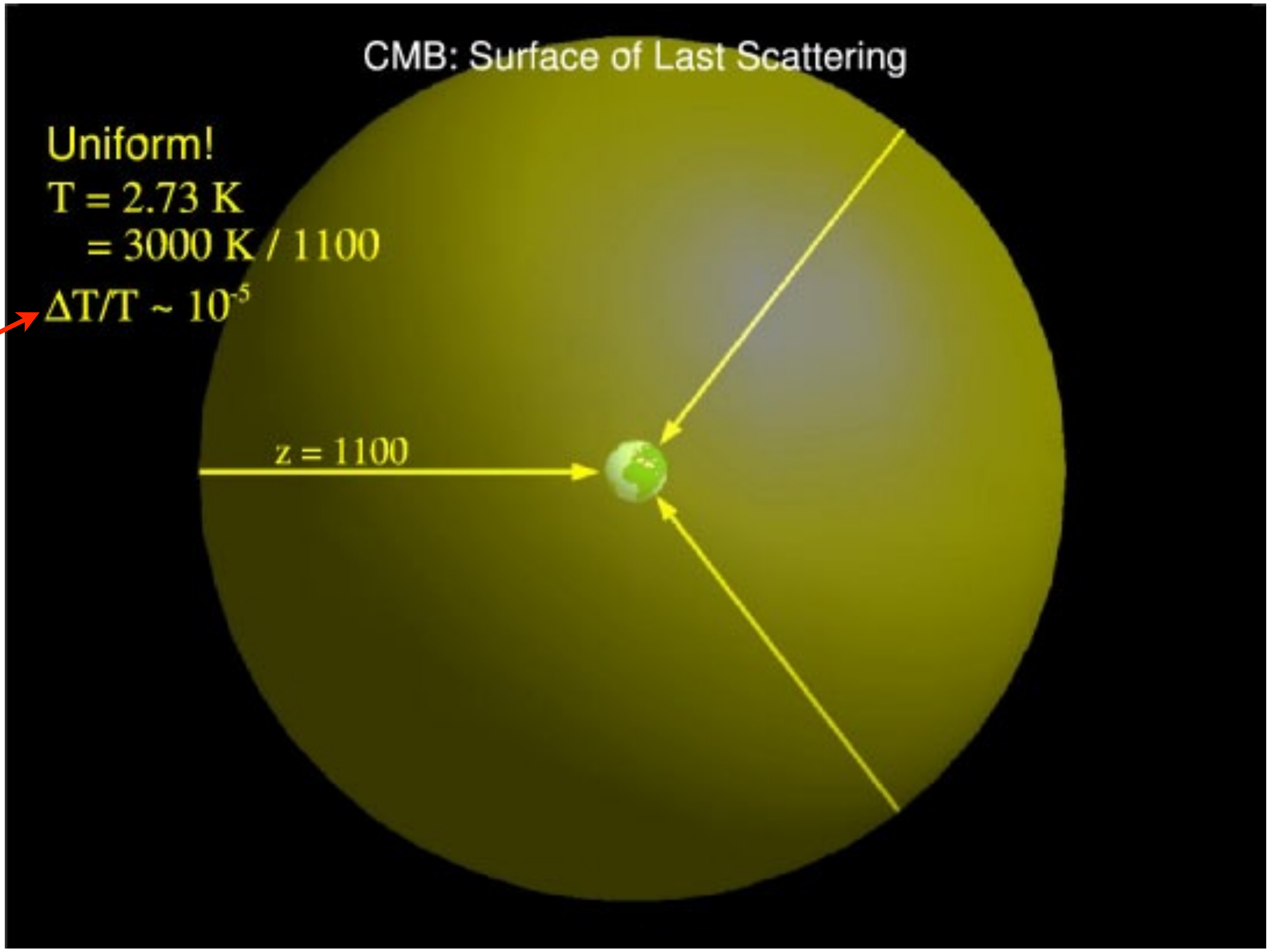


W. Kinney

Small temperature perturbations

CMB anisotropies

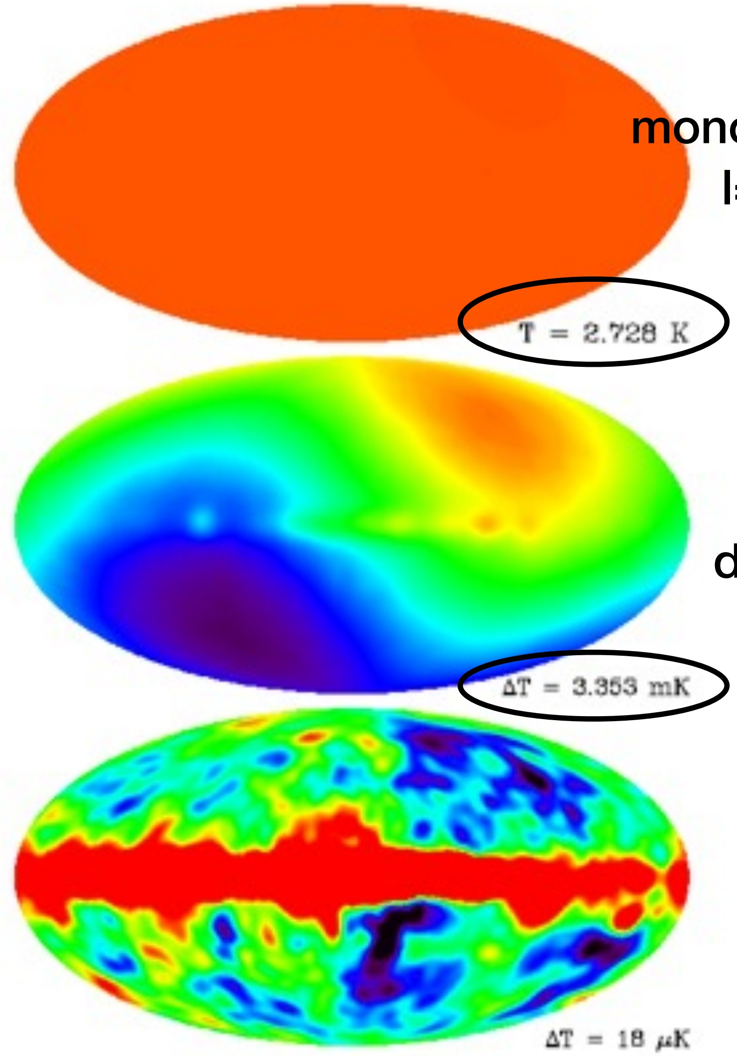
Cosmology 2

- Expand temperature fluctuations in spherical harmonics:

$$\Theta(\hat{\mathbf{n}}) = \frac{\Delta T}{T} = \sum_{\ell m} \Theta_{\ell m} Y_{\ell m}(\hat{\mathbf{n}})$$

$$\langle \Theta^*_{\ell m} \Theta_{\ell' m} \rangle = \delta_{\ell' \ell} \delta_{m m'} C_\ell$$

DMR data from the
53 GHz band



monopole :
l=0

dipole :
l=1

dipole
component
subtracted

COBE/
NASA

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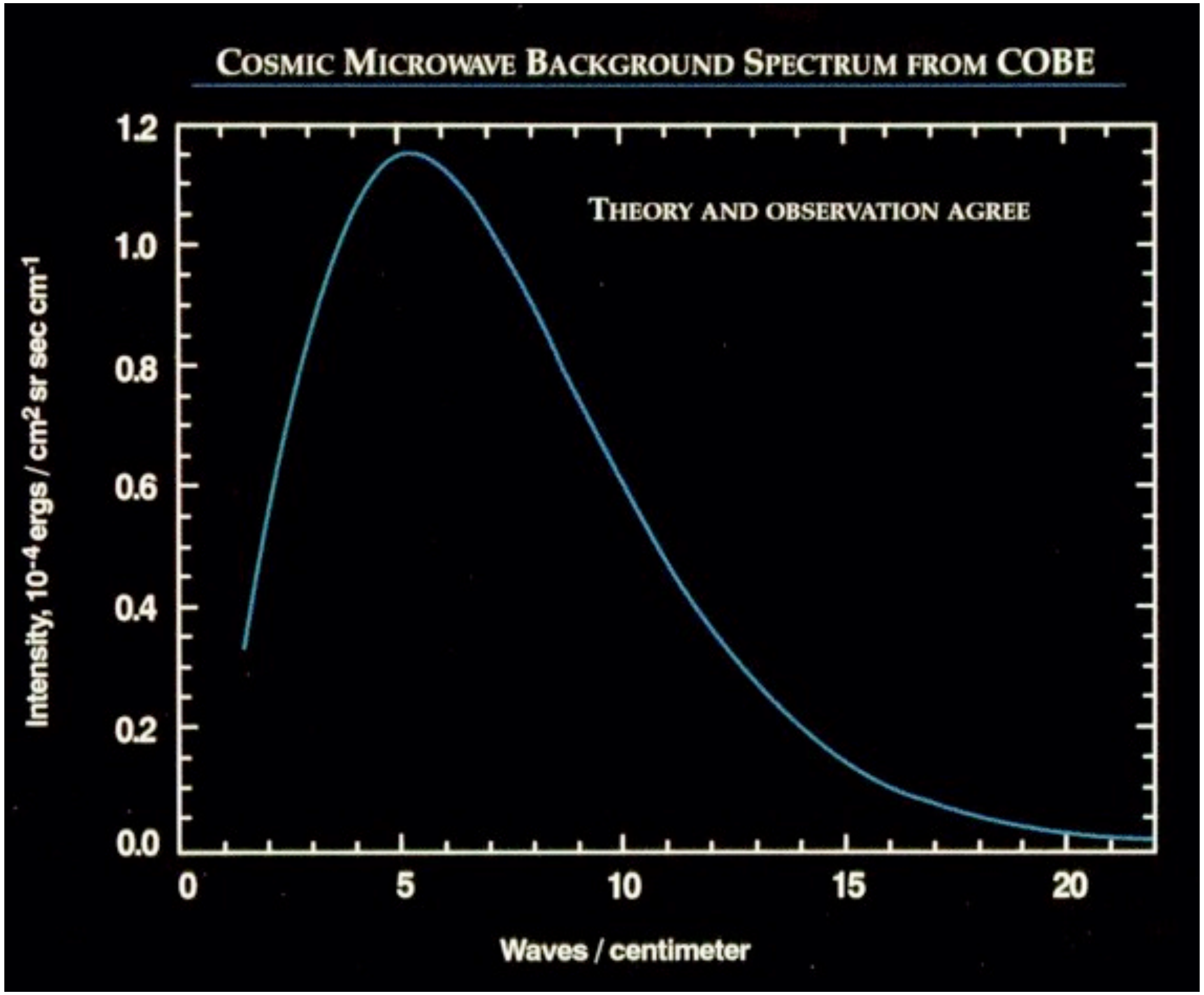

monopole

$$T_\gamma = 2.7255 \pm 0.0006\mathrm{K}$$

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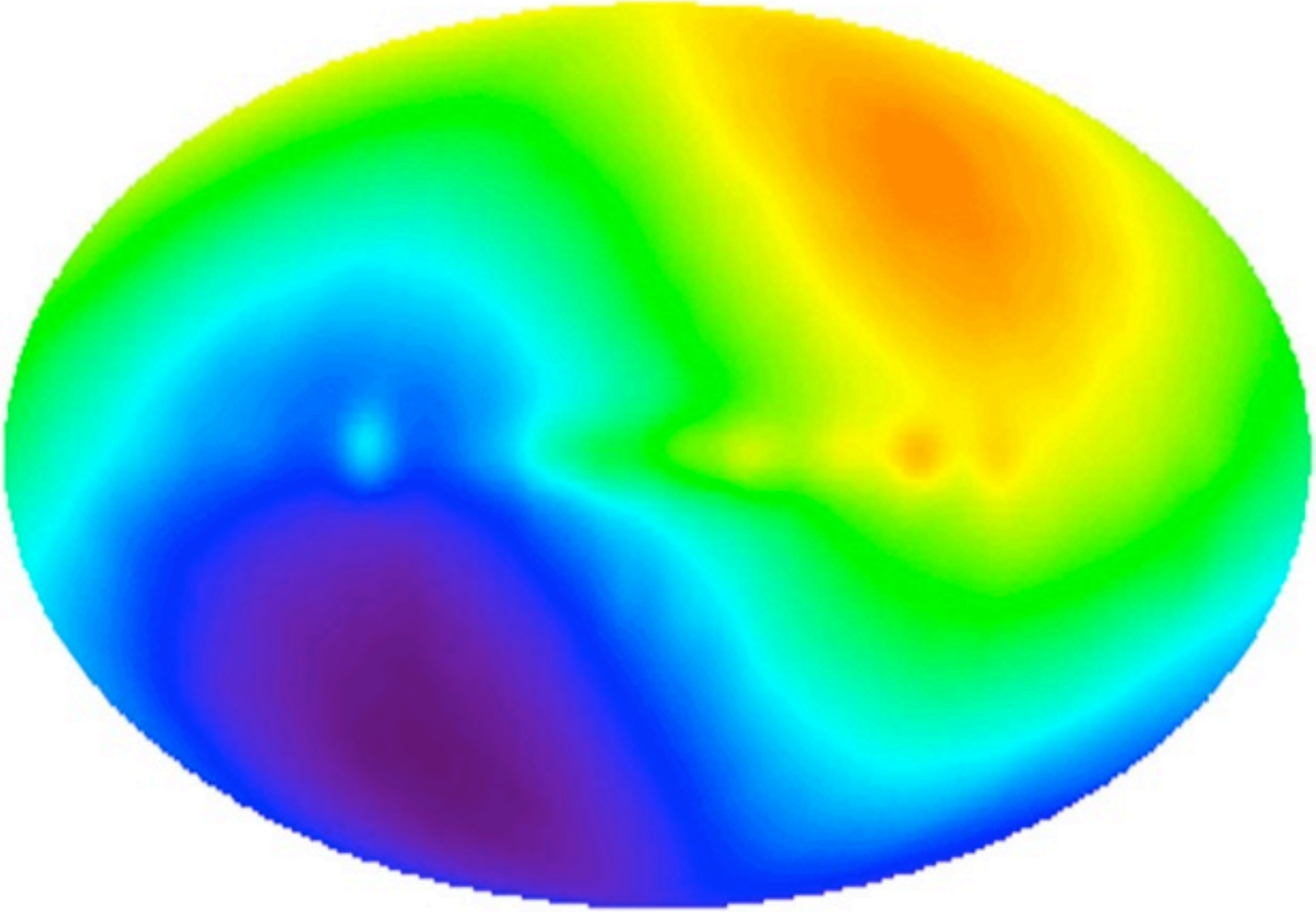
Astronomy Picture of the Day

2014 June 15



CMB Dipole: Speeding Through the Universe

Image Credit: DMR, COBE, NASA, Four-Year Sky Map

Explanation: Our Earth is not at rest. The Earth moves around the Sun. The Sun orbits the center of the Milky Way Galaxy. The Milky Way Galaxy orbits in the Local Group of Galaxies. The Local Group falls toward the Virgo Cluster of Galaxies. But these speeds are less than the speed that all of these objects together move relative to the cosmic microwave background radiation (CMBR). In the above all-sky map from the COBE satellite, radiation in the Earth's direction of motion appears blueshifted and hence hotter, while radiation on the opposite side of the sky is redshifted and colder. The map indicates that the Local Group moves at about 600 kilometers per second relative to this primordial radiation. This high speed was initially unexpected and its magnitude is still unexplained. Why are we moving so fast? What is out there?

Dipole

$$T_\gamma = 3.355 \pm 0.008\mathrm{mK}$$

Cosmology 2

- Dipole

(PDG 2014)

- Result of Doppler shift caused by motion of solar system relative to the nearly isotropic black body field. The motion of the observer with velocity $\beta = v/c$ relative to an isotropic Planck radiation field of temperature T_0 produces a Doppler shifted temperature pattern

$$T(\theta) = T_0(1-\beta^2)^{\frac{1}{2}}/(1-\beta\cos\theta) \simeq T_0(1+\beta\cos\theta + \frac{\beta^2}{2}\cos 2\theta + \mathcal{O}(\beta^3))$$

- At every point in the sky a black body spectrum at $T(\theta)$ is observed.

- Velocity of solar system barycenter assuming $T_0 = T_\gamma$

$v = 369.0 \pm 0.9 \mathrm{kms}^{-1}$ towards $(l, b) = (263.99^\circ \pm 0.14^\circ, 48.26^\circ \pm 0.03^\circ)$

- Dipole is frame-dependent ⇨ determine “absolute rest frame” in which CMB dipole would be zero.

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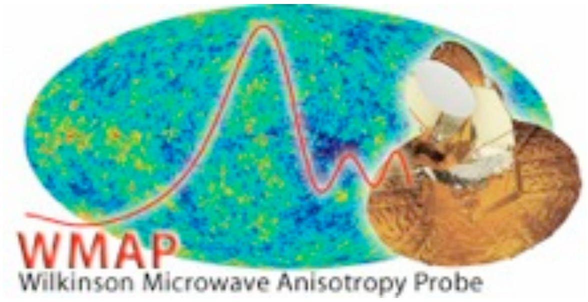
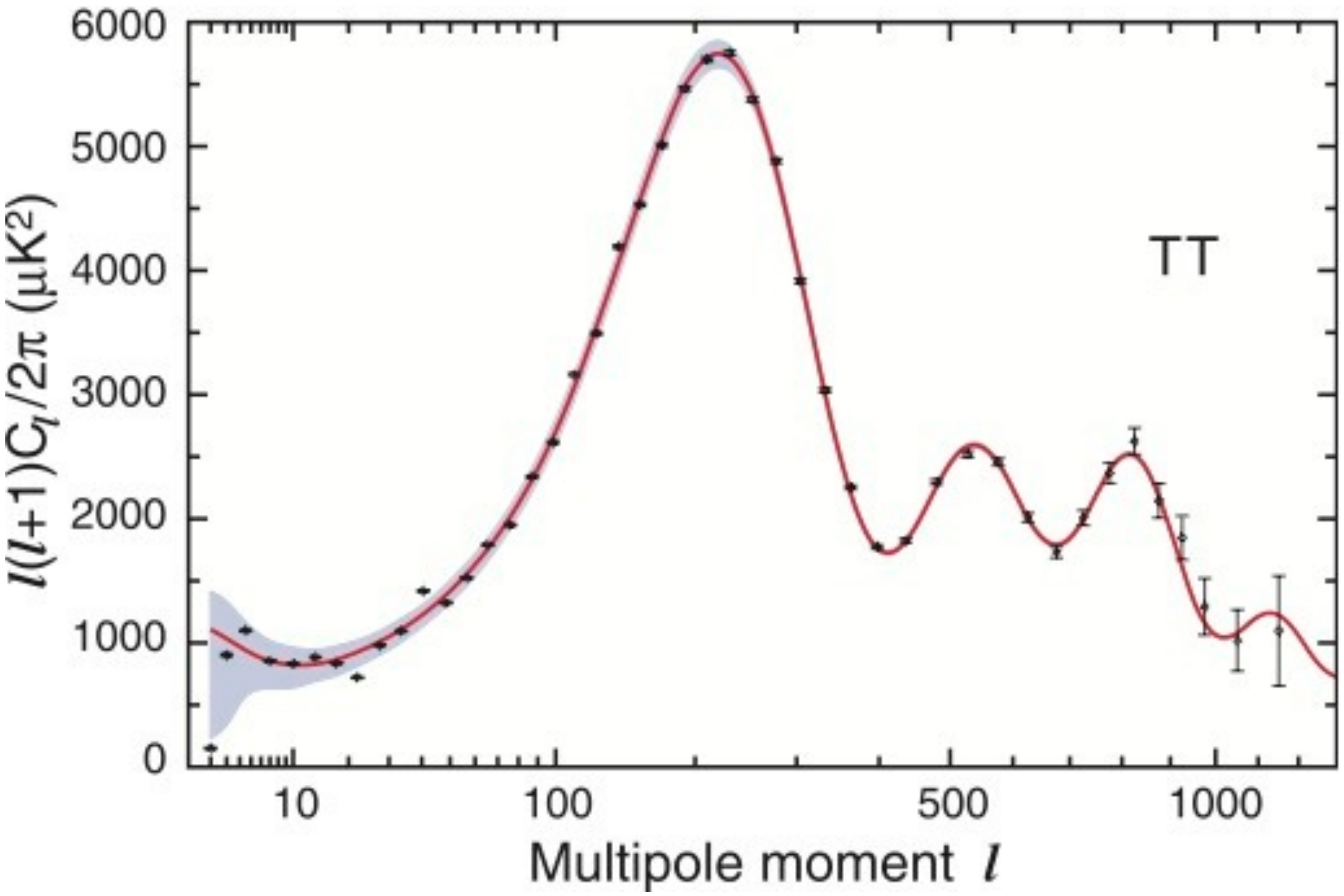
- Higher order multipoles $\ell \geq 2$
- result of perturbations in the density of the early universe, present before last scattering.

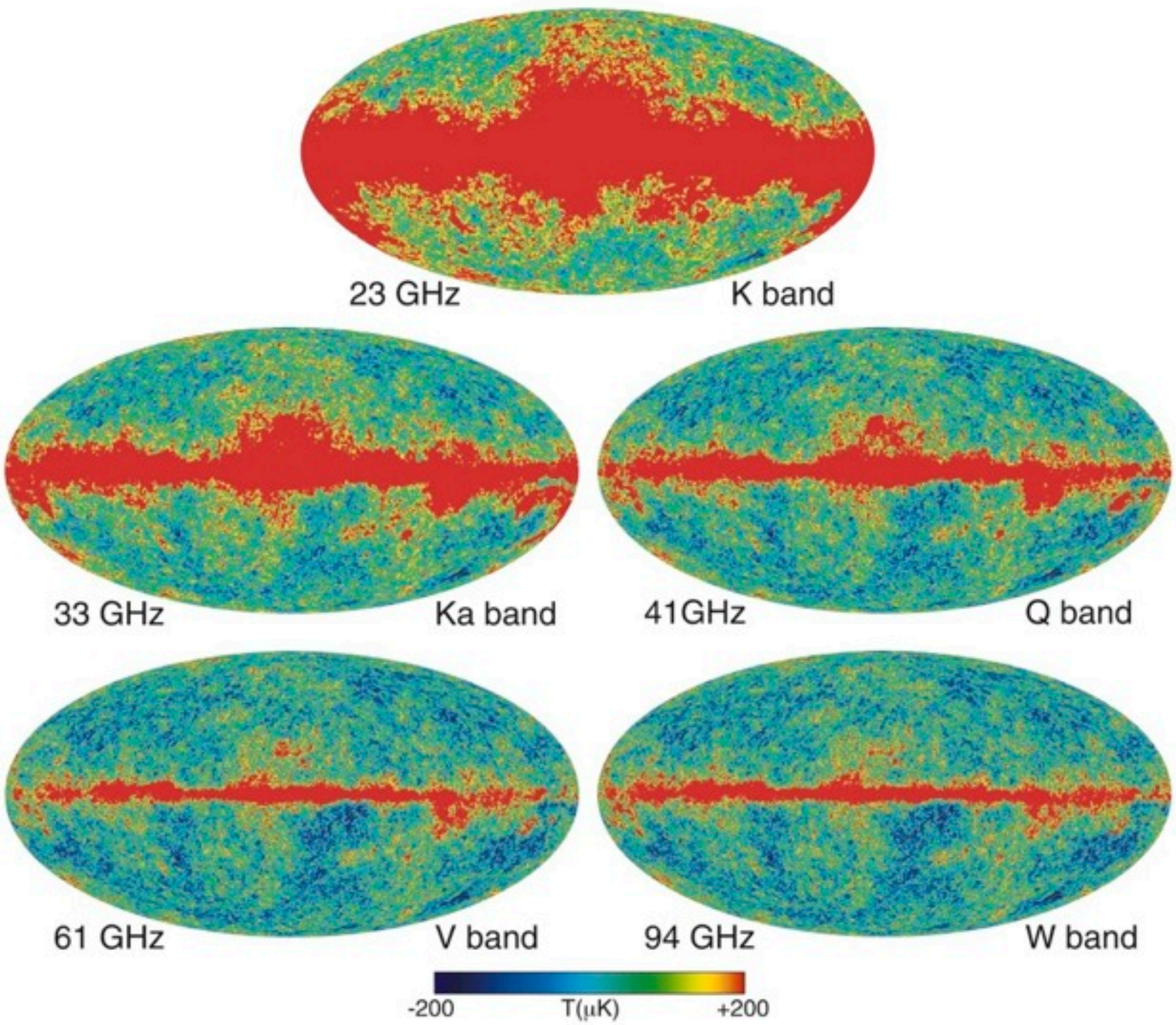




WMAP 9:
temperature angular
power spectrum

Bennett et al. 2013

Cosmology 2

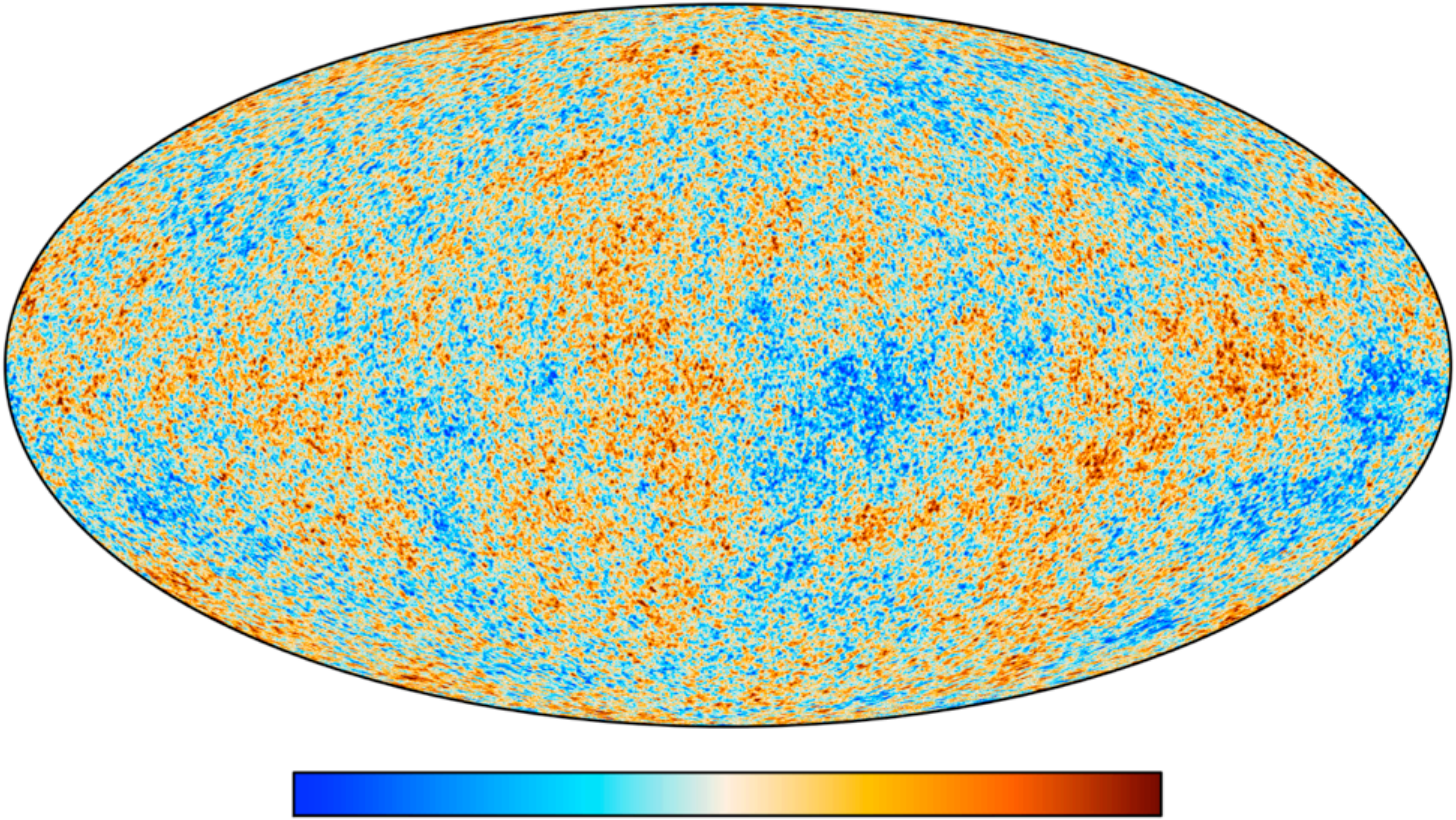


WMAP 9:
temperature sky maps

Bennett et al. 2013

Cosmology 2

Planck 15:
temperature sky maps



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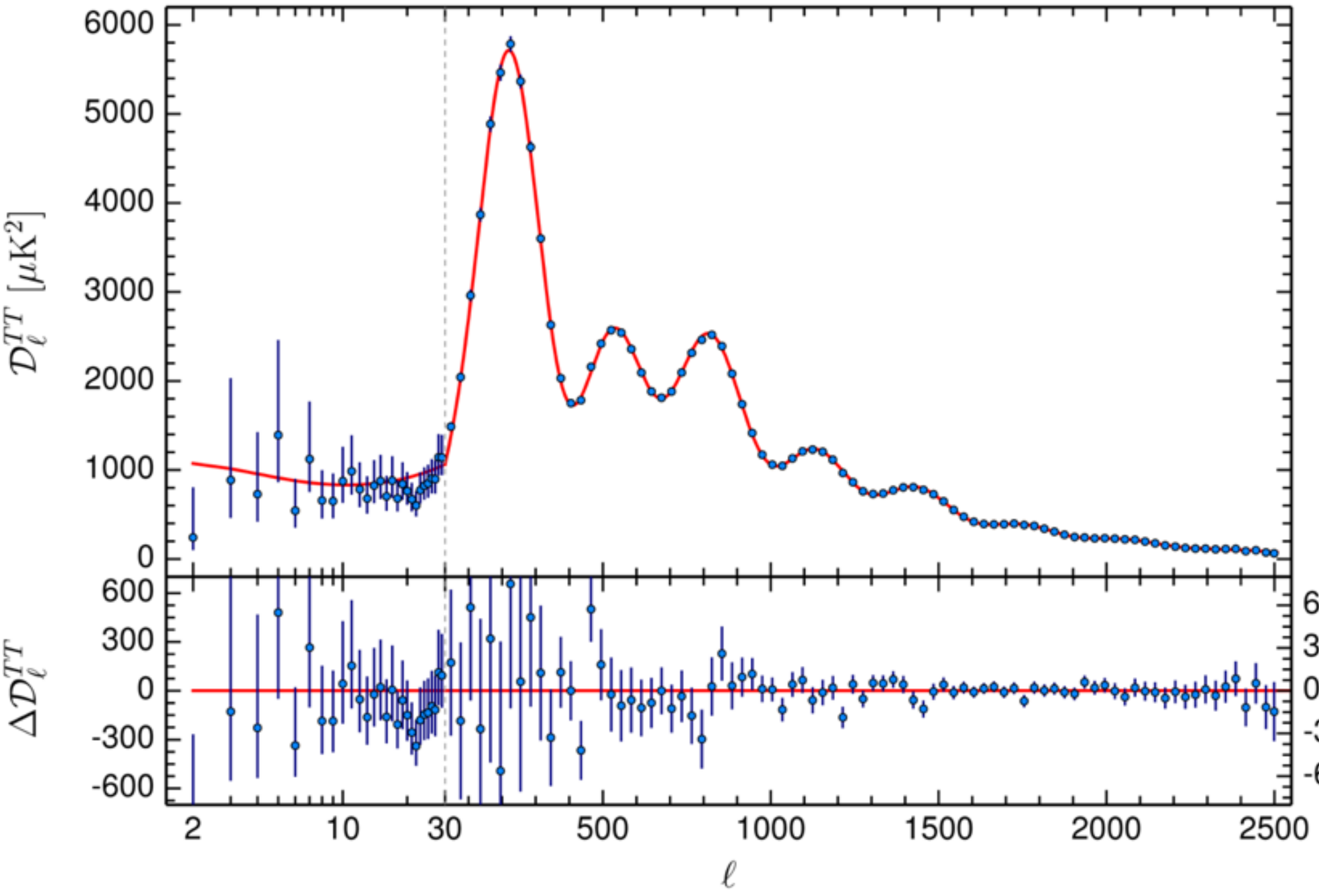
Planck 15:
temperature angular
power spectrum



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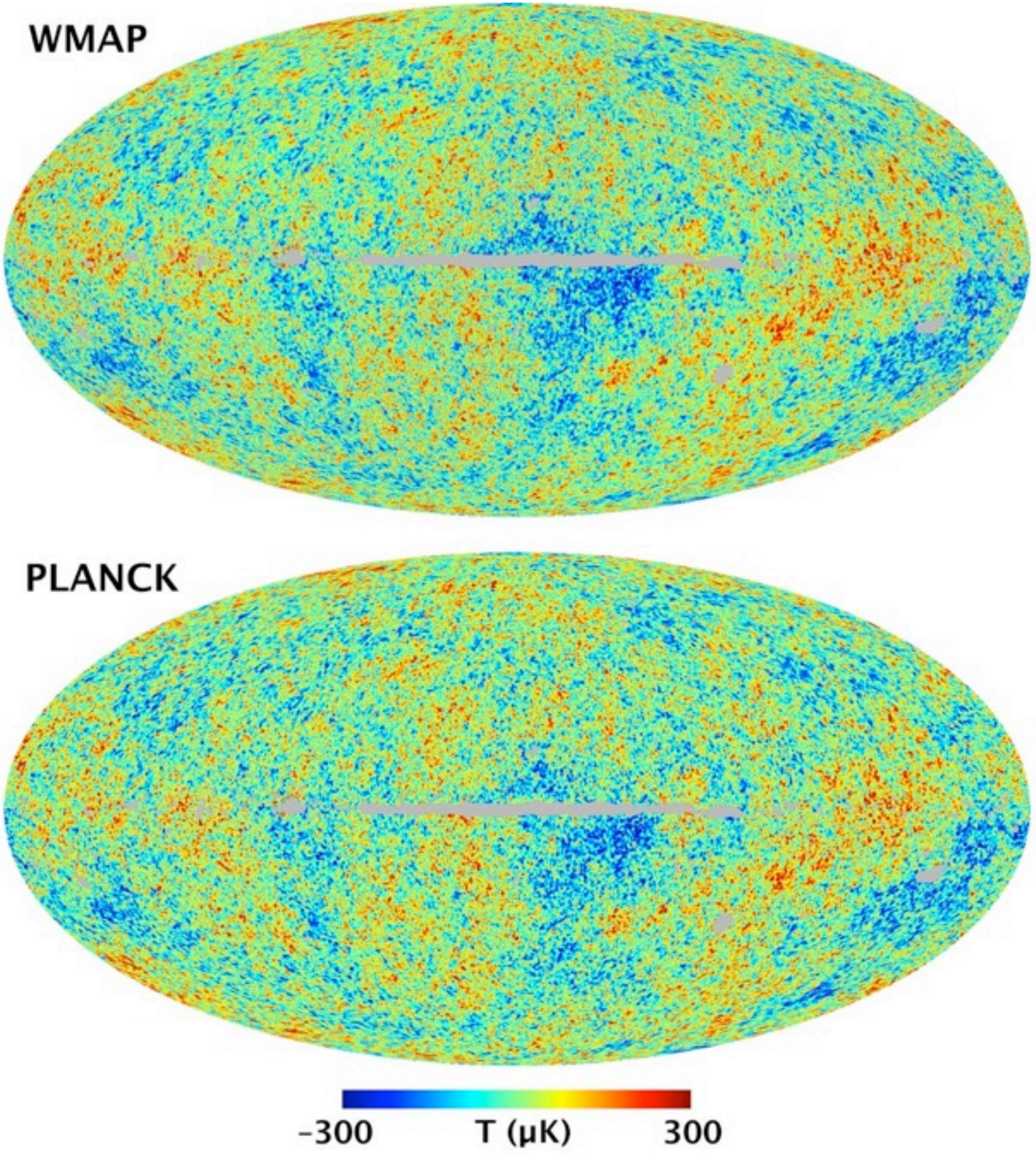
WMAP 9 vs. Planck13



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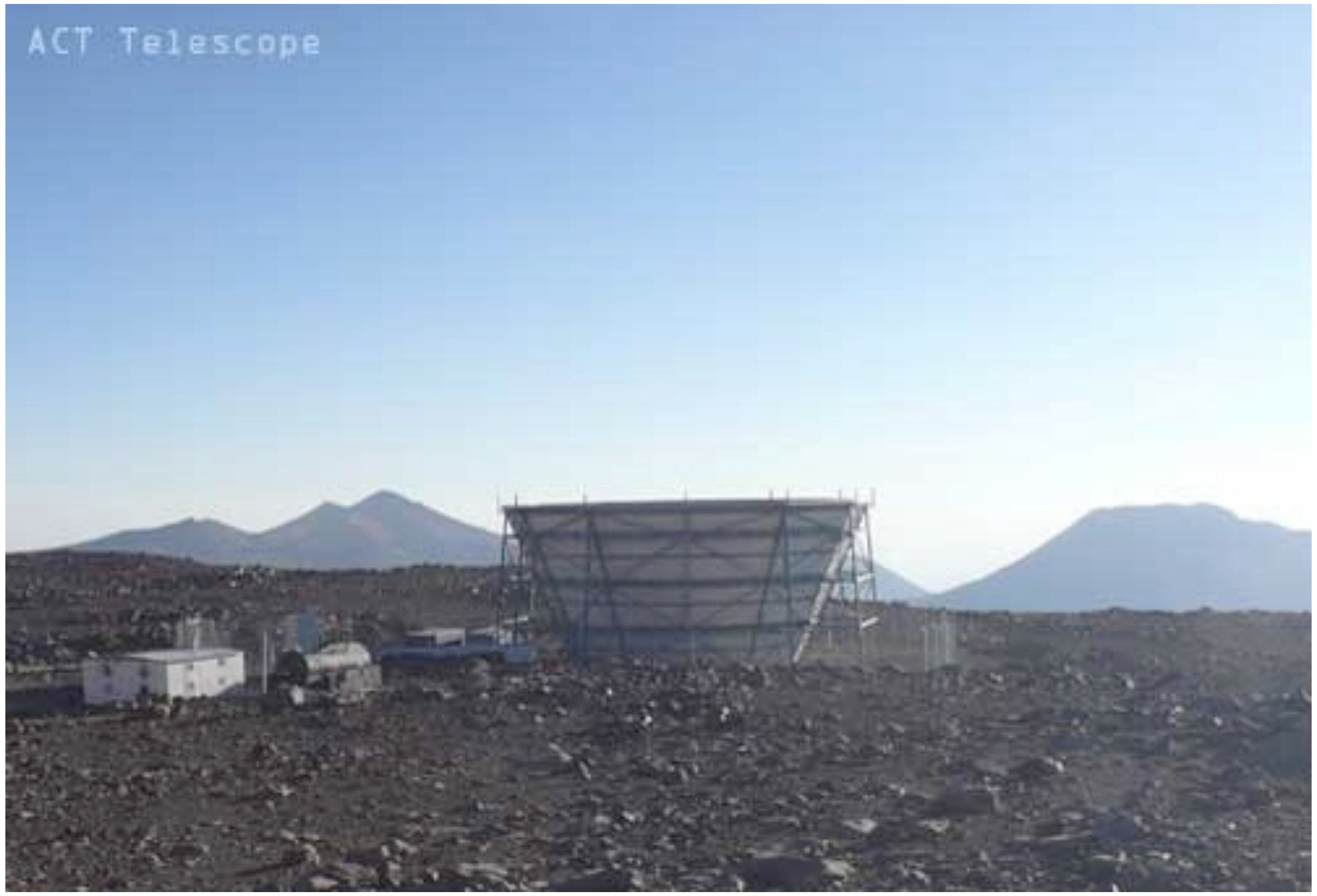
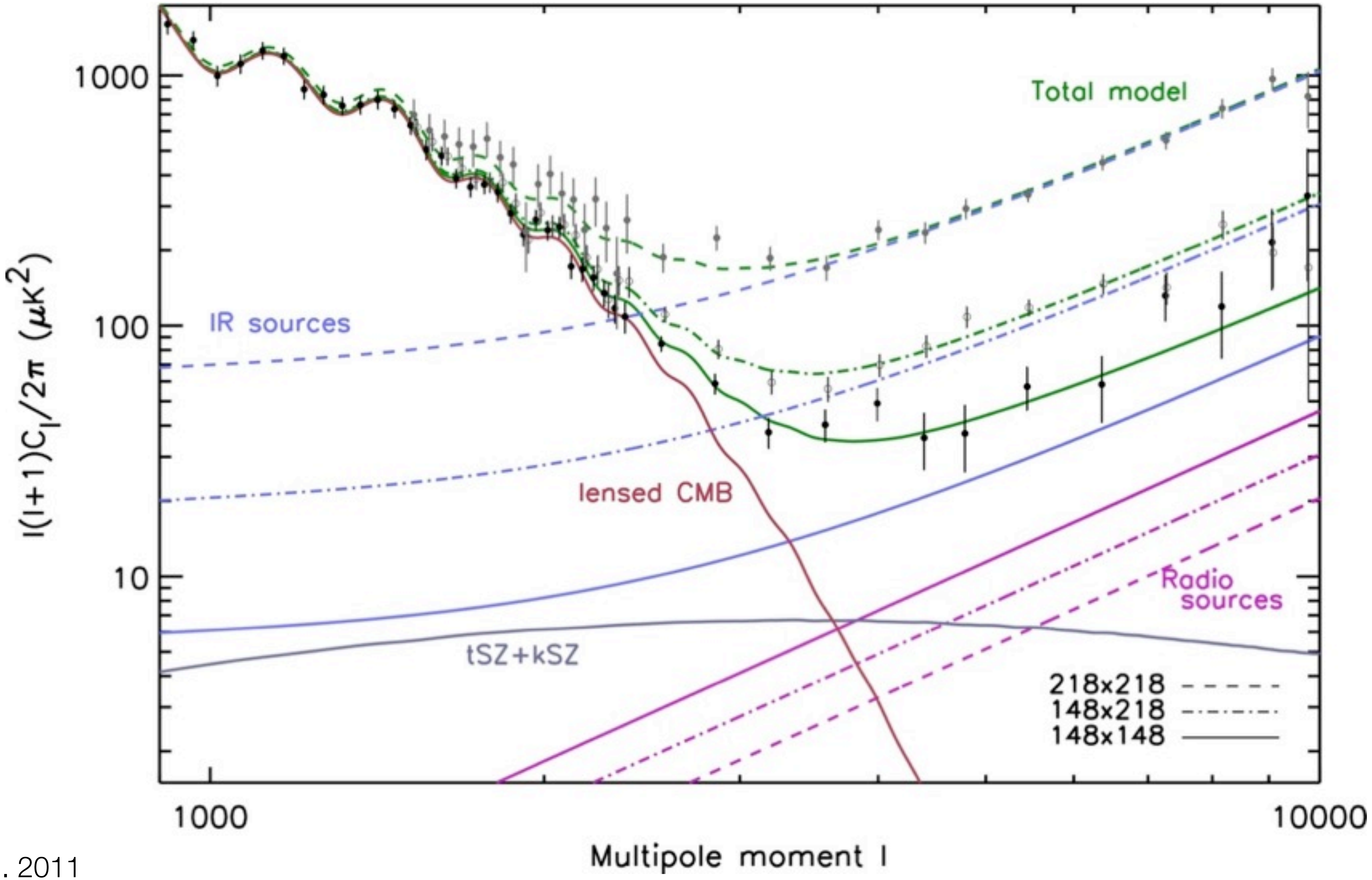
The Atacama Cosmology Telescope (ACT) is a 6 meter telescope designed to map the Cosmic Microwave Background (CMB) over a large sky area with an angular resolution of 1 arcmin. The instrument observes at three frequencies (148, 218, and 277 GHz). In order to minimize disturbance from atmospheric effects, the telescope is situated on the Atacama Plateau in northern Chile, at an elevation of 5190 m.



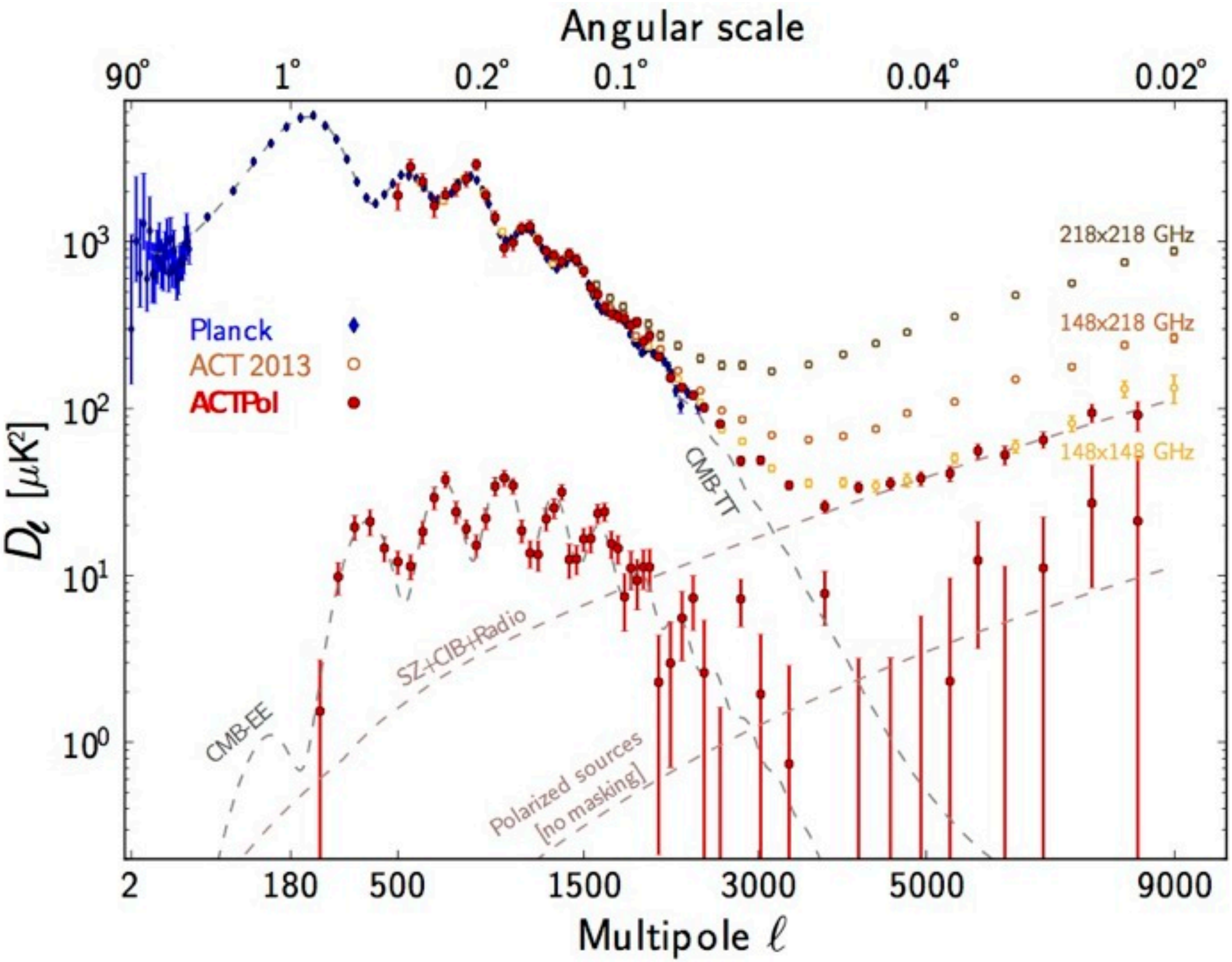
Atacama Cosmology Telescope (ACT)

Cosmology 2



Dunkley et al. 2011

Cosmology 2



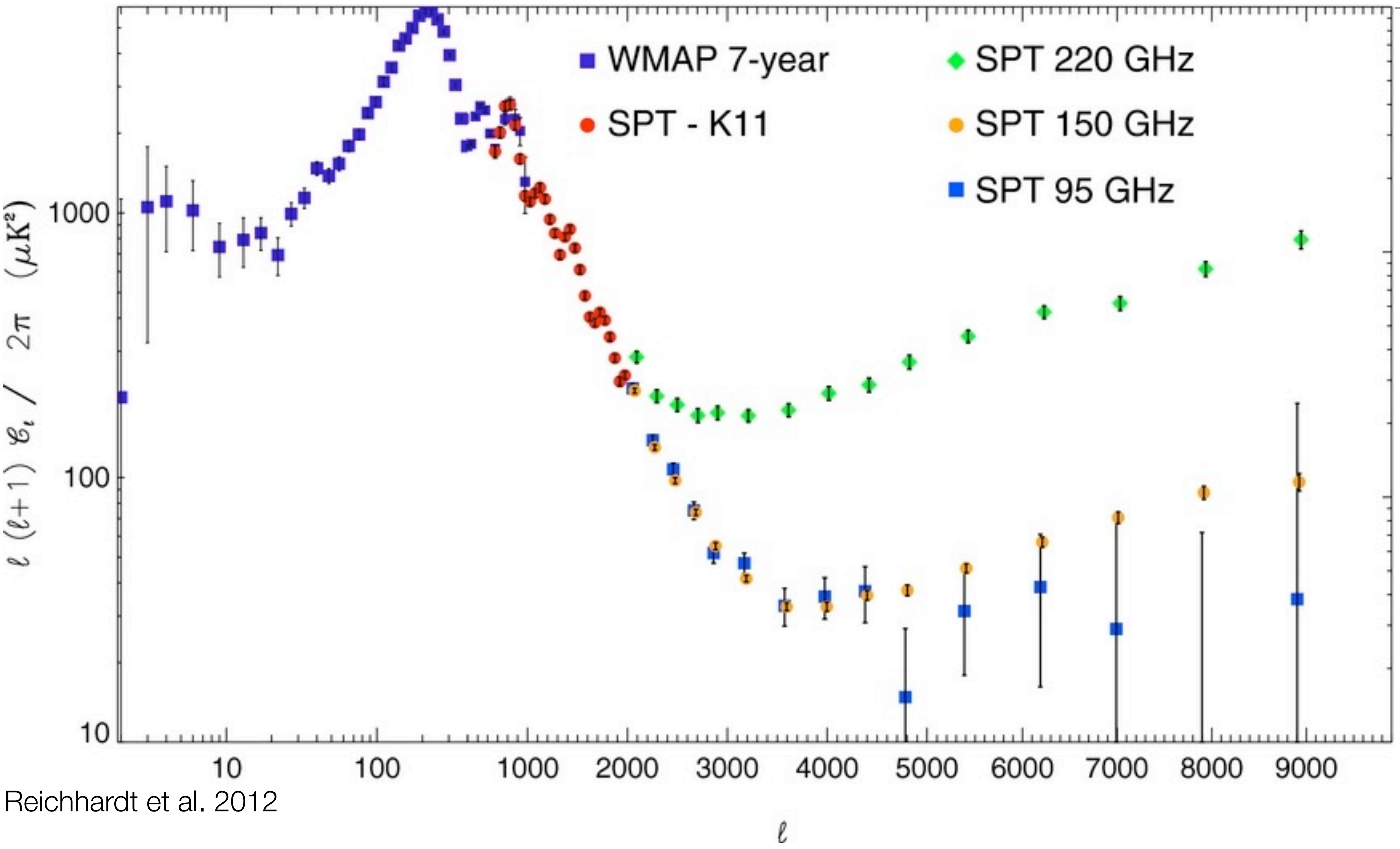
Naess et al. 2014

Cosmology 2

The South Pole Telescope is a 10 meter diameter telescope operating at the NSF South Pole research station. The telescope is designed for conducting large-area millimeter and sub-millimeter wave surveys of faint, low contrast emission, as required to map primary and secondary anisotropies in the cosmic microwave background.

South Pole Telescope (SPT)

Cosmology 2



Reichhardt et al. 2012

*WMAP*7 and SPT bandpowers. Below ℓ = 2000, the primary CMB anisotropy is dominant at all frequencies. On smaller scales, the CIB, radio sources, and secondary CMB anisotropies contribute to the signal. With the SPT source masking, the CIB is the largest source of power on sub-arcminute scales at 150 and 220 GHz. Due to the relative spectral behavior of the CIB and synchrotron emission, the 95 GHz bandpowers also have a significant contribution from radio sources.

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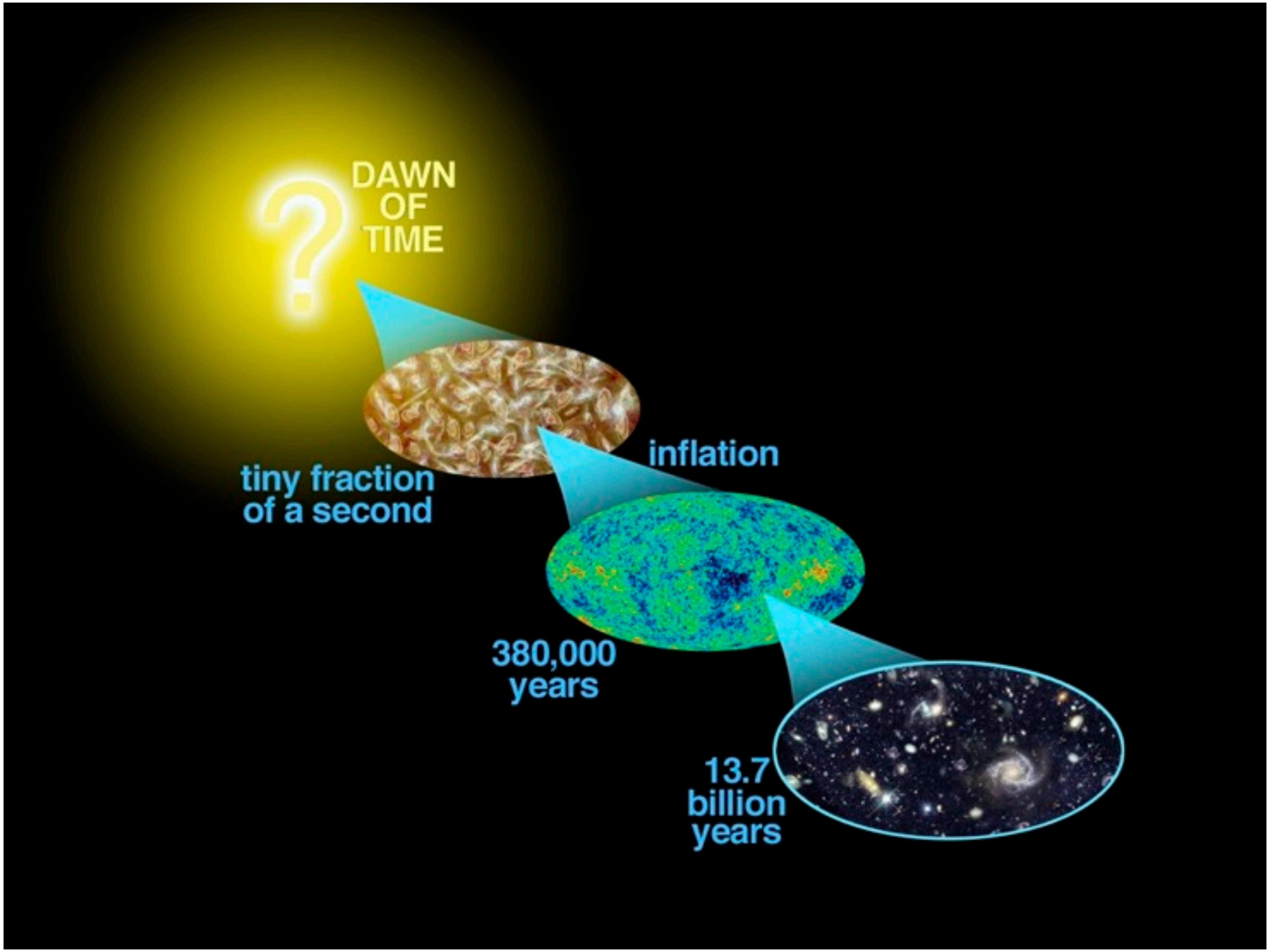


NASA

Cosmology 2

- **Origin of CMB anisotropies?**

- Ripples in space-time and matter ⇒ perturb FRW metric and energy momentum tensor

- At linear order: 3 types of perturbations: scalar, vector and tensor

(flat) FRW

$$ds^2 = a^2(\eta)(d\eta^2 - \delta_{ij}dx^i dx^j)$$

$$\Big\downarrow$$

most general linear perturbation

$$ds^2 = a^2(\eta)\left[(1-2A)d\eta^2 + 2B_i d\eta dx^i - \left[(1+2D)\,\delta_{ij} + 2E_{ij}\right) dx^i dx^j\right]$$

expand functions in **scalar, vector and tensor harmonics**

. . . for details Kodama, Sasaki ProgTheorPhysSup 78 (1984) 1 or text book on CMB physics

Cosmology 2

- **Perturbed Boltzmann equation**

- determines CMB temperature anisotropies and polarization

$$q = a(\eta)p(\eta, \mathbf{x})$$

- Photon phase-space distribution

$$f(\eta, \mathbf{x}, \mathbf{n}, q) = f(q) + \delta f(\eta, \mathbf{x}, \mathbf{n}, q)$$

$$f(q) = \frac{1}{e^{q/T_0} - 1}$$

unperturbed universe

- define **brightness function**

$$\Theta \equiv \delta T/T$$

$$f(\eta, \mathbf{x}, \mathbf{n}, q) = \frac{1}{e^{q/T_0(1+\Theta)} - 1} \Rightarrow \delta f(\eta, \mathbf{x}, \mathbf{n}, q) = -q\frac{df(q)}{dq}\Theta(\eta, \mathbf{x}, \mathbf{n})$$

Cosmology 2

- ⇨ Boltzmann equation for $\Theta(\eta, \mathbf{k}, \mathbf{n})$

collision term

$$\frac{\partial \Theta}{\partial \eta} + ik\mu\Theta - \frac{\partial \Phi}{\partial \eta} + ik\mu\Psi = C[\Theta]$$

$\mu = \hat{\mathbf{k}} \cdot \mathbf{n}$

Expand $\Theta(\eta, \mathbf{k}, \mathbf{n})$ in spherical harmonics

Boltzmann hierarchy for $\Theta_\ell(\eta, \mathbf{k})$

scalar mode perturbation,
conformal Newtonian gauge

$$ds^2 = a^2(\eta)\left[-(1+2\Psi)d\eta^2 + (1-2\Phi)\delta_{ij}dx^i dx^j\right]$$

$$\Theta_0 = \frac{\delta_\gamma}{4}, \quad \Theta_1 = \frac{V_\gamma}{3}, \quad \Theta_2 = \frac{\Pi_\gamma}{12}$$

Lyth, Liddle “The primordial density pertubation”

Cosmology 2

- To solve the Boltzmann equation (hierarchy) together with evolution equations of all matter components of the cosmic fluid (and additional ones you want to put...) there are open source **CMB Boltzmann codes**

  - **COSMOS (Bertschinger)**
  - **CMBFAST (Seljak, Zaldarriaga 1996)**
    http://lambda.gsfc.nasa.gov/toolbox/tb_cmbfast_ov.cfm
  - **CAMB (Lewis et al. 2000)**
    http://camb.info/

cosmomc:
Markov Chain Monte Carlo

exploration of parameter space
http://cosmologist.info/cosmomc/

Cosmology 2

- More Boltzmann codes...

  - **CMBEASY (Doran 2005)**
    http://www.thphys.uni-heidelberg.de/~robbers/cmbeasy/

  - **CLASS (Blas et al. 2011)**
    http://class-code.net/

montepython:
Markov Chain Monte Carlo

exploration of parameter space
https://github.com/baudren/montepython_public

Cosmology 2

- Below T<1 MeV the cosmic fluid has four components:

  - ✳ **baryons**
  - ✳ **cold dark matter (CDM)**
  - ✳ **photons**
  - ✳ **(light) neutrinos**

baryons=nuclei and electrons since their number densities are basically equal at each point in space because of Coulomb interaction

Cosmology 2

- Observations of CMB anisotropies → **scalar mode**

→ **ΛCDM (cosm. constant + cold dark matter) model**

adiabatic mode

baryons=nuclei and electrons

extensions:

•include **tensor mode** - test inflation
•massive neutrinos
•primordial magnetic fields
•....

- Vector modes **decay in standard** ΛCDM but can be sourced by primordial magnetic fields (Shaw, Lewis (2010); KEK (2012))

Cosmology 2

- **Scalar mode**

gauge-invariant formalism

- just focus on density perturbation and velocity of photons and baryons

Kodama, Sasaki (1984),
Doran et al. (2003),
KEK (2011)

$$\dot{\Delta}_{\gamma} = -\frac{4}{3} k V_{\gamma},$$

$$\dot{V}_{\gamma} = k(\Psi - \Phi) + \frac{k}{4}\Delta_{\gamma} - \frac{k}{6}\pi_{\gamma} + \tau_c^{-1}(V_b - V_{\gamma}),$$

$$\dot{\Delta}_{b} = -kV_b - 3c_s^2 \mathcal{H} \Delta_b.$$

$$\dot{V}_{b} = (3c_s^2 - 1)\mathcal{H} V_b + k(\Psi - 3c_s^2\Phi) + kc_s^2\Delta_b + R\tau_c^{-1}(V_{\gamma} - V_b)$$

$$\tau_c^{-1} = a n_e \sigma_T.$$

mean free path of photons between scatterings

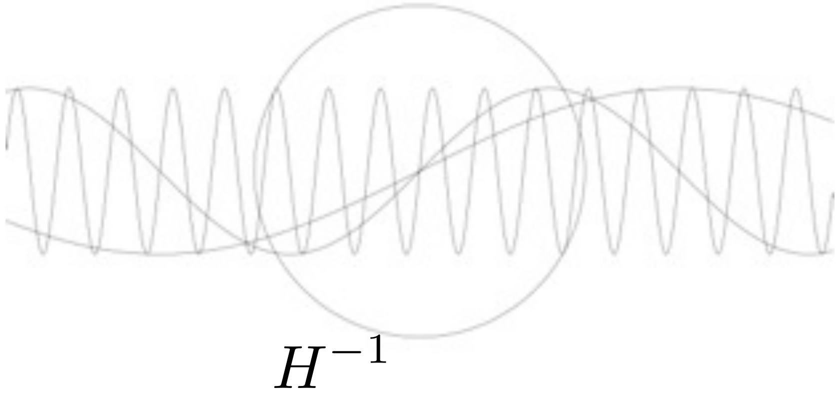
$$R \equiv \frac{4}{3}\frac{\rho_{\gamma}}{\rho_b}.$$

$c_s^2 = \frac{\partial \bar{p}}{\partial \bar{\rho}}$ is the adiabatic sound speed

Cosmology 2

- **Initial conditions**

- set on superhorizon scales $k\eta \ll 1$



- **adiabatic initial conditions**

- Radiation-matter fluid specific entropy: $S_{\gamma b} = S_\gamma / n_b$

$$\frac{\delta S_{\gamma b}}{S_{\gamma b}} = \frac{\delta S_\gamma}{S_\gamma} - \frac{\delta n_b}{n_b} = 3\frac{\delta T_\gamma}{T_\gamma} - \frac{\delta n_b}{n_b} = \frac{\delta \rho_\gamma}{\rho_\gamma + p_\gamma} - \frac{\delta n_b}{n_b}$$

generalize to all components j

$$\frac{\delta S_{\gamma b}}{S_{\gamma b}} = 0 \Rightarrow \frac{3}{4}\delta_\gamma = \delta_b$$

adiabatic i.c.

$$\boxed{\frac{S_{\gamma j}}{S_{\gamma j}} = \frac{\delta_\gamma}{w_\gamma + 1} - \frac{\delta_j}{1 + w_j}}$$

$$p_j = w_j \rho_j$$

Cosmology 2

Adiabatic i.c.

$$\frac{\delta S_{\gamma j}}{S_{\gamma j}} = 0$$

$$\boxed{\frac{1}{4}\delta_\gamma = \frac{1}{4}\delta_\nu = \frac{1}{3}\delta_b = \frac{1}{3}\delta_c}$$

curvature perturbation ζ

- Gauge-invariant formalism: $\zeta = \frac{\Delta_\gamma}{4}$

- Single field inflation generates adiabatic initial conditions. Inflaton decays into the usual species, their overall ratios are fixed

$$\delta(n_A/n_B) = 0 \Rightarrow \delta S_{A,B}/S_{A,B} = 0$$

Cosmology 2

- Curvature perturbation from inflation

$$\zeta = -H\frac{\delta\rho}{\dot{\rho}} \Rightarrow \zeta = -H\frac{\delta\phi}{\dot{\phi}}$$

$$\langle \zeta_{\mathbf{k}}\zeta_{\mathbf{k}'}\rangle = \frac{2\pi^2}{k^3}\mathcal{P}_\zeta \delta_{\mathbf{k},\mathbf{k}'}$$

$$P_{\delta\phi} = \left(\frac{H_k}{2\pi}\right)^2$$

$$\mathcal{P}_\zeta(k) = \frac{1}{4\pi}\left(\frac{H^2}{\dot{\phi}}\right)^2\Bigg|_k$$

slow roll inflation

$$\boxed{\mathcal{P}_\zeta(k) = \frac{1}{24\pi^2 M_P^4}\frac{V}{\epsilon}\Bigg|_{k=aH}}$$

Spectral index

$$\boxed{n - 1 \equiv \frac{d\ln\mathcal{P}_\zeta(k)}{d\ln k}}$$

spectral index

$$n(k) - 1 = -6\epsilon + 2\eta$$

running of spectral index

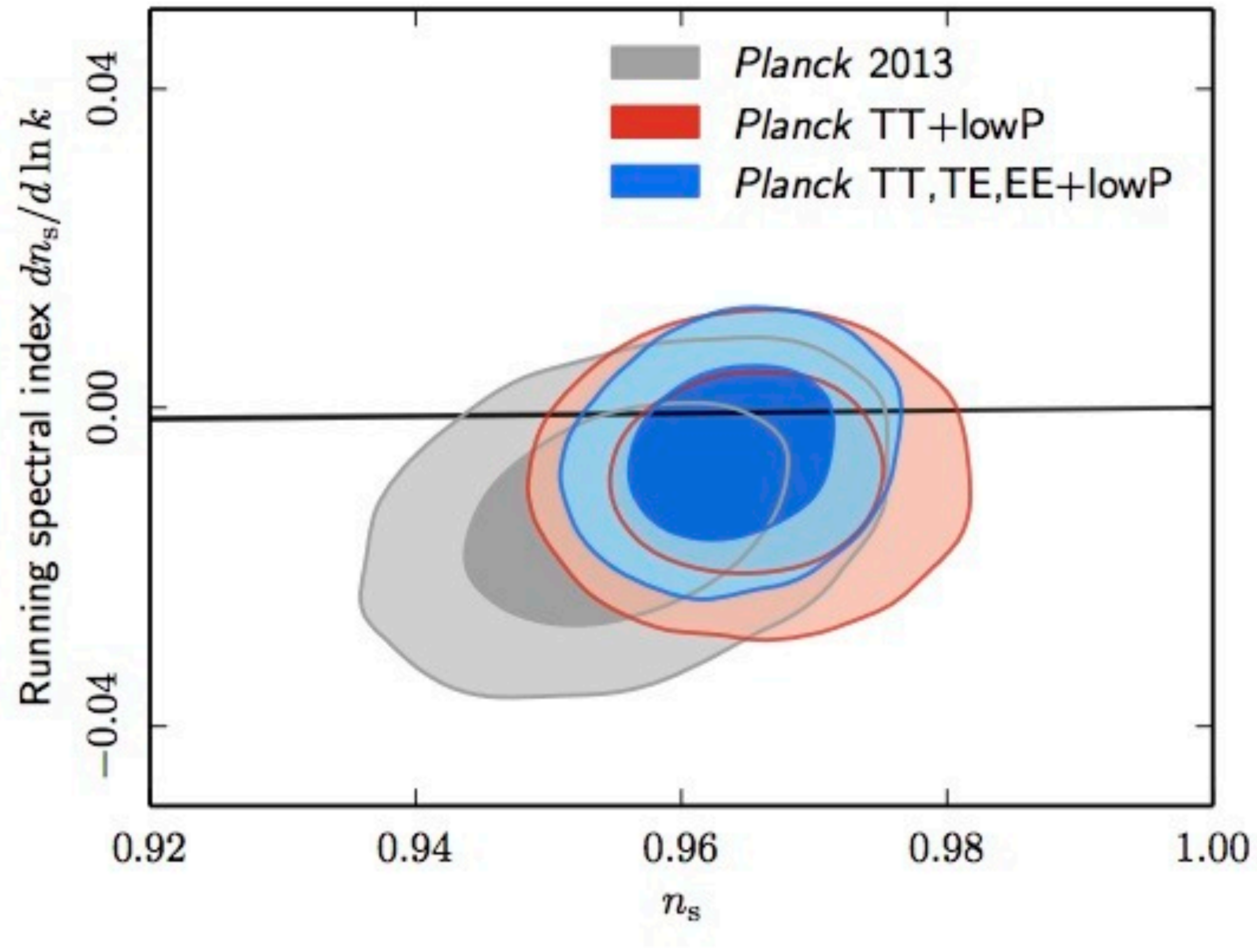
$$dn/d\ln k = -16\epsilon\eta + 24\epsilon^2 + 2\xi$$

slow roll parameters

$$\epsilon(\phi) = \frac{M_P^2}{16\pi}\left(\frac{V'}{V}\right)^2 \qquad \eta = \frac{M_P^2}{8\pi}\frac{V''}{V} \qquad \xi \equiv \frac{M_P^4}{64\pi^2}\frac{V'V'''}{V^2}$$

Cosmology 2

- Constraints from Planck 15

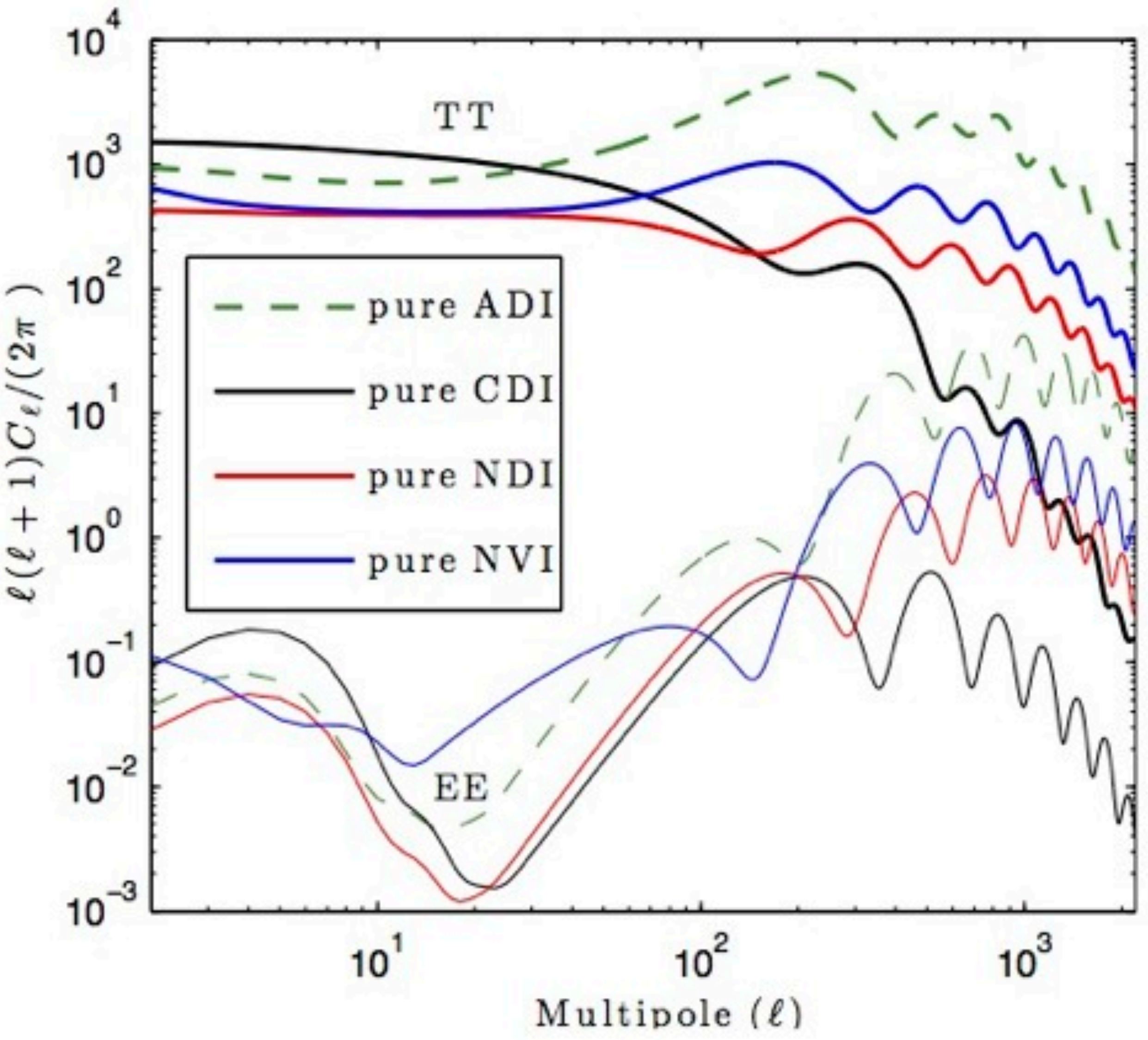


Ade et al.2015 Planck 2015.XX.

Cosmology 2

- Another type of initial condition: isocurvature i.c. $\zeta = 0$

$$\frac{\delta S_{ij}}{S_i} = const. \neq 0$$



ADI - adiabatic mode
CDI - CDM density isocurvature mode
NDI - neutrino density isocurvature mode
NVI - neutrino velocity isocurvature mode

Ade et al.2015 Planck 2015.XX.

Cosmology 2

- Now going back to the baryon-photon fluid. In the tight-coupling limit the equations can be combined to the equation of a forced harmonic oscillator:

$$\ddot{\Delta}_\gamma + \frac{\dot{R}_b}{1+R_b}\dot{\Delta}_\gamma + c^2_{sb\gamma}k^2\Delta_\gamma \simeq \frac{4k^2}{3}\frac{2+R_b}{1+R_b}\Phi,$$

where $R_b \equiv \frac{1}{R}$ and $c^2_{sb\gamma} \equiv \frac{1}{3}\frac{1}{R_b+1}$

$\uparrow$

sound speed of baryon-photon fluid

which is solved by

$$\begin{aligned}\Delta_\gamma(\tau) = \frac{1}{(1+R_b)^{1/4}}\Bigg[&\Delta_\gamma(0)\cos(kr_s(\tau)) \\ &+ \frac{\sqrt{3}}{k}\left[\dot{\Delta}_\gamma(0) + \frac{1}{4}\dot{R}_b(0)\Delta_\gamma(0)\right]\sin(kr_s(\tau)) \\ &+ \frac{\sqrt{3}}{k}\int_0^\tau d\tau'(1+R_b(\tau'))^{3/4} \\ &\times \sin[kr_s(\tau) - kr_s(\tau')]F(\tau')\Bigg],\end{aligned}$$

$$F(\tau) \equiv \frac{4k^2}{3}\frac{2+R_b}{1+R_b}\Phi$$

sound horizon $r_s(\tau) \equiv \int_0^\tau c_{sb\gamma}d\tau'$.

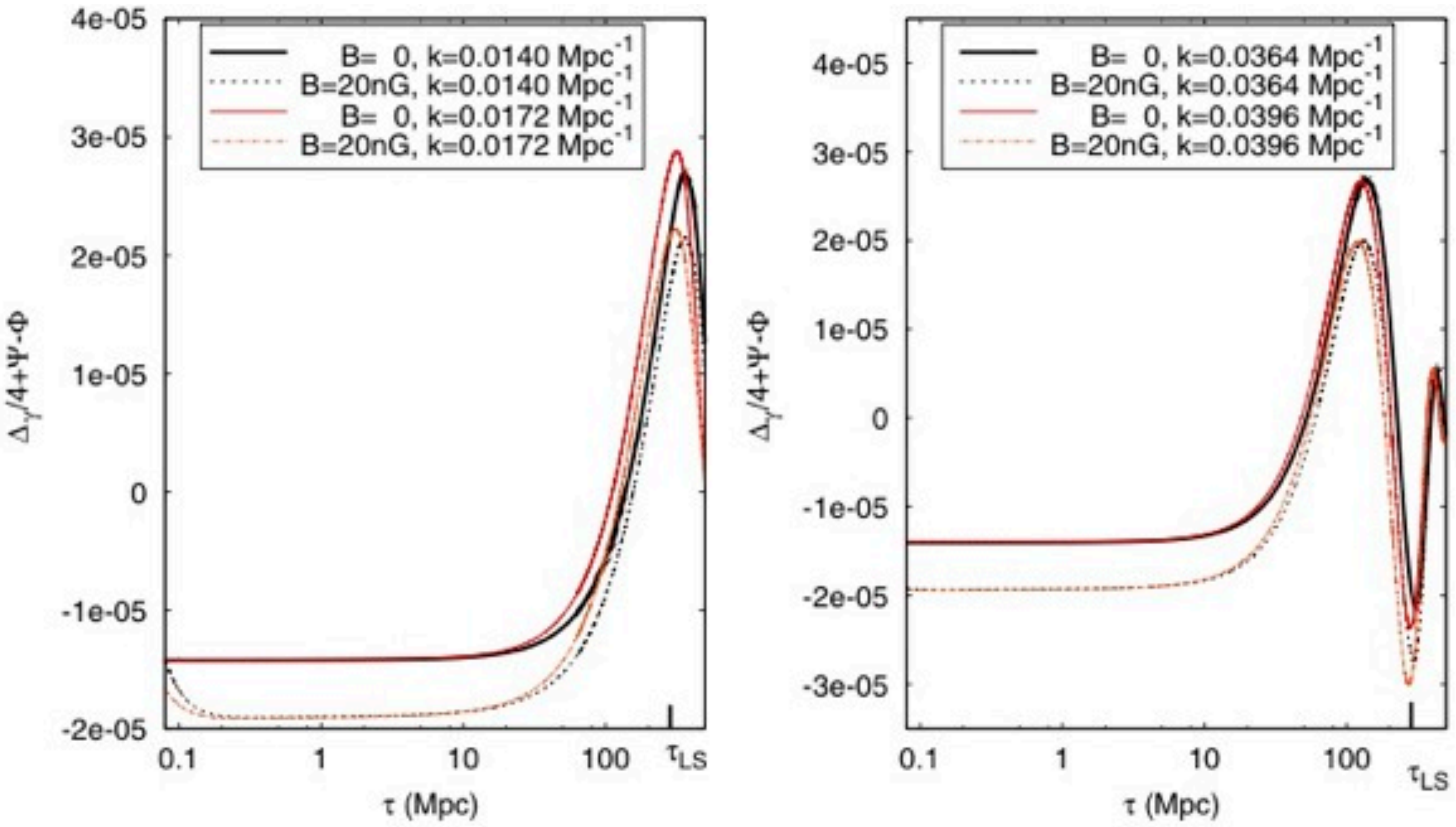
Hu, Sugiyama

Cosmology 2

Effective temperature perturbation for different wave numbers

$$\frac{\Delta_\gamma}{4} + \Psi - \Phi$$

(ignore magnetic field...)



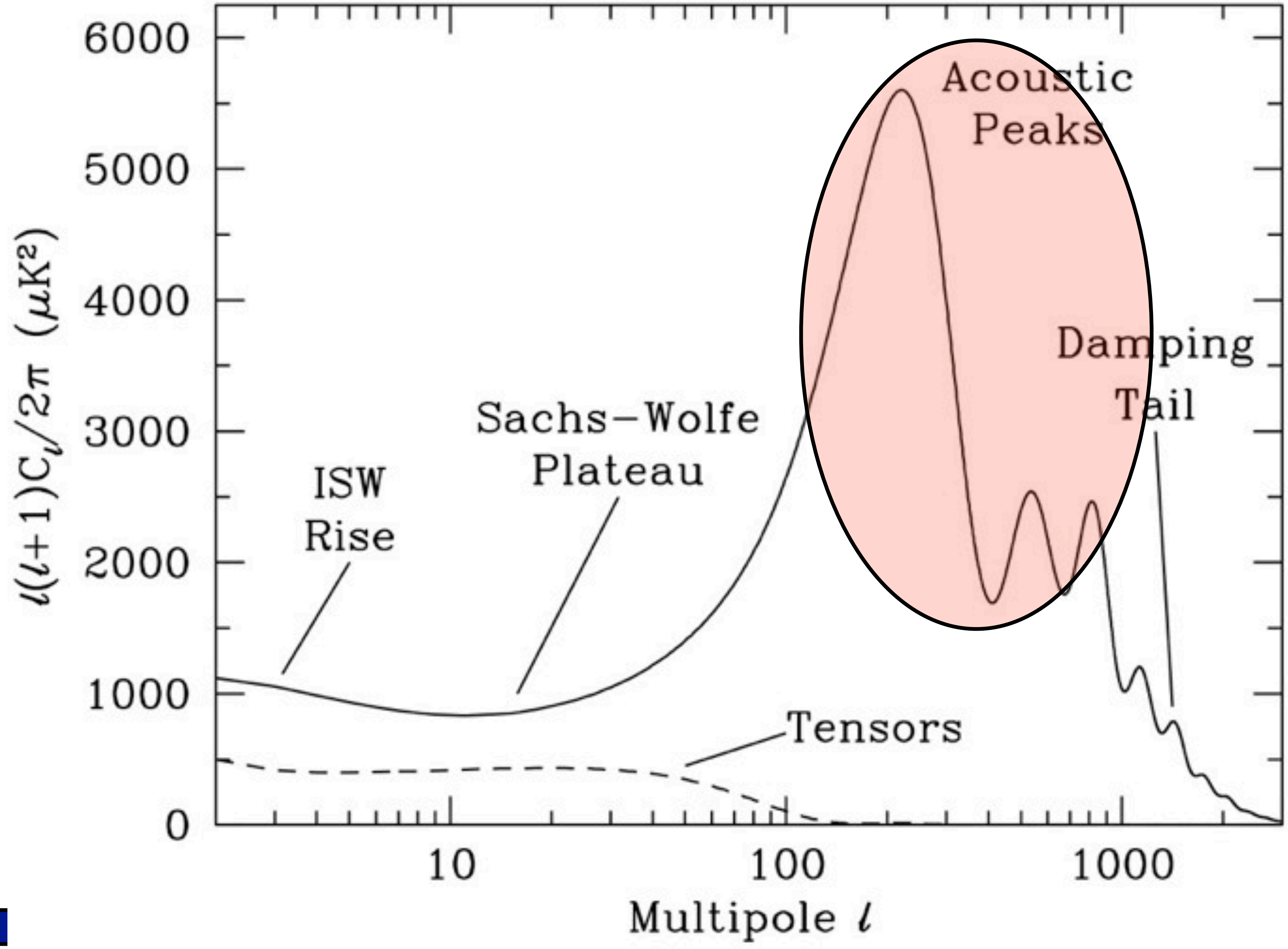
KEK (2011)

FIG. 6 (color online). The numerical solution of the evolution of the effective temperature perturbation is shown for different wave numbers. The WMAP7 best fit solution is shown in comparison with the solution in presence of a stochastic magnetic field with $B = 20$ nG and magnetic spectral index $n_B = -2.9$. Indicated is the time of last scattering, which in this case is $\tau_{\rm LS} = 285$ Mpc. *Left*: The solutions for the wave numbers $k = 0.0140$ Mpc^{-1} and $k = 0.0172$ Mpc^{-1} have a maximum at the time of last scattering. These wave numbers correspond to the region of the first acoustic peak, whereas the former corresponds to $\ell = 200$, the latter corresponds to $\ell = 244$. *Right*: The solutions for the wave numbers $k = 0.0364$ Mpc^{-1} and $k = 0.0396$ Mpc^{-1} have a minimum at the time of last scattering. These wave numbers correspond to the region of the second acoustic peak, whereas the former corresponds to $\ell = 523$, the latter corresponds to $\ell = 569$.

Cosmology 2

(PDG 2014)

- Features in the angular power spectrum



Cosmology 2

- Damping tail

- Close to last scattering photons and baryons are no longer strongly coupled leading to diffusion damping (Silk damping) of density perturbations.

- Amplitudes are multiplied by a factor

$$\exp(-k^2/k_D^2(\eta))$$

Silk scale (photon diffusion scale) k_D^{-1}
is roughly the comoving distance that
a photon has time to travel since
some some initial time.

Cosmology 2

- To calculate photon diffusion scale: Model movement of photon in local baryon rest frame as random walk. Mean time between collisions:

$$t_c \sim (n_e \sigma_T)^{-1}$$

- Average number of steps in time t:

$$N = t/t_c$$

- During t the photon diffuses a distance: $d \sim \sqrt{N} t_c \sim (t t_c)^{1/2}$

⇒ $$\boxed{a k_D^{-1} \simeq \left(\frac{t}{n_e \sigma_T} \right)^{\frac{1}{2}}}$$

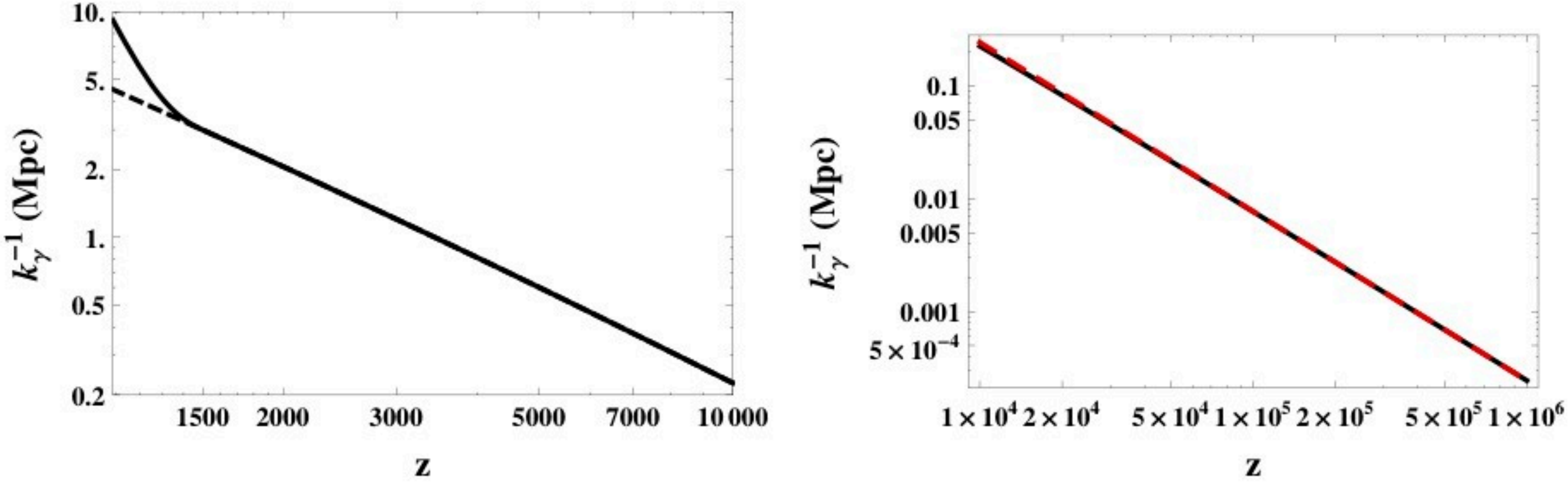
- during matter domination: $k_D^{-1} \sim a^{5/4}$

- during radiation domination: $k_D^{-1} \sim a^{3/2}$

Each scale k^{-1} starts out bigger than the Silk scale at horizon entry with photon diffusion damping setting in when

$$k_D(\eta) = k$$

Cosmology 2



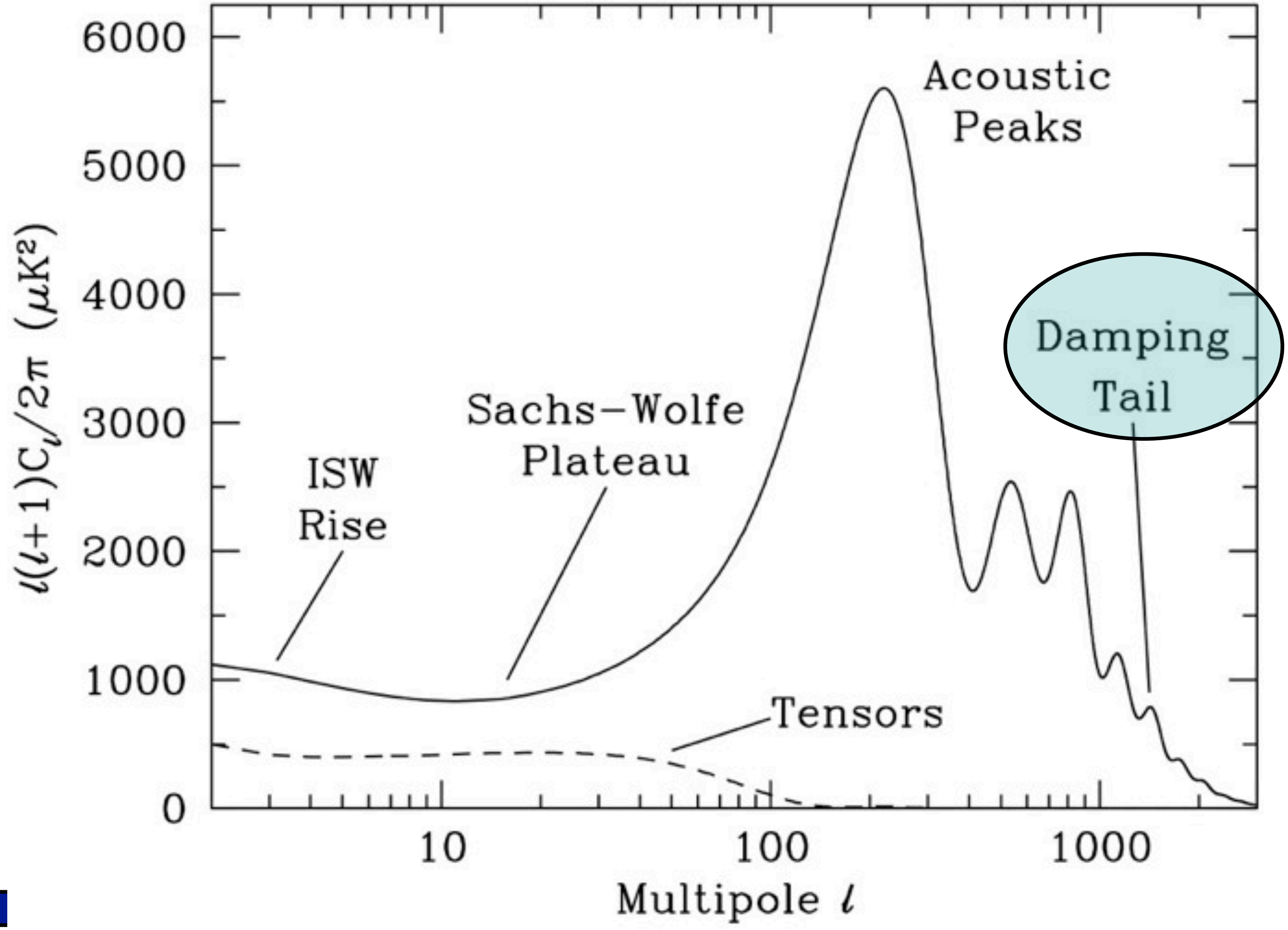
Evolution of photon diffusion scale as function of redshift z

(KEK, Komatsu (2014) based on model of Hu, Sugiyama (1995))

Cosmology 2

(PDG 2014)

- Features in the angular power spectrum



Cosmology 2

- **Sachs-Wolfe contribution**

- For all scales the solution of the Boltzmann hierarchy is formally given by a **line-of-sight integral** (Seljak, Zaldarriaga):

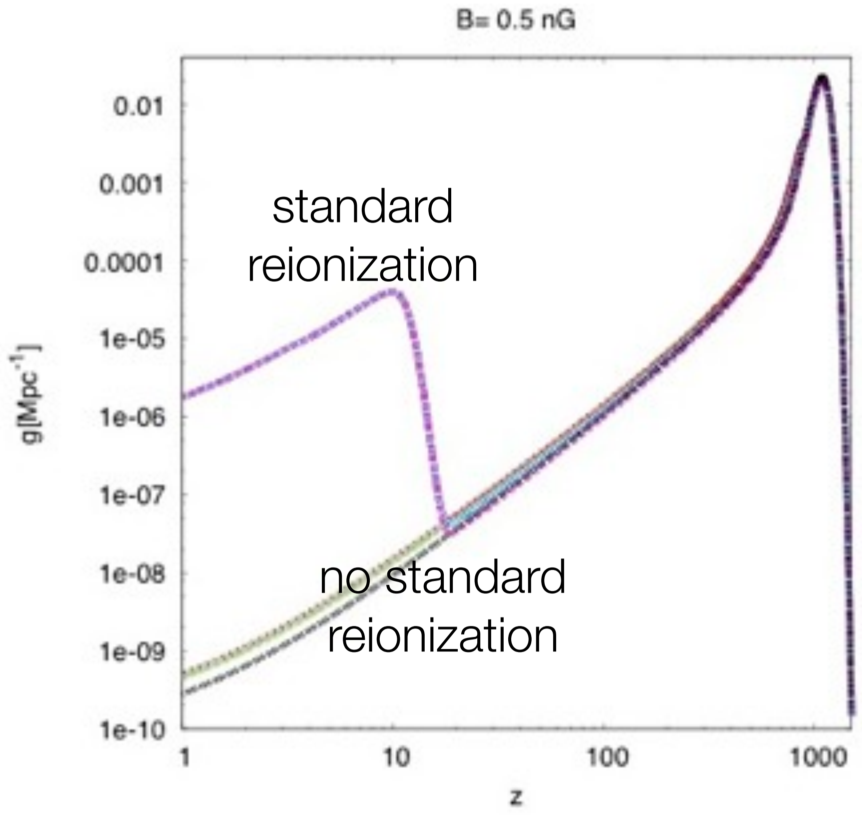
$$\Delta_\ell^{(s)}(q) = \int_{\eta_{in}}^{\eta_0} d\eta \underbrace{S(k,\eta)}_{\text{source function}} j_\ell[k(\eta_0 - \eta)]$$

- Split source function into contributions from the Sachs-Wolfe term (SW), integrated Sachs-Wolfe term (ISW), the Doppler term (dop) and a term related to polarisation (pol), in the newtonian gauge:

Cosmology 2

$$\Delta_\ell^{(s)}(q) = \int_{\eta_{in}}^{\eta_0} d\eta S(k,\eta) j_\ell[k(\eta_0-\eta)]$$

$$S = \sum_i S_i$$



visibility function

$$g = \dot\tau e^{-\tau}$$

optical depth

$$S_{SW} = g\left(\frac{\delta_\gamma}{4}+\psi\right)$$

$$S_{ISW} = g\,(\phi-\psi) + e^{-\tau} 2\dot\phi$$

$$S_{dop} = k^{-2}\left(g\dot\theta_b + \dot g\theta_b\right)$$

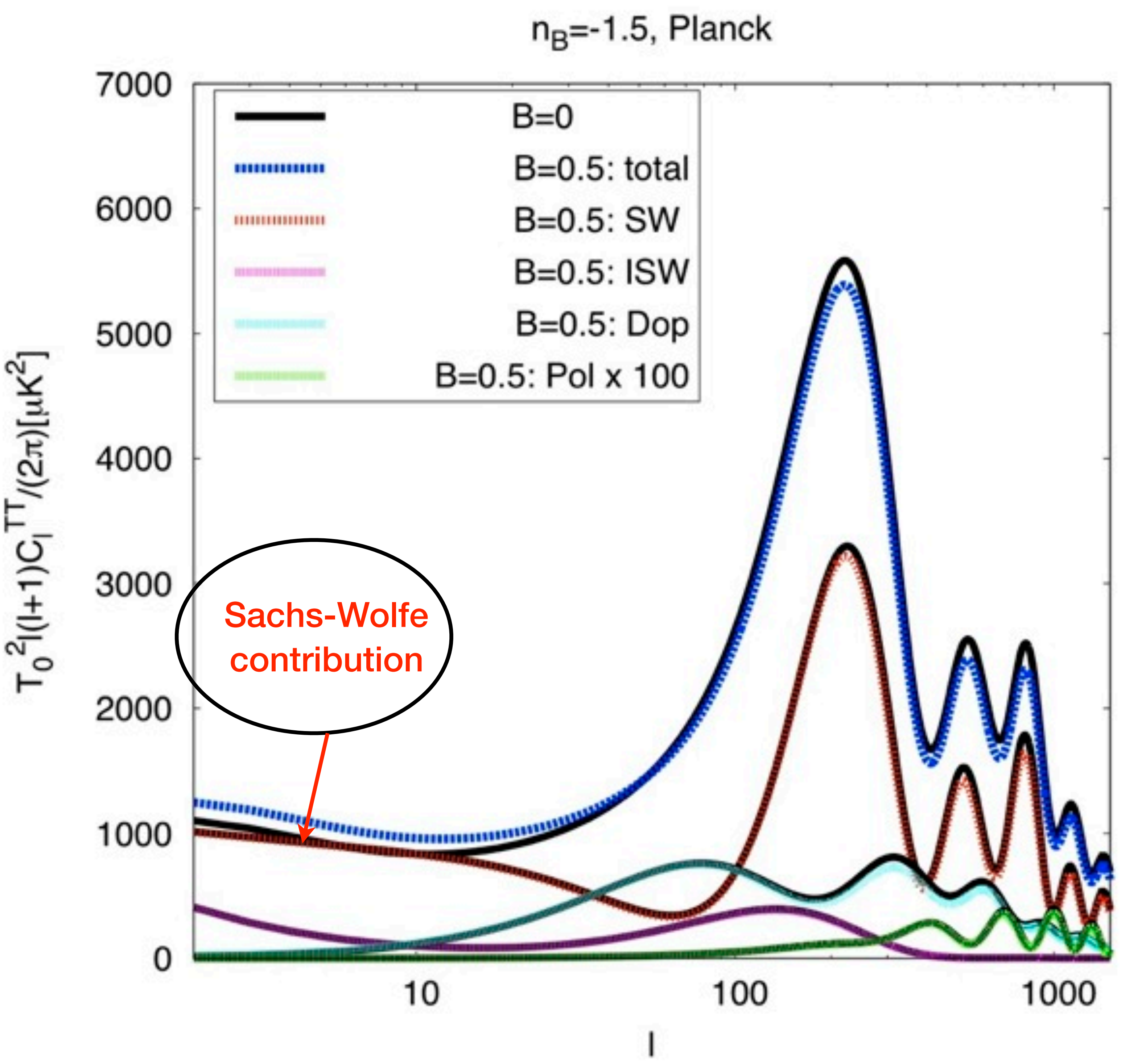
$$S_{pol} = gP^{(0)}$$

$$\tau(t) = \sigma_T \int_t^{t_0} n_e(t)dt$$

number density of free electrons

$e^{-\tau(t)}$: probability that a CMB photon observed today has not scattered since time t.

Cosmology 2



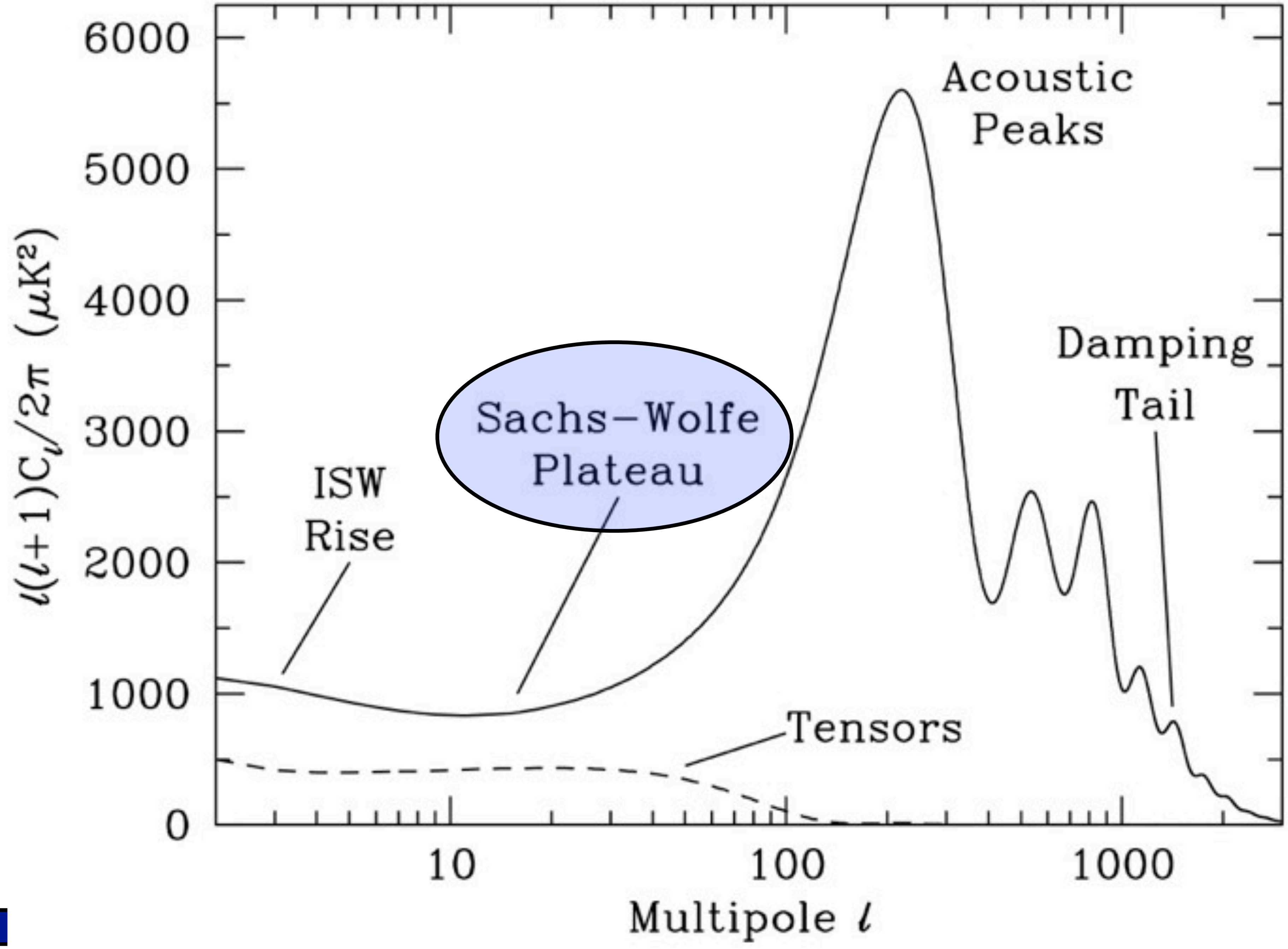
Sachs-Wolfe contribution

Ignore magnetic field parameters (B, nB)

Cosmology 2

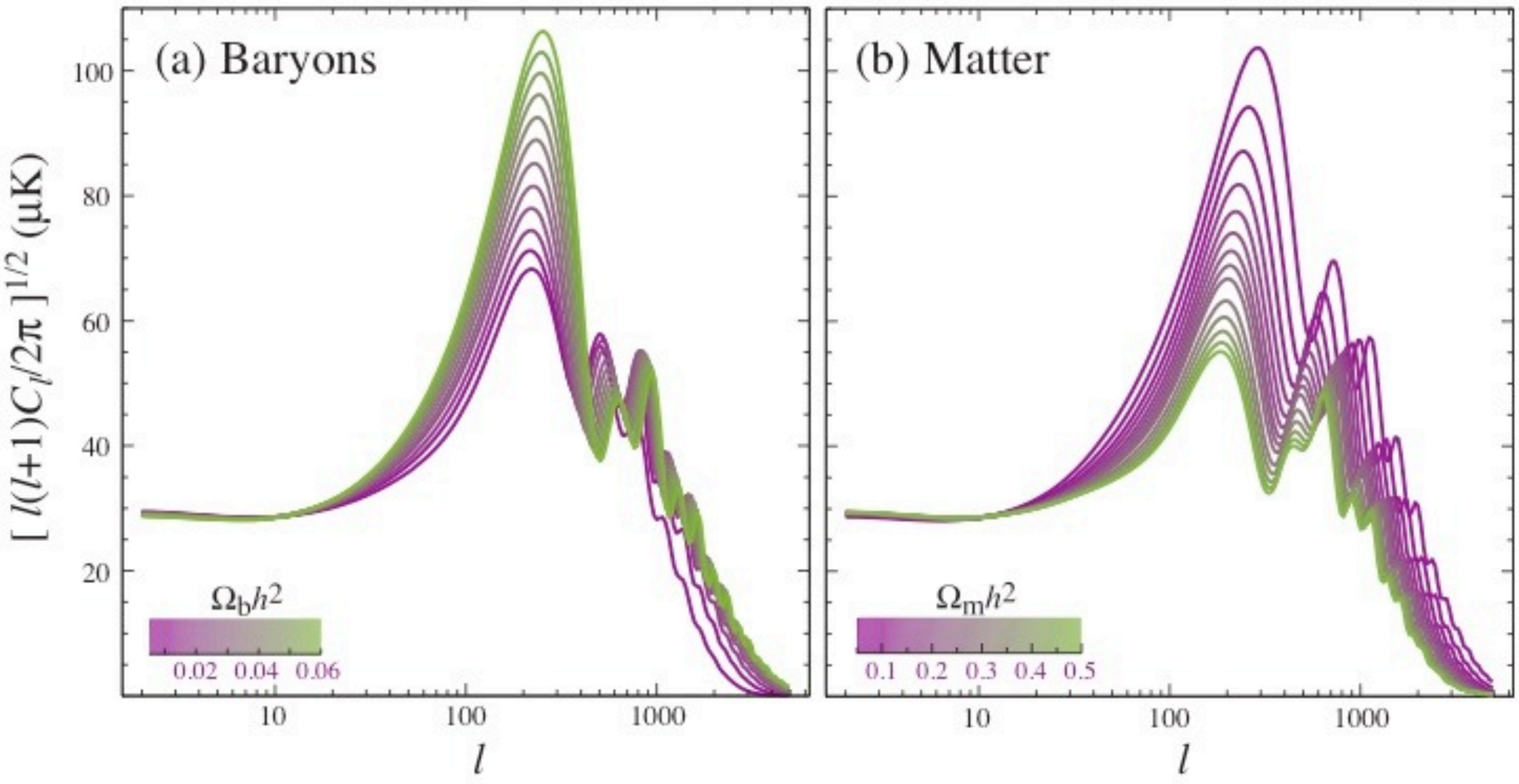
(PDG 2014)

- **Features in the angular power spectrum**



Cosmology 2

- Changing cosmological parameters



Hu (2008)

Cosmology 2

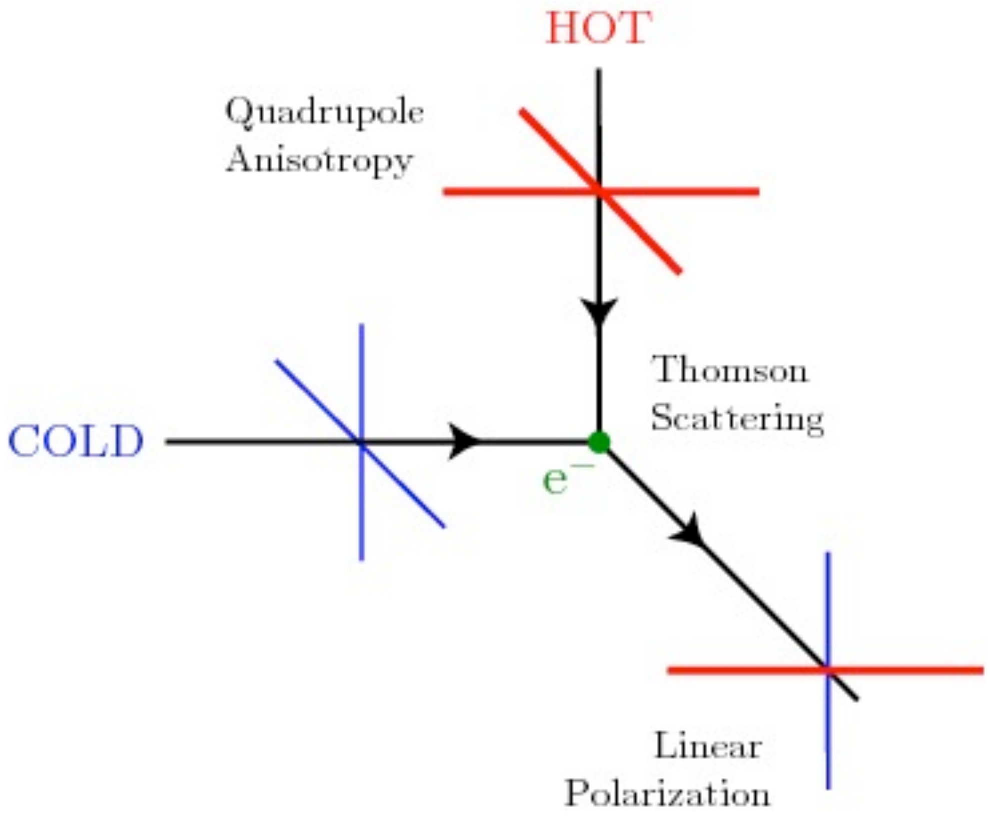
- What else do we see?

➡ Polarization

Thomson scattering

●Isotropic radiation scatters into unpolarized radiation

●Radiation with quadrupole anisotropy scatters into linearly polarized radiation.



Hu,White

Cosmology 2

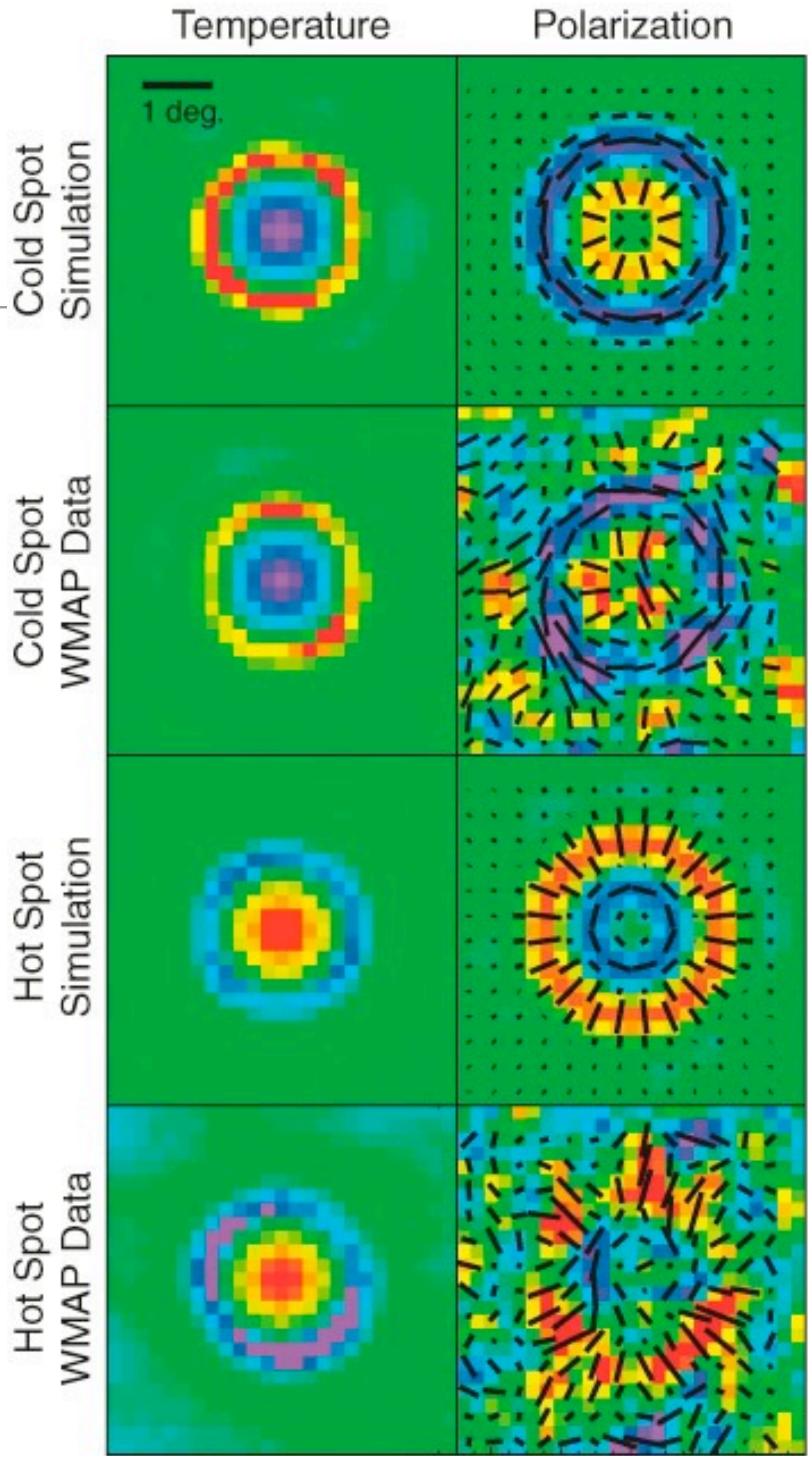
- To describe polarization use polarization tensor

- For linearly polarized radiation it is parametrized by the Stokes parameters:

  I: intensity
  Q, U : specify
  plane polarization

- Q,U $\xrightarrow{\text{transform}}$ E-mode, B-mode

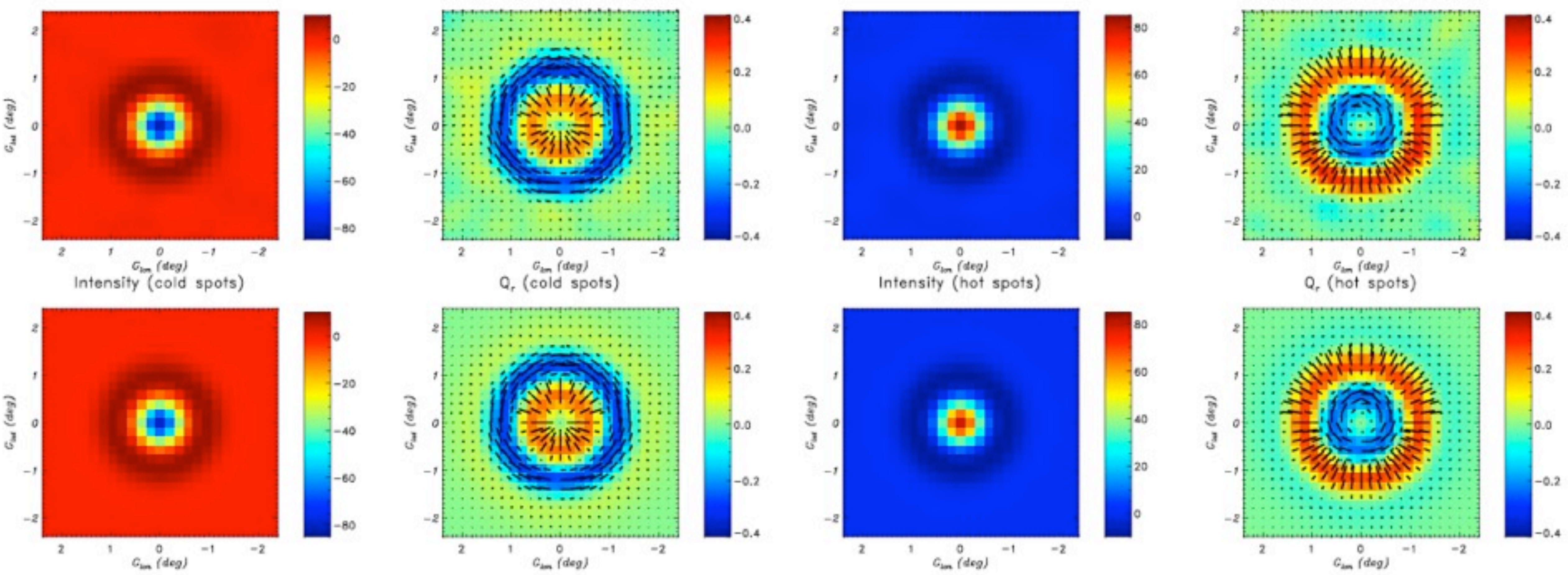
  E-mode: "grad" component
  B-mode: "curl" component



WMAP 7

Cosmology 2

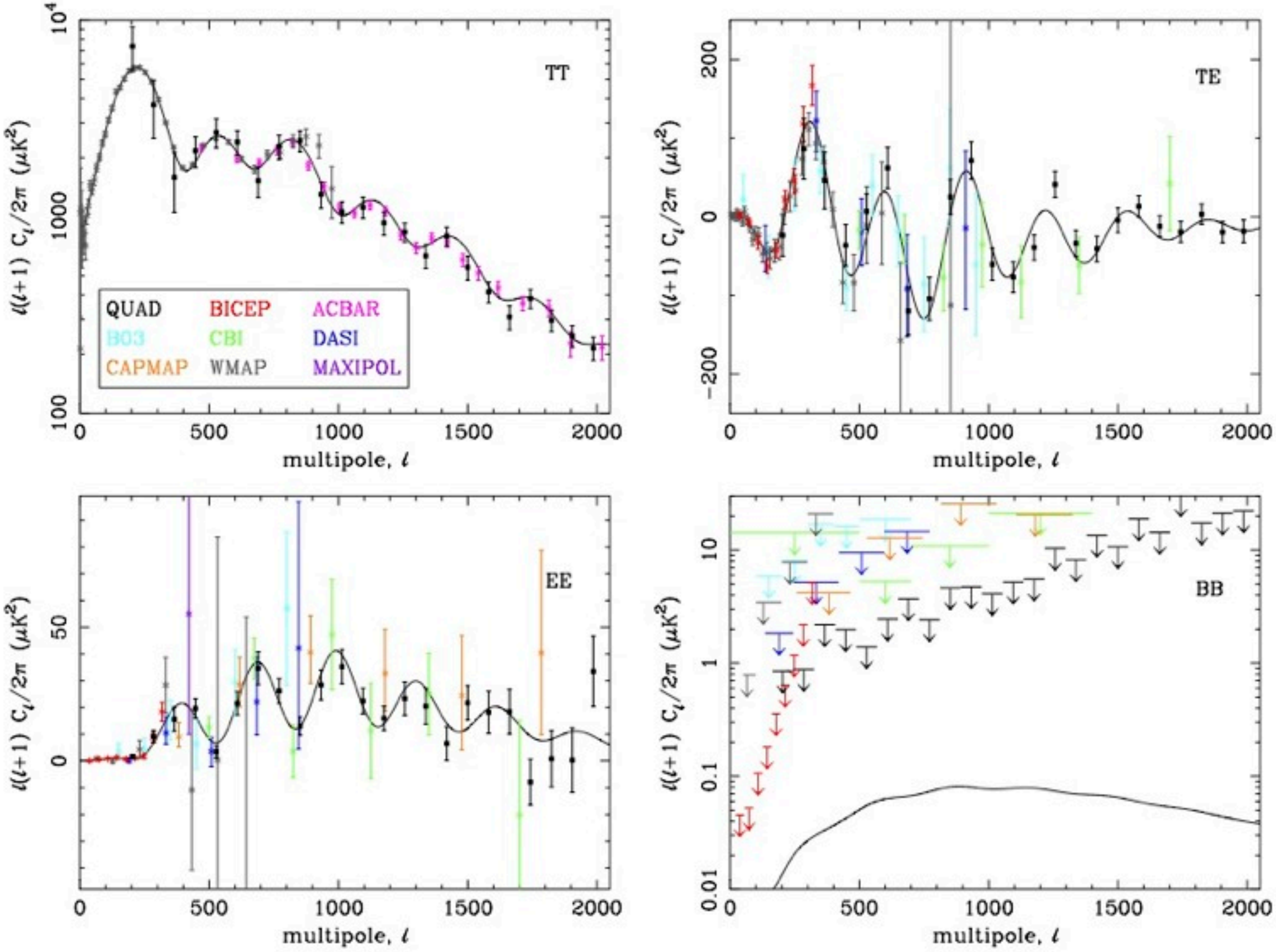
measured



simulation

Planck13

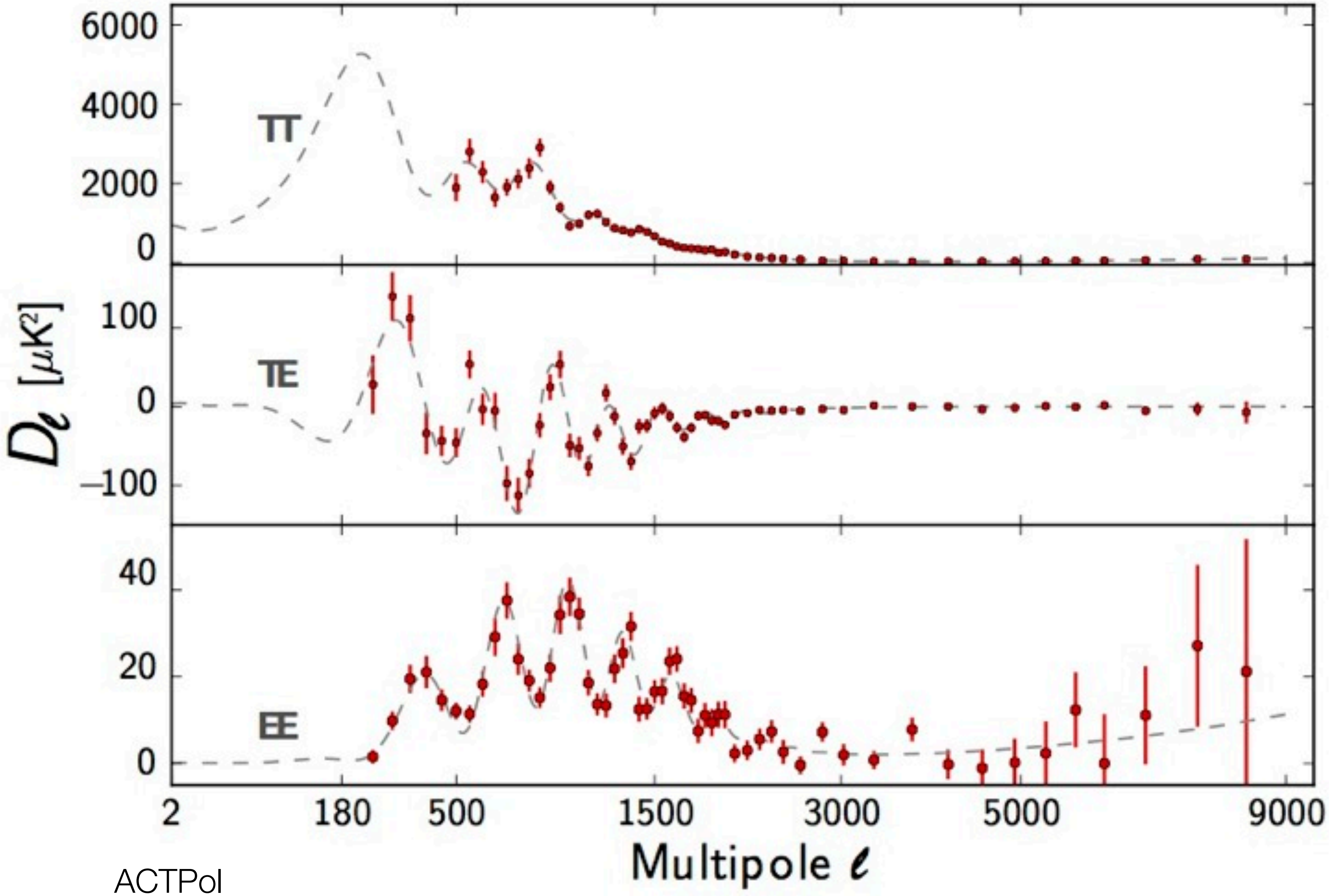
Cosmology 2



QUaD
Brown et al. 2009

Cosmology 2

The **ACTPol** TT, TE, and EE power spectra, together with the best-fitting ΛCDM cosmological model and foreground components.

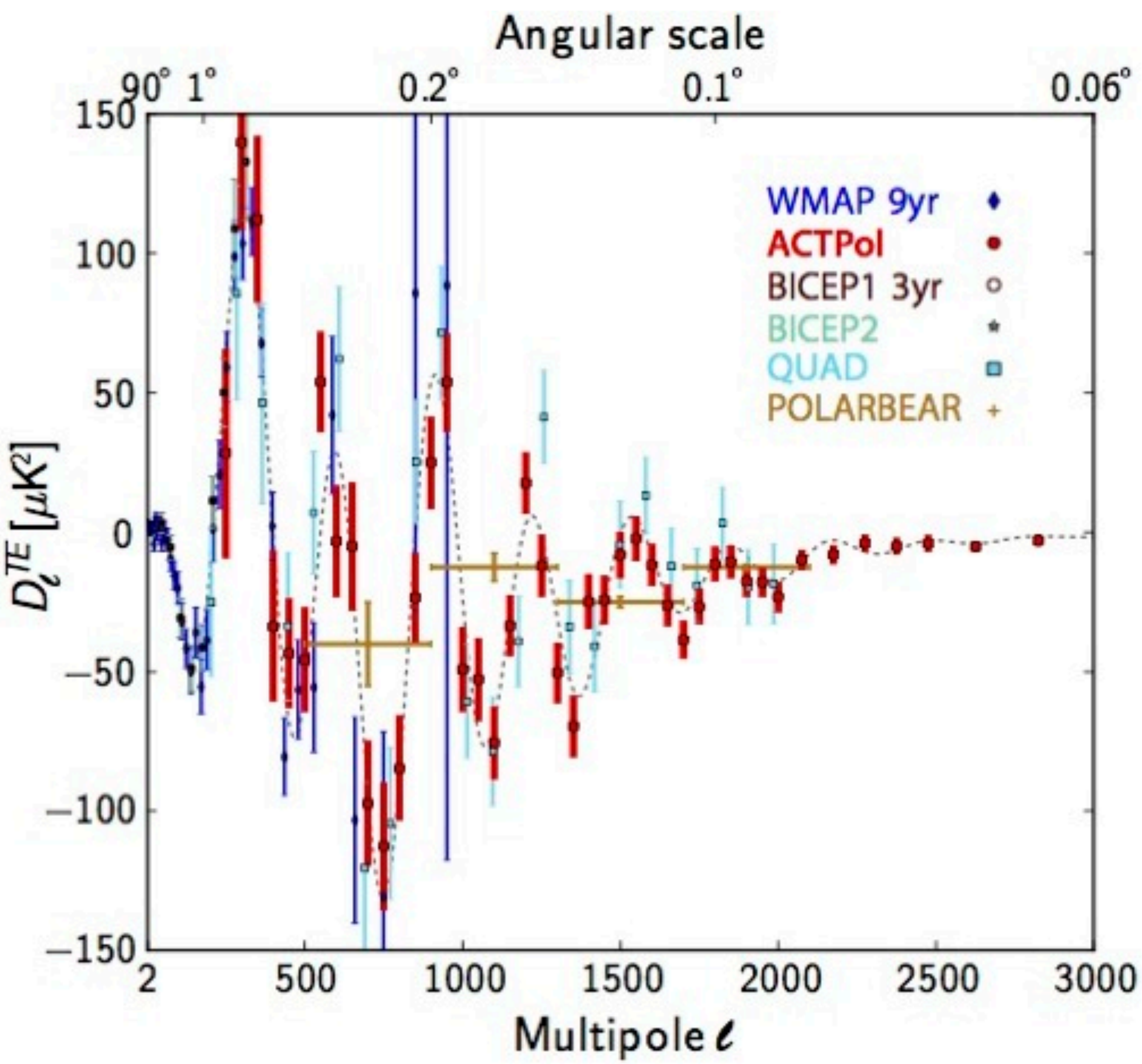


ACTPol
Naess et al. 2014

Six acoustic peaks are seen in the E-mode polarization, out of phase with the temperature peaks and with the TE correlation pattern predicted by the standard model.

Cosmology 2

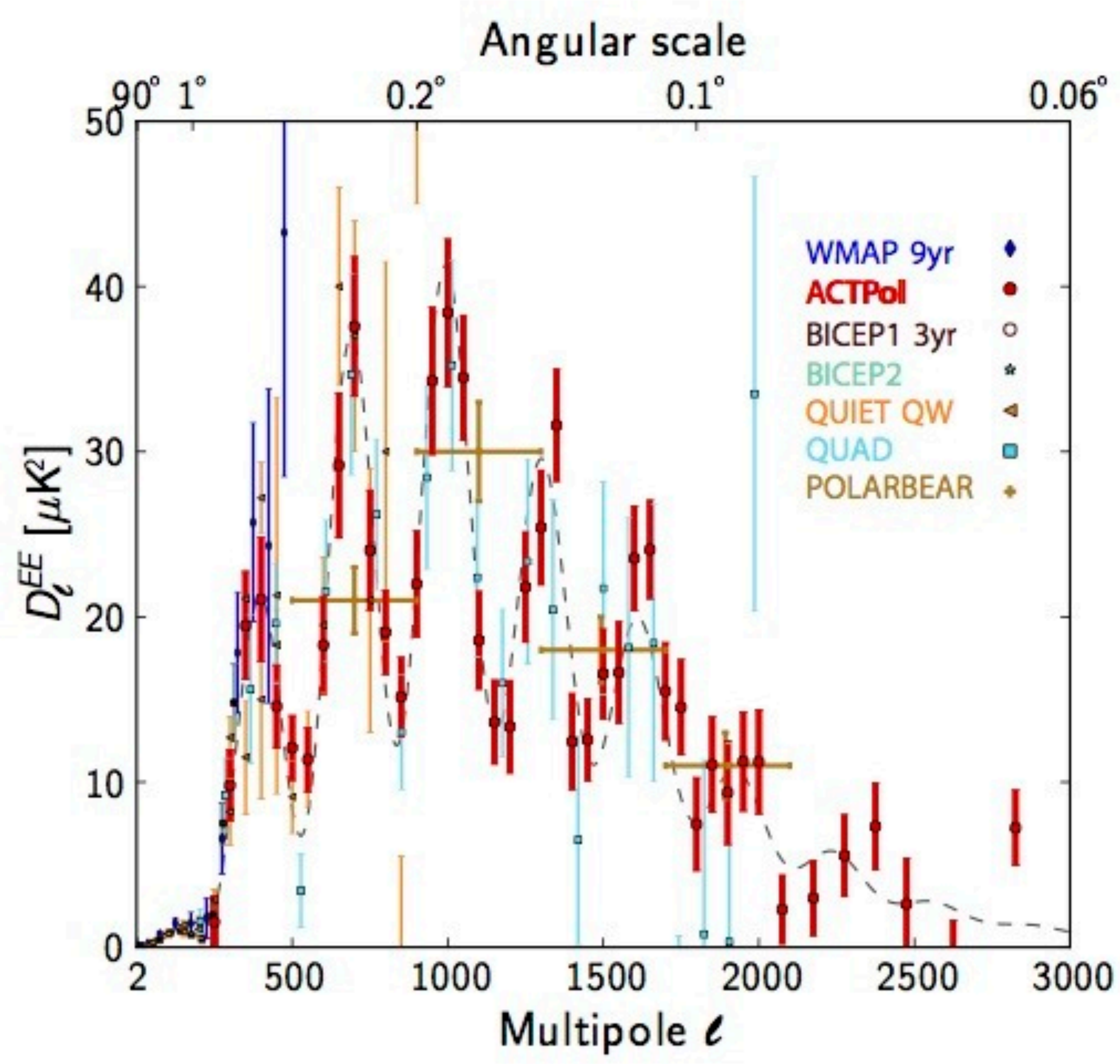
TE cross correlation



ACTPol
Naess et al. 2014

Cosmology 2

EE auto correlation



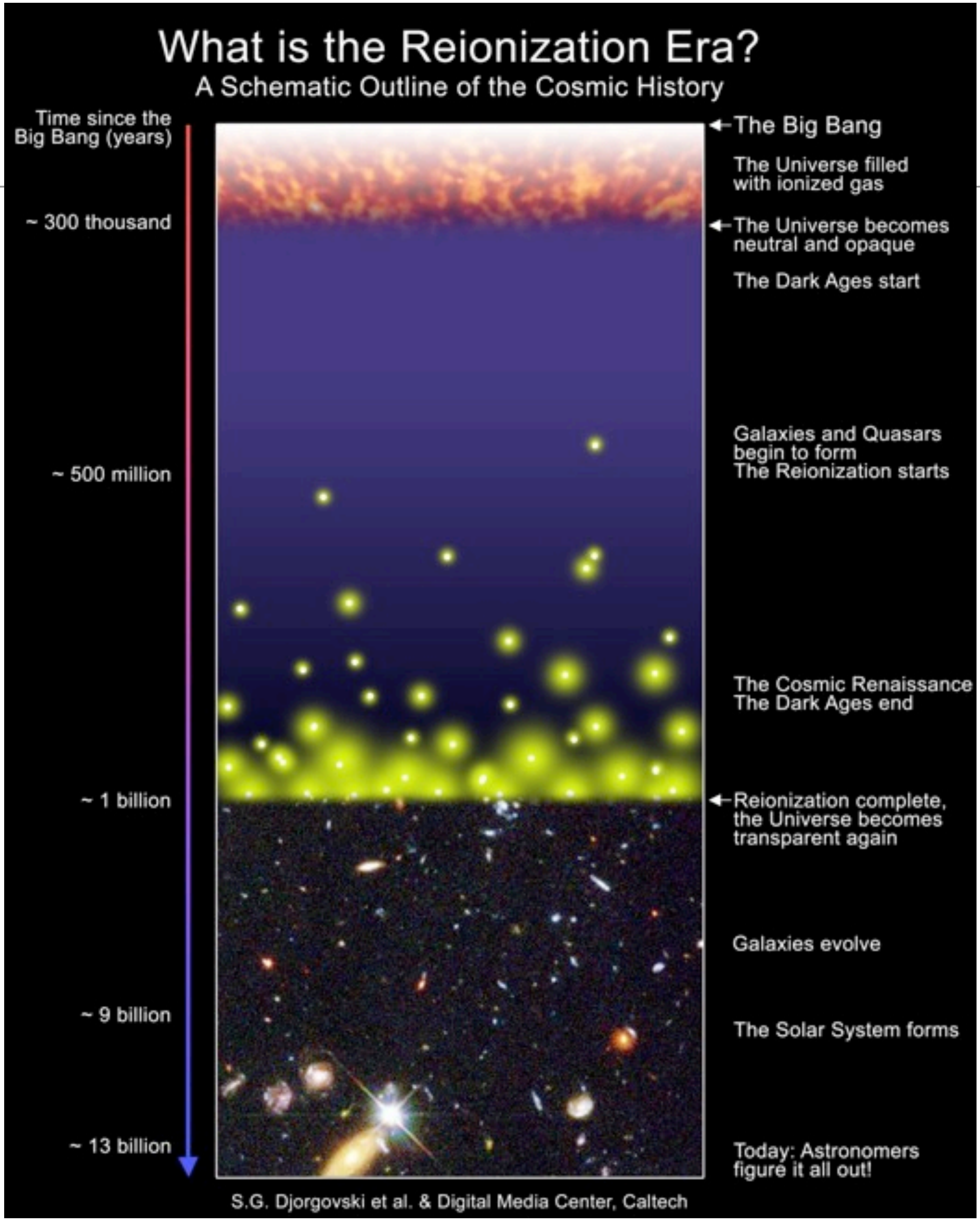
ACTPol
Naess et al. 2014

Cosmology 2

- **Reionization**

An interesting feature in the CMB polarization signal has been detected which is related to the more recent history of the universe: the universe is completely **reionized** today.

Although, to be precise, the fact that the universe is reionized today was detected by observations of quasars before that.

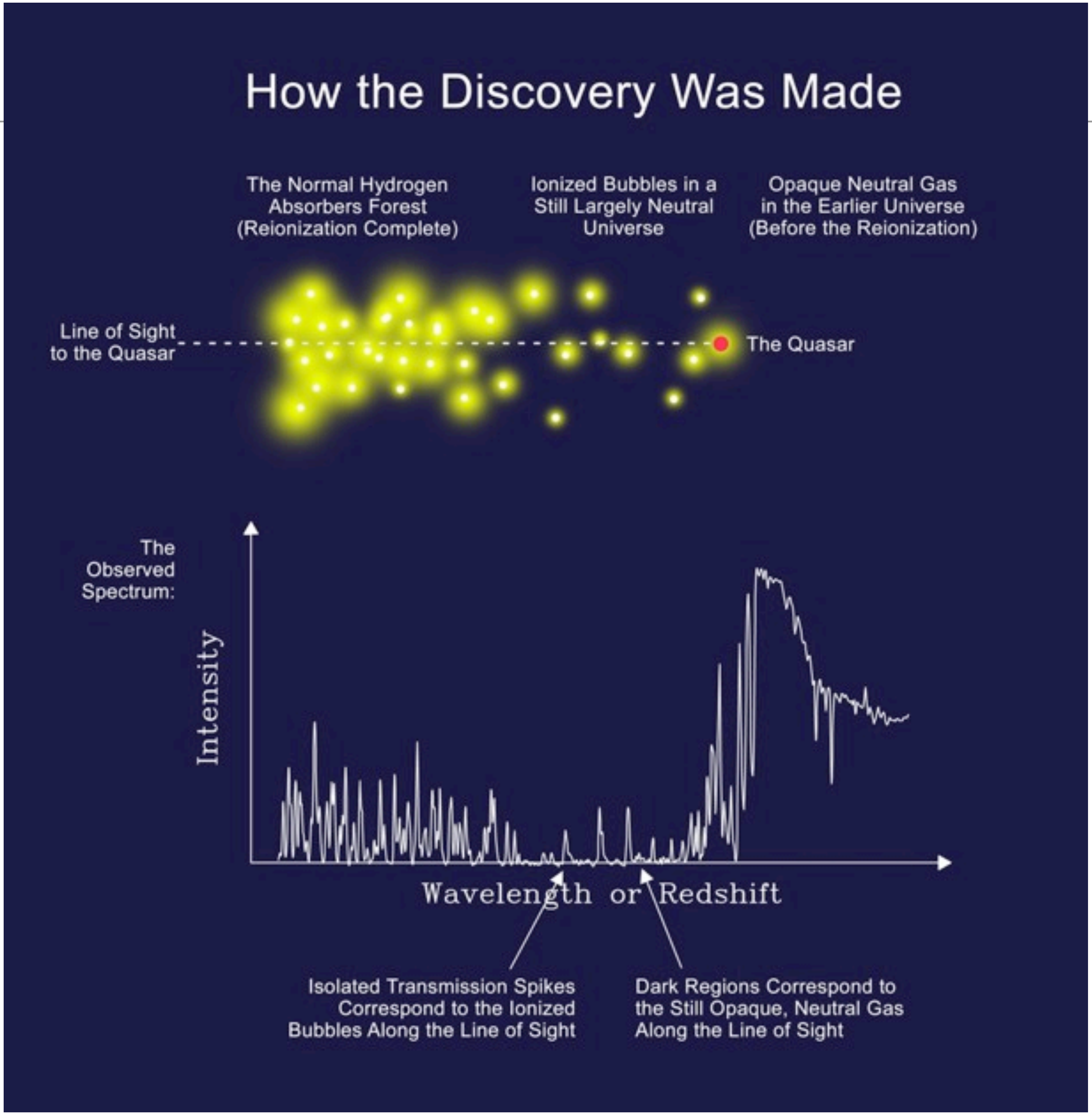


Caltech

Cosmology 2

- Reionization

Evidence from quasar spectrum

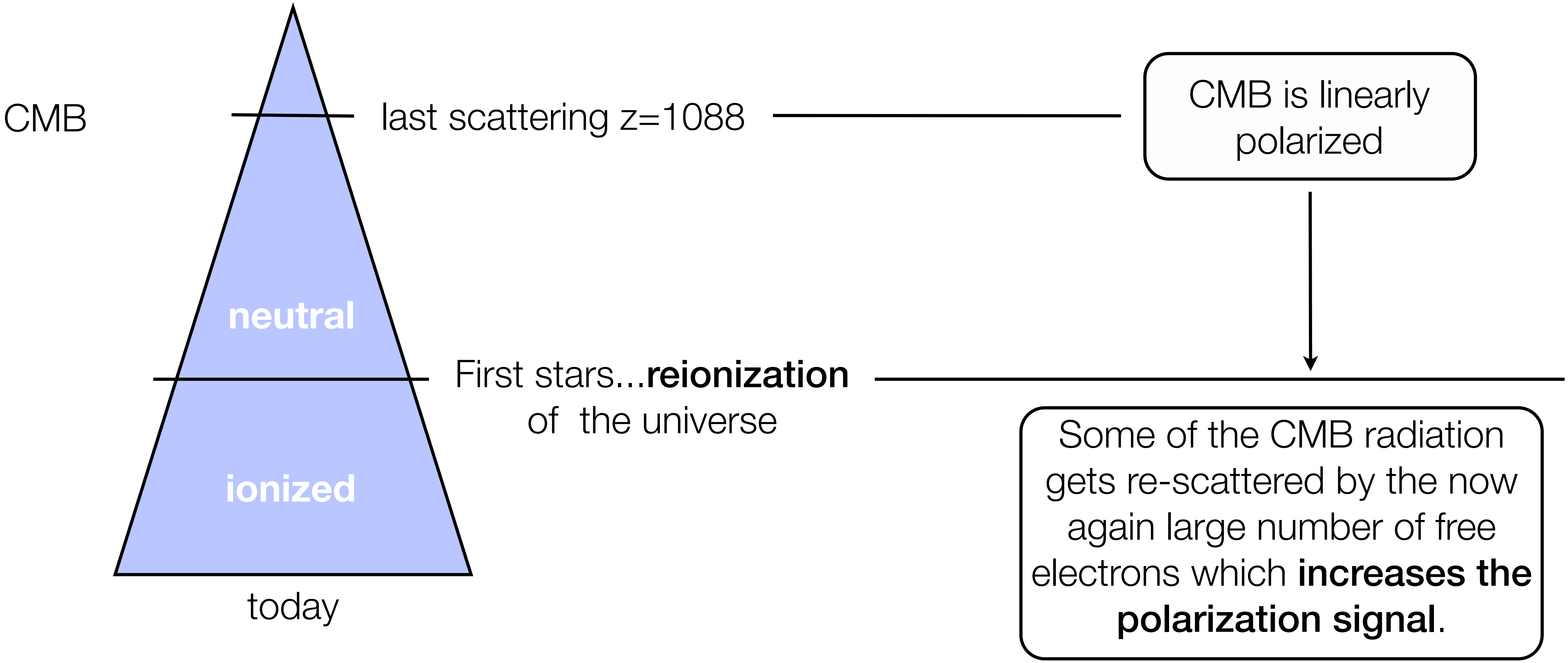


If neutral hydrogen present, then absorption at Lyα transition. So if there is transmission, hydrogen is ionized. (Gunn-Petersen)

Cosmology 2

- Reionization

- Evidence from the ***polarization of the cosmic microwave background***



last scattering z=1088

CMB is linearly polarized

First stars...**reionization** of the universe

Some of the CMB radiation gets re-scattered by the now again large number of free electrons which **increases the polarization signal**.

Cosmology 2

- The reionization generated polarization signal is redshift dependent:

- allows to constrain ionization history

- allows to determine ***when*** reionization took place

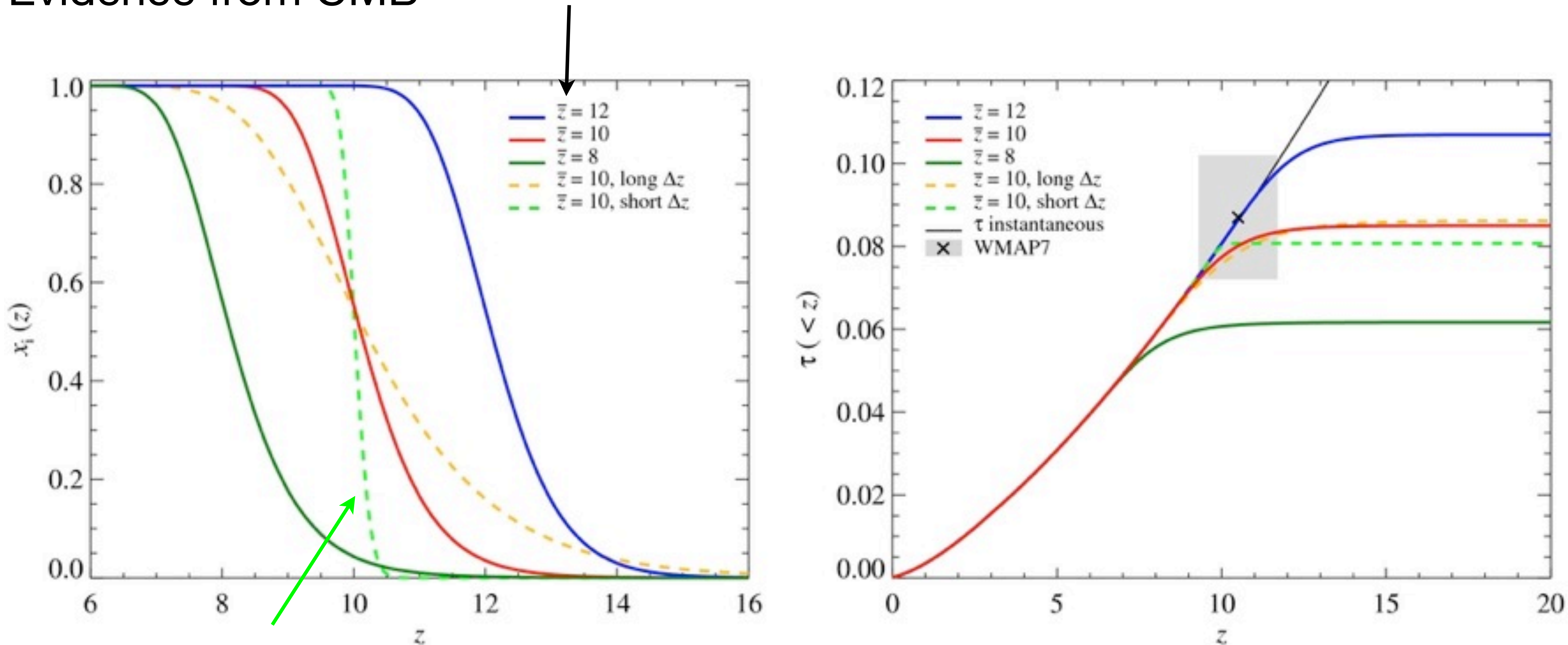
Cosmology 2

- Reionization

ionization history

- Evidence from CMB

reionization redshift



instant reionization

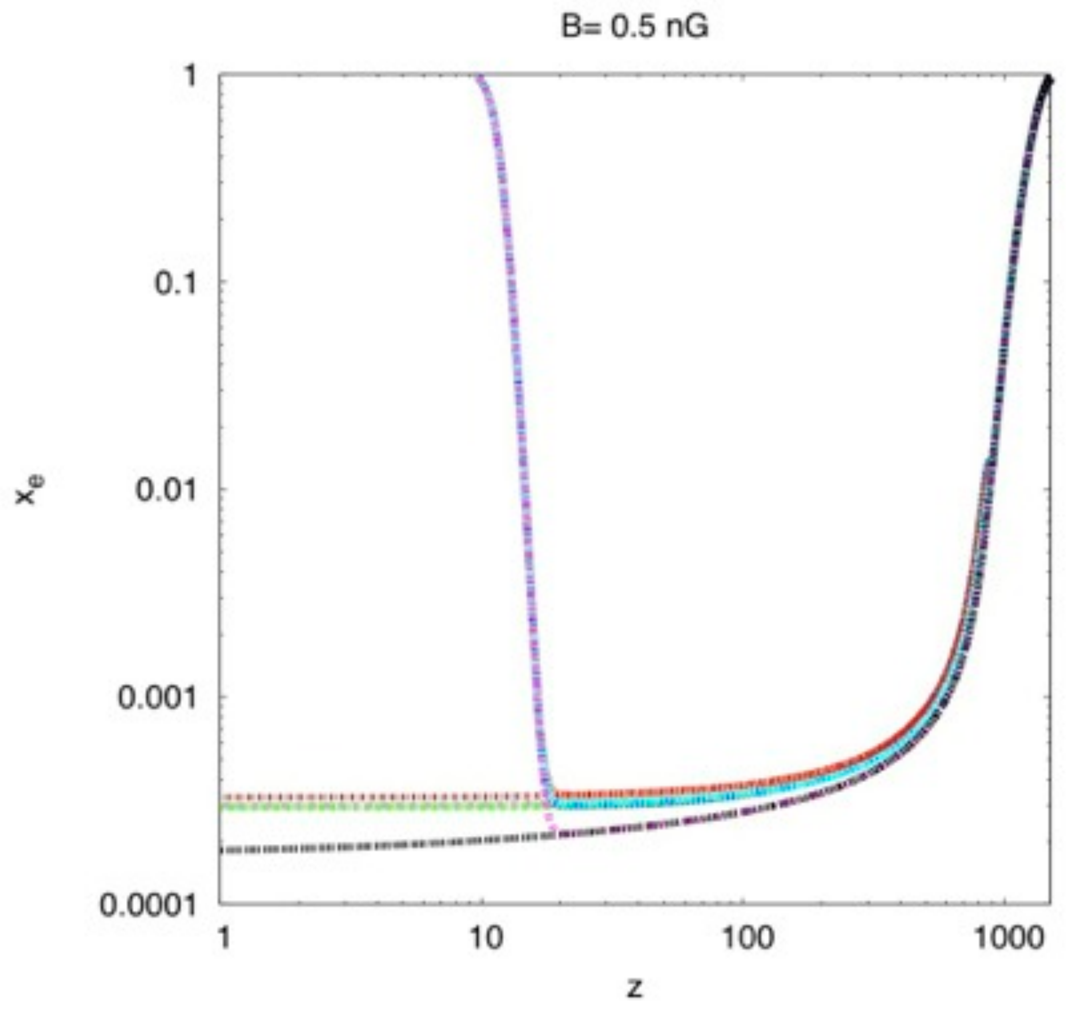
Battaglia et al. 2013

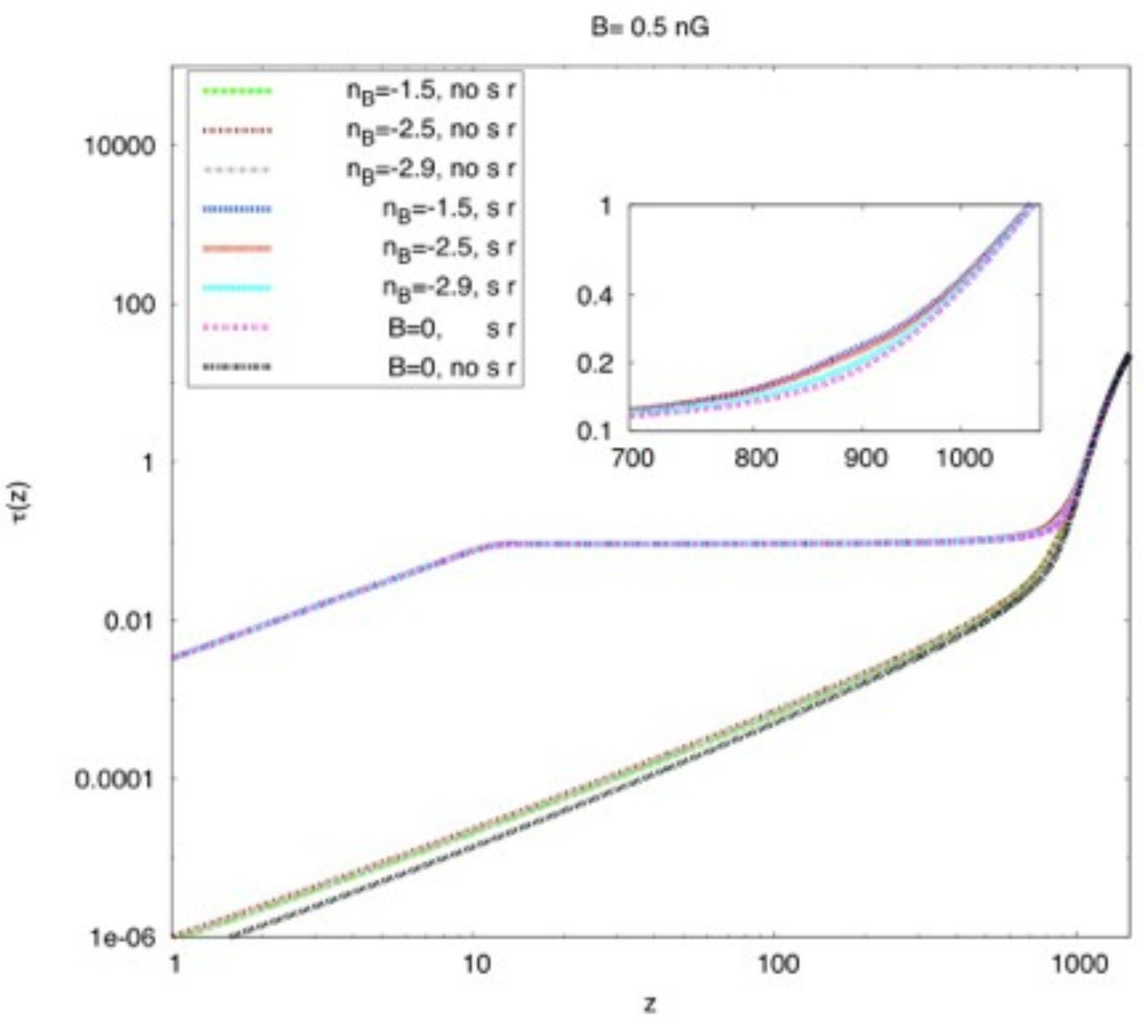
Cosmology 2

- Reionization

ionization history: from decoupling to close to the present

to put it in context (ignore magnetic field contributions...)



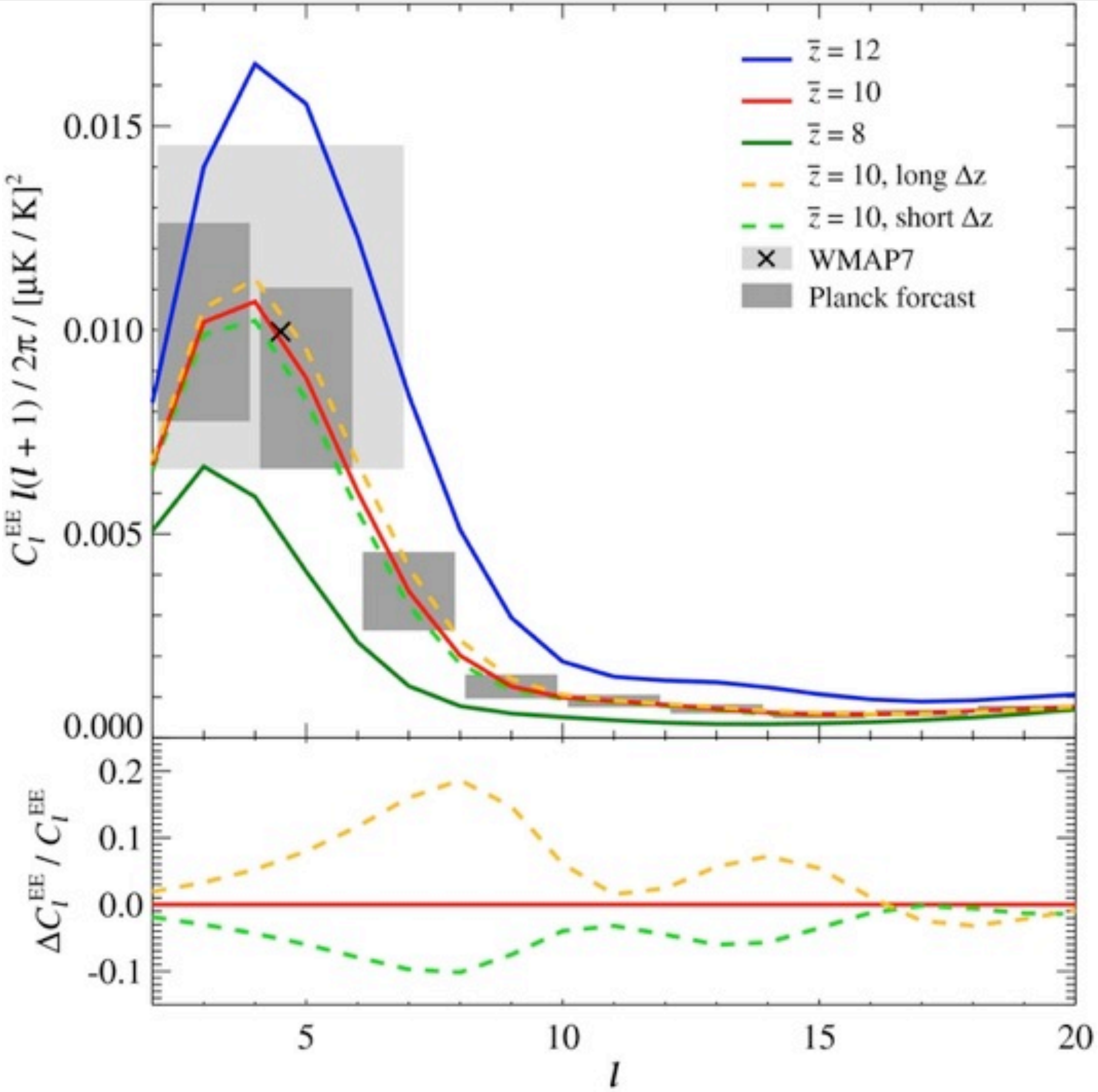


KEK, Komatsu 2015

Cosmology 2

- Reionization

low l EE polarization
power spectrum



Battaglia et al. 2013

Cosmology 2

- CMB spectral distortions

- Spectrum well fitted by Planck black body spectrum

$$n_\nu = \left[\exp\left(\frac{h\nu}{kT}\right) - 1\right]^{-1}$$

$$B_\nu(T) = \frac{2h\nu^3/c^2}{\exp\left(\frac{h\nu}{kT}\right) - 1}$$

- Spectral distortions: y- and μ-type are small

FIXSEN ET AL. 1996

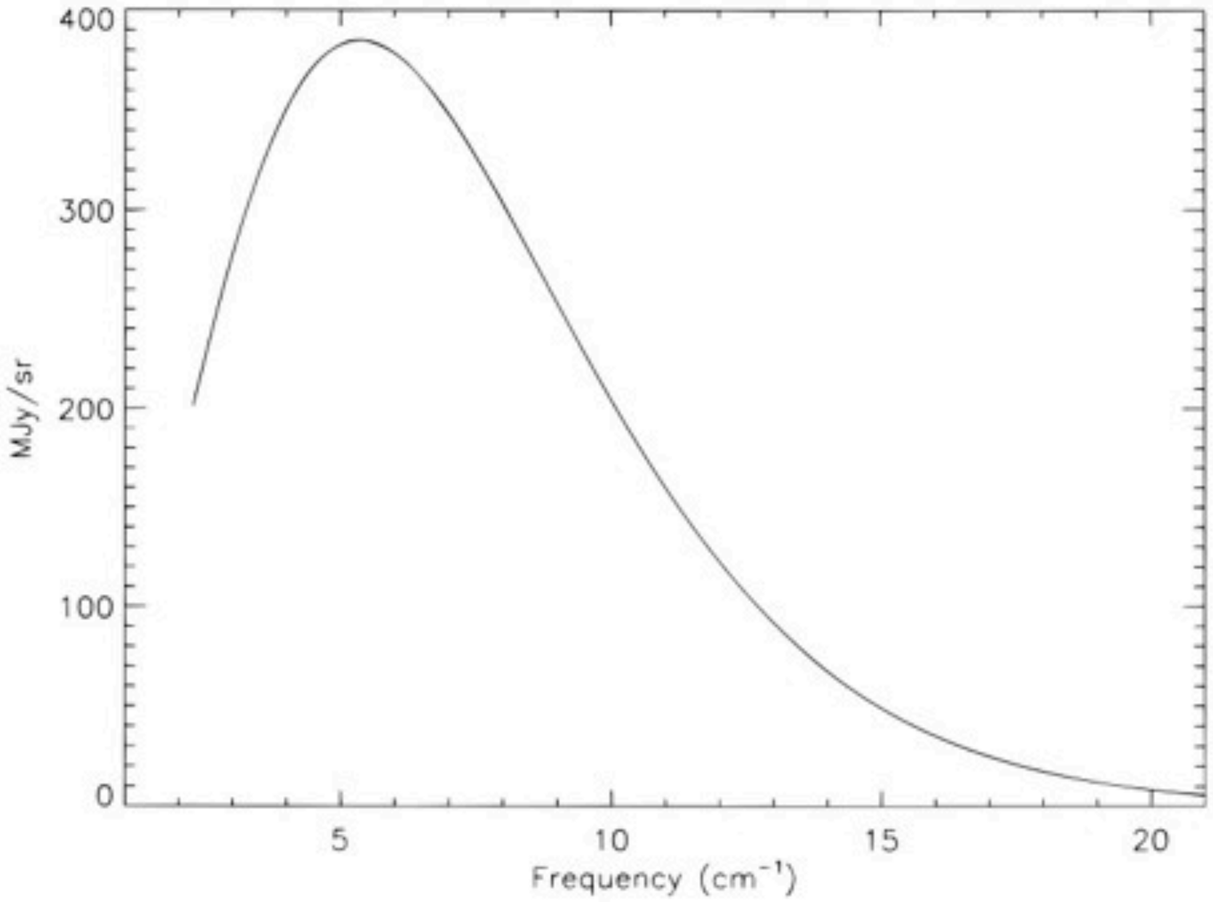


FIG. 4.—Uniform spectrum and fit to Planck blackbody (T). Uncertainties are a small fraction of the line thickness.

Cosmology 2

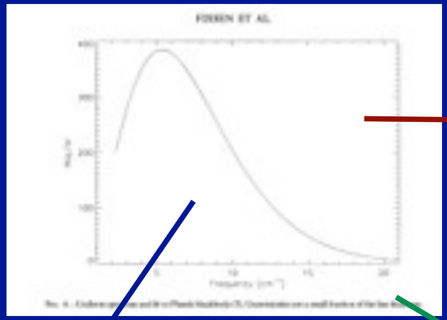
Energy injection

due to:

- $m\bar{m} \rightarrow \gamma\gamma$
  $X \rightarrow ...\gamma$
- damping of small scale density perturbations before recombination
- .....
- damping of magnetic fields: before and after recombination

at some redshift z_{inj}

thermal background radiation



$z_{inj} < 5 \times 10^4$

elastic Compton scattering becomes ineffective

↓

$B_\nu(T) + y\frac{\partial S_y}{\partial y}$ $\quad y = \int \frac{k(T_e - T_\gamma)}{m_e c^2} d\tau_e$

y-type distortion

$z_{inj} > 2 \times 10^6$

bremsstrahlung

$e^- + X \rightarrow e^- + X + \gamma$

double (inelastic) Compton scattering

$e^- + \gamma \rightarrow e^- + \gamma + \gamma$

↓

Planck spectrum

$5 \times 10^4 < z_{inj} < 2 \times 10^6$

elastic Compton scattering

$e^- + \gamma \rightarrow e^- + \gamma$

↓

Bose-Einstein spectrum

$f = [\exp(\mu + h\nu/kT_e) - 1]^{-1}$

μ-type distortion

Hu, Silk 1993

Sunyaev, Zeldovich 1970
Illarionov, Sunyaev 1975
Burigana, Danese, DeZotti 1991
Hu, Scott, Silk 1994
Jedamzik, Katalinic, Olinto 2000
Khatri, Sunyaev, Chluba 2012
Khatri, Sunyaev 2012
KEK, Komatsu 2014

Cosmology 2

Pre-decoupling era

- μ-type distortion

Hu, Silk 1993

$$\frac{d\mu}{dt} = -\frac{\mu}{t_{DC}(z)} + \frac{1.4}{3}\frac{\frac{dQ}{dt}}{\rho_\gamma}$$

mixture of black body spectra: 1/3 of injected energy leads to spectral distortions, 2/3 to raise average temperature (Khatri, Sunyaev, Chluba 2012)

time scale for double Compton scattering

$$t_{DC} = 2.06 \times 10^{33} \left(1 - \frac{Y_P}{2}\right)^{-1} \left(\Omega_b h^2\right)^{-1} z^{-\frac{9}{2}} \;\; \mathrm{s}$$

Cosmology 2

- Observational limits

COBE FIRAS

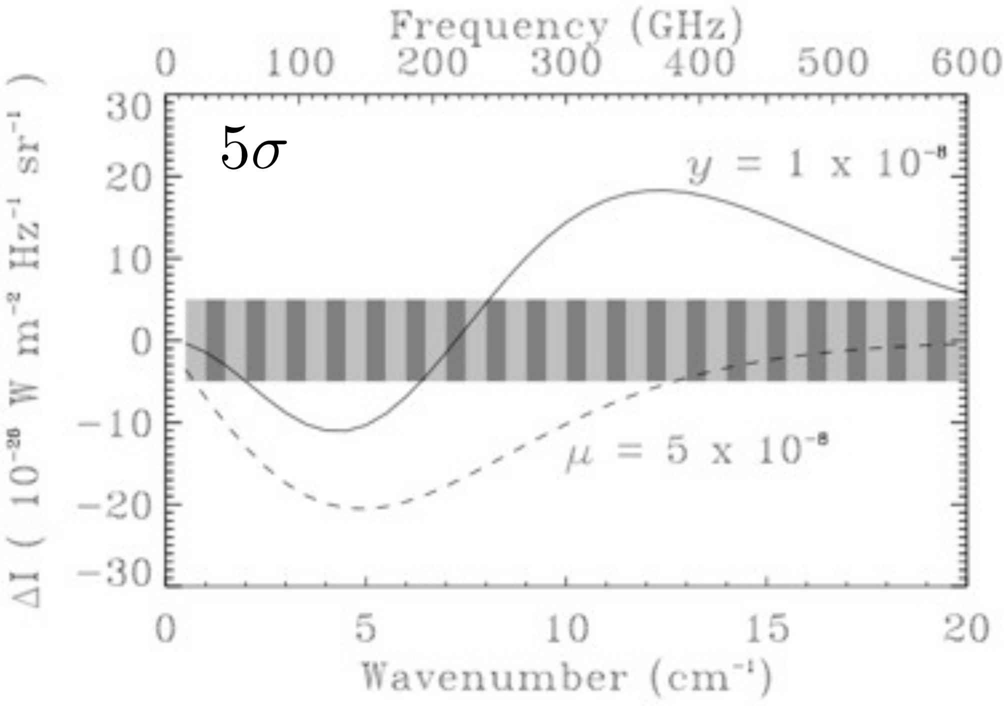
Fixsen et al. 1996

$|y| < 1.5 \times 10^{-5}$ $|\mu| < 9 \times 10^{-5}$ $(95\%\mathrm{CL})$

- Future experiments

PIXIE (Primordial Inflation Explorer)

Kogut et al. 2011

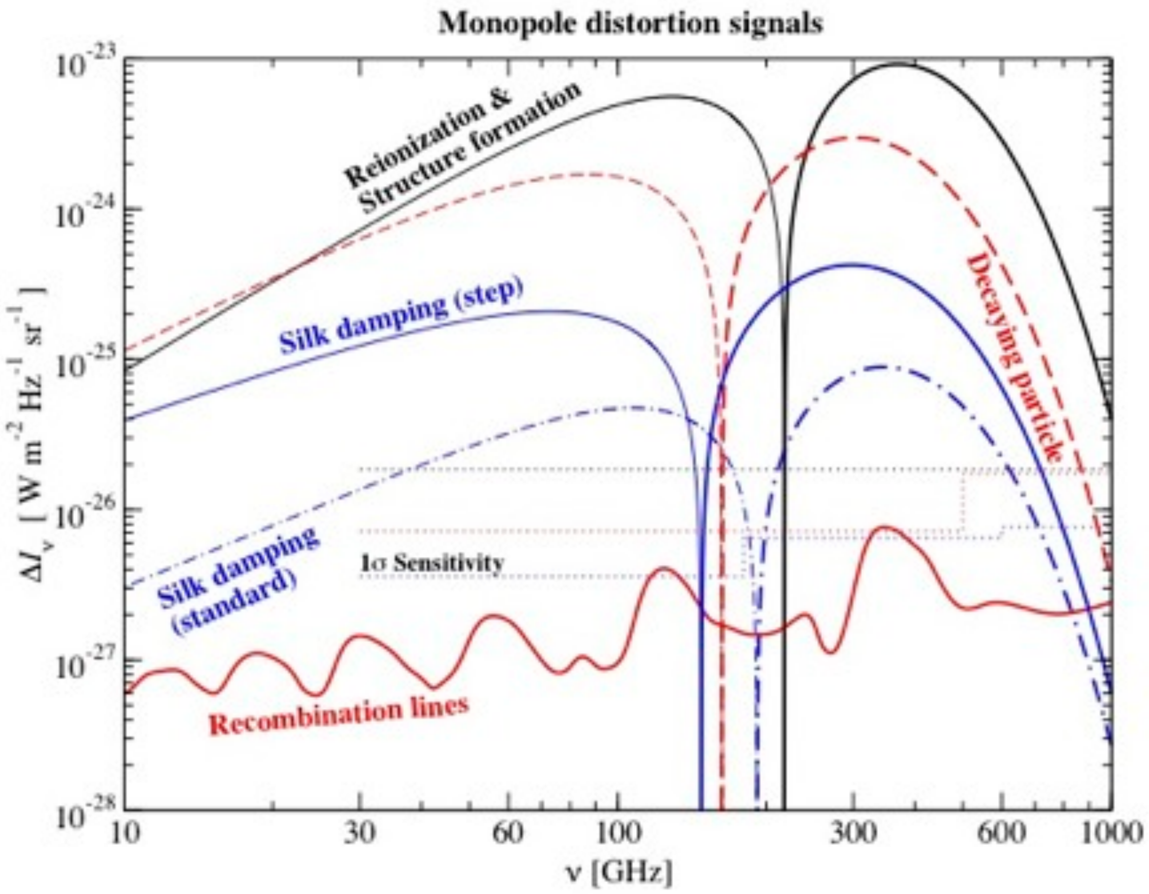


Cosmology 2

- Future experiments

PRISM (Polarized Radiation Imaging and Spectroscopy Mission)

Andre et al. 2013



Cosmology 2

- The matter power spectrum

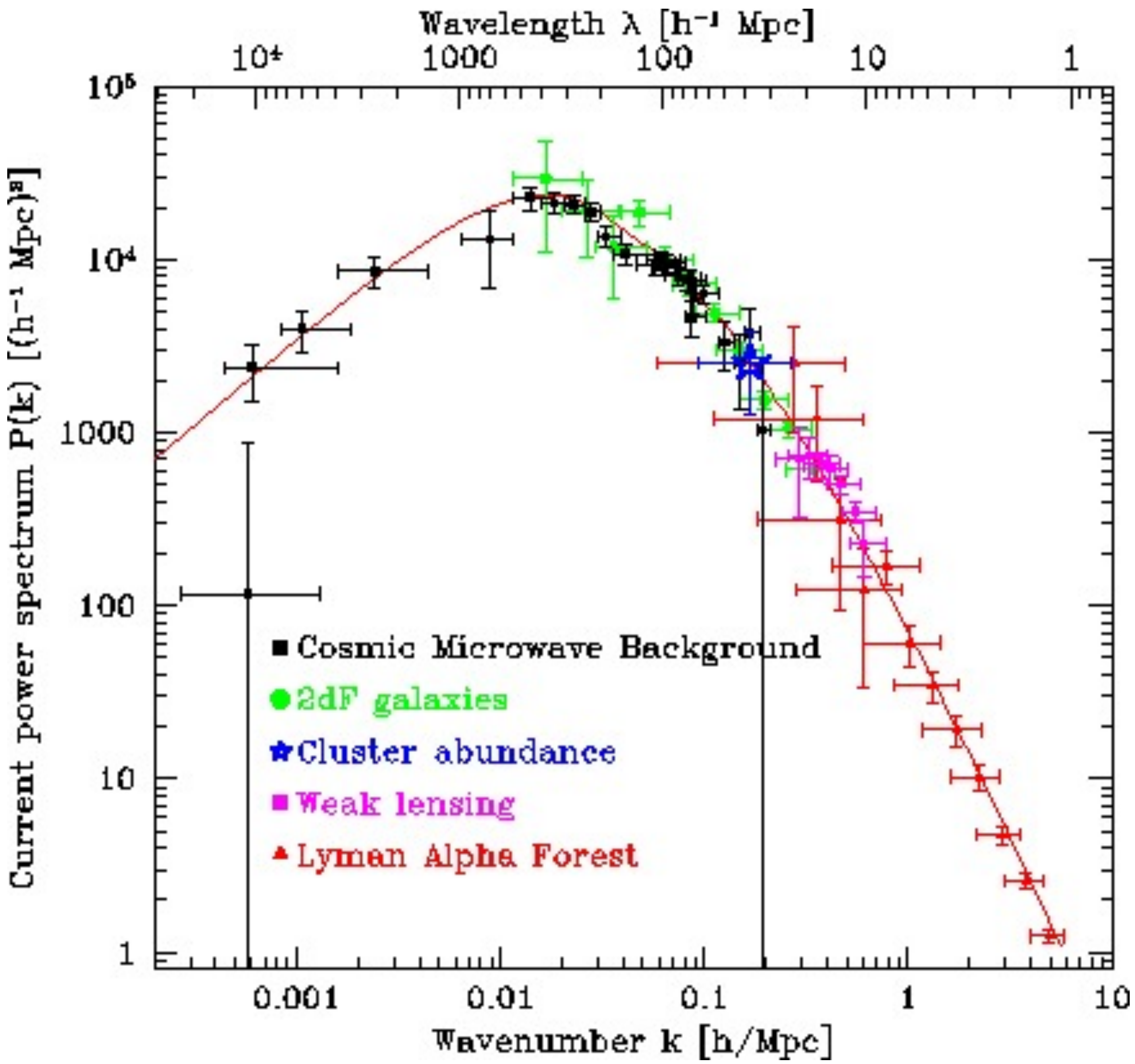
total matter perturbation

$$\Delta_m \equiv R_c\Delta_c + R_b\Delta_b$$

$$R_i \equiv \frac{\rho_i}{\rho_{matter}}$$

(during matter domination)

$$P_m(k) = \frac{k^3}{2\pi^2}|\Delta_m|^2$$



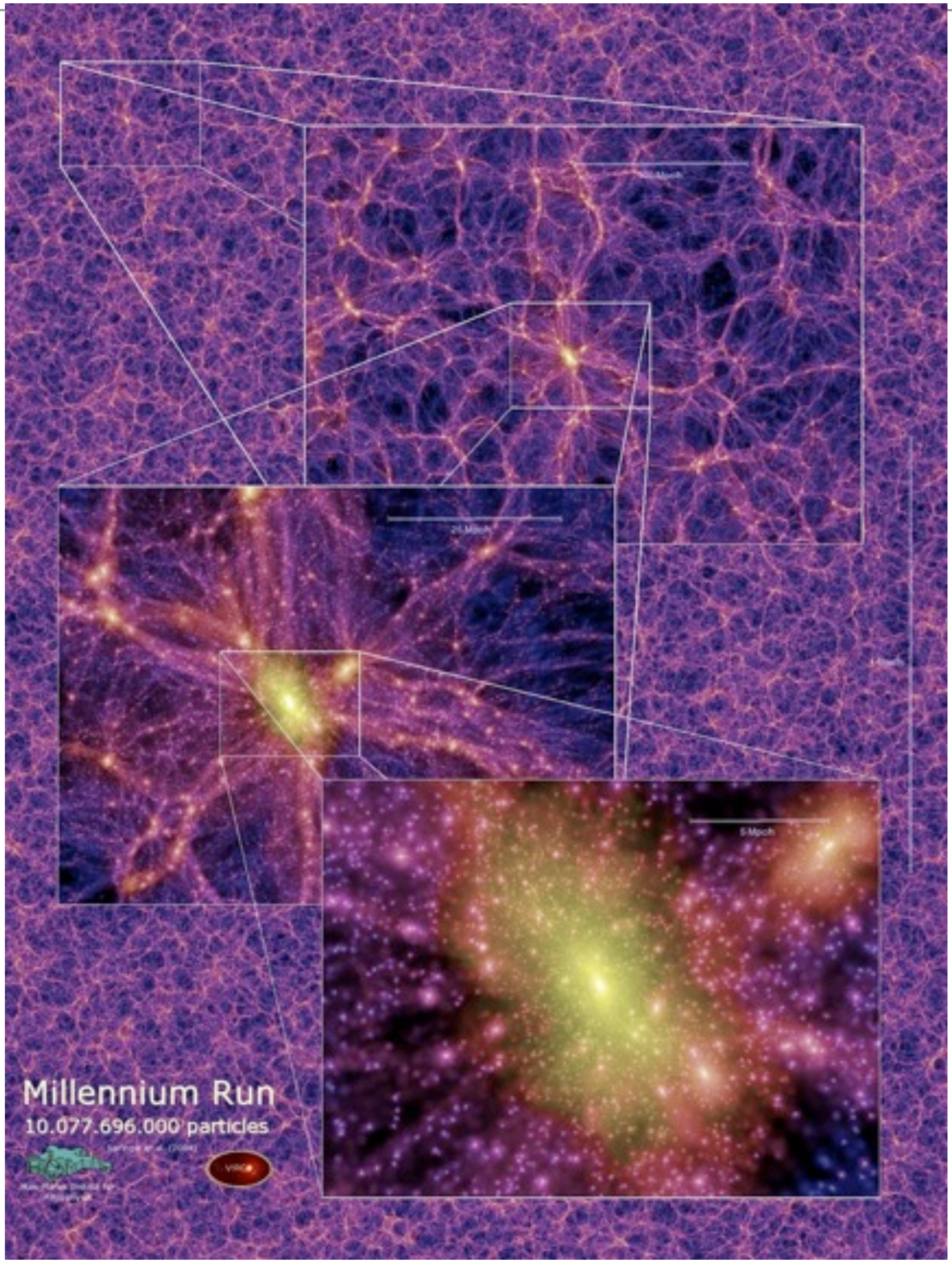
Tegmark (2002)

Cosmology 2

- On small scales: nonlinear effects become important
- numerical simulations
- analytical techniques....renormalization group approach

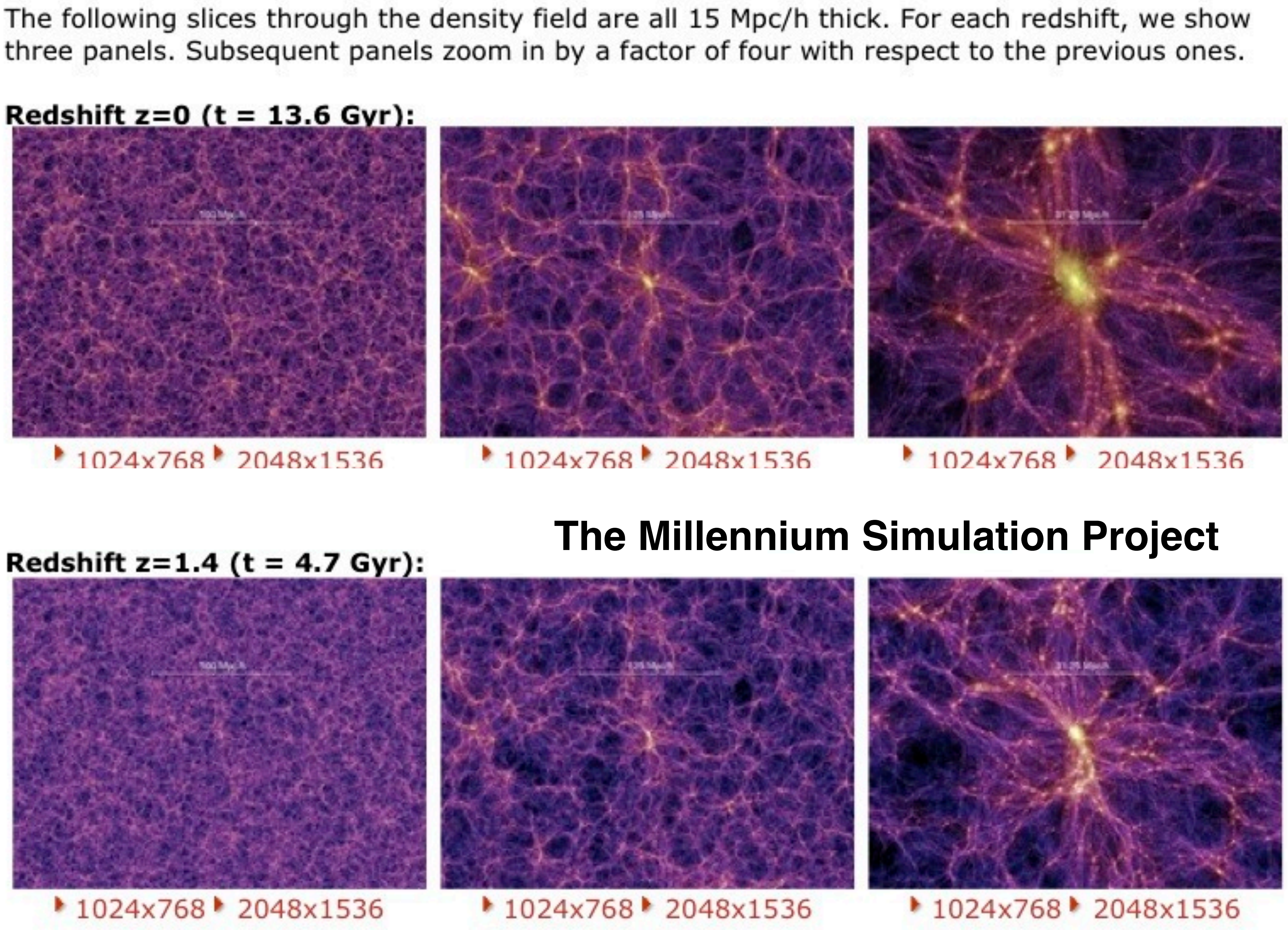
Cosmology 2

The *Millennium Run* used more than 10 billion particles to trace the evolution of the matter distribution in a cubic region of the Universe over 2 billion light-years on a side.



http://www.mpa-garching.mpg.de/galform/virgo/millennium/

Cosmology 2



The following slices through the density field are all 15 Mpc/h thick. For each redshift, we show three panels. Subsequent panels zoom in by a factor of four with respect to the previous ones.

Redshift z=0 (t = 13.6 Gyr):

▸ 1024x768 ▸ 2048x1536 ▸ 1024x768 ▸ 2048x1536 ▸ 1024x768 ▸ 2048x1536

Redshift z=1.4 (t = 4.7 Gyr):

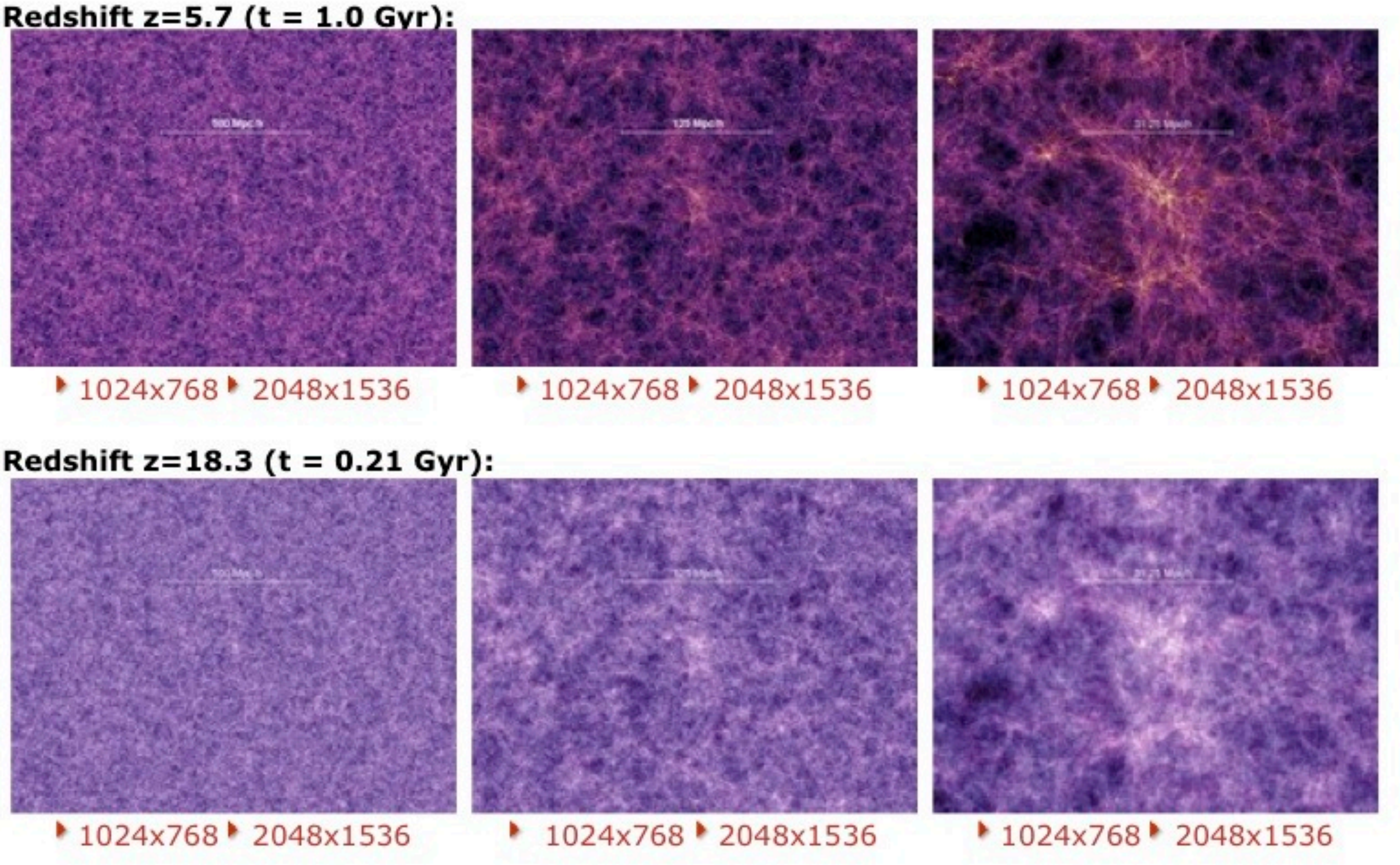
▸ 1024x768 ▸ 2048x1536 ▸ 1024x768 ▸ 2048x1536 ▸ 1024x768 ▸ 2048x1536

The Millennium Simulation Project

THE VIRGO CONSORTIUM

Cosmology 2

The Millennium Simulation Project



Redshift z=5.7 (t = 1.0 Gyr):

▸ 1024x768 ▸ 2048x1536 ▸ 1024x768 ▸ 2048x1536 ▸ 1024x768 ▸ 2048x1536

Redshift z=18.3 (t = 0.21 Gyr):

▸ 1024x768 ▸ 2048x1536 ▸ 1024x768 ▸ 2048x1536 ▸ 1024x768 ▸ 2048x1536

THE VIRGO CONSORTIUM

http://www.mpa-garching.mpg.de/galform/virgo/millennium/