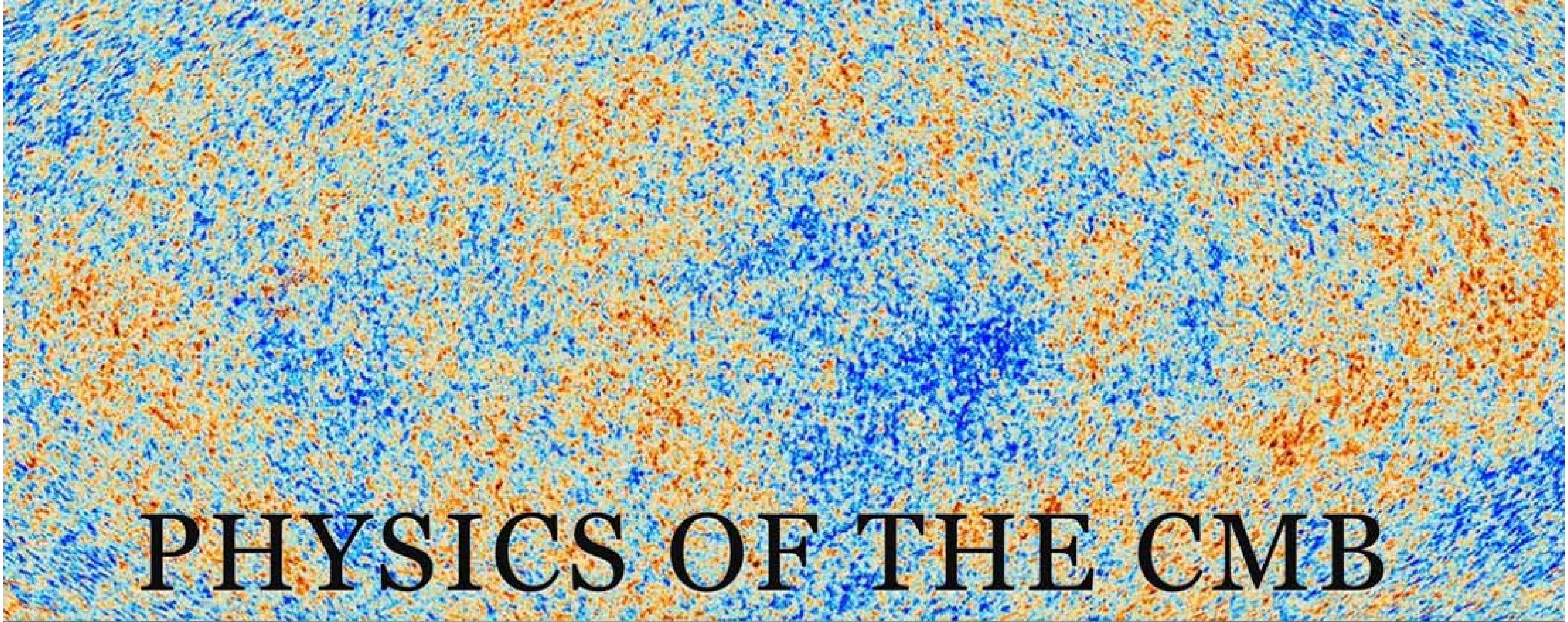
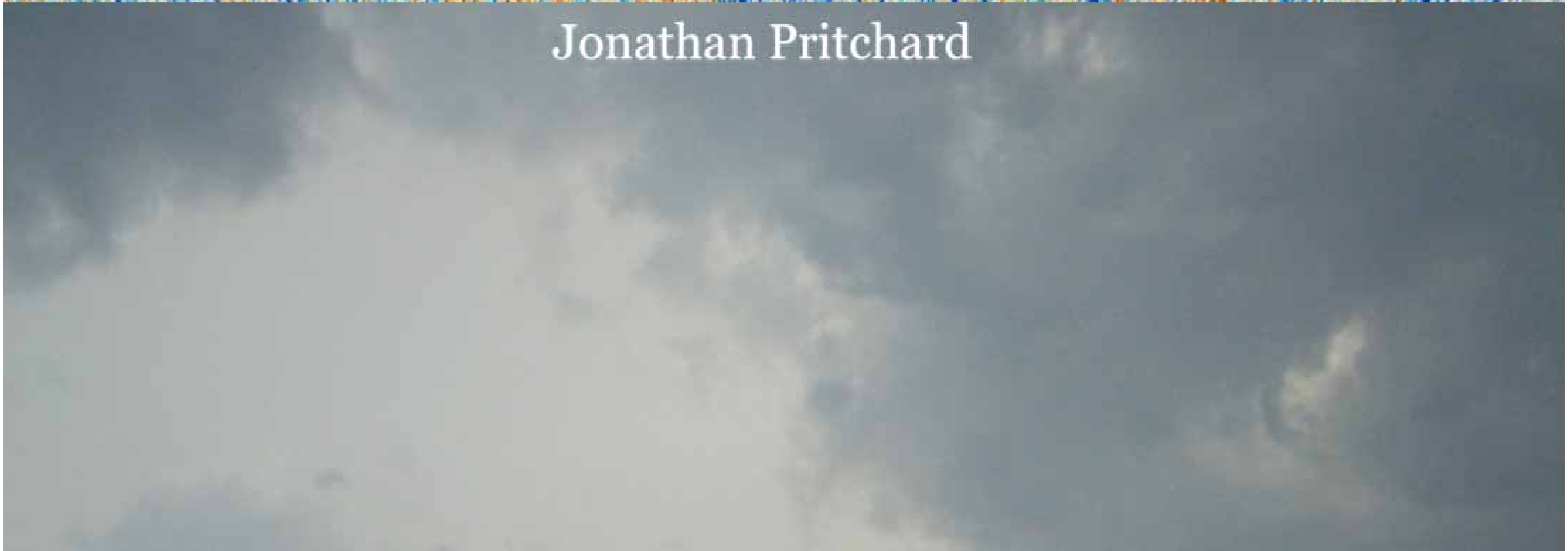


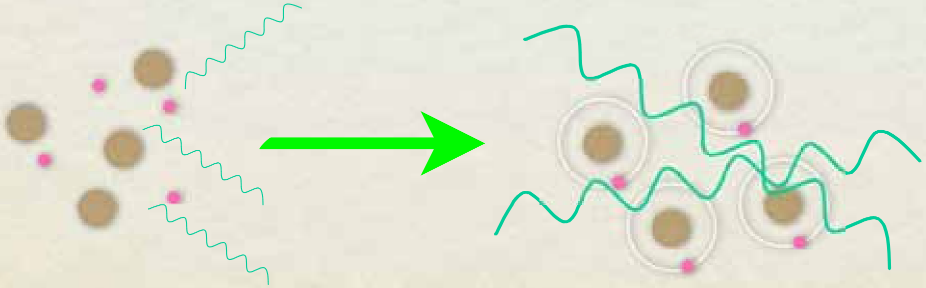
PHYSICS OF THE CMB

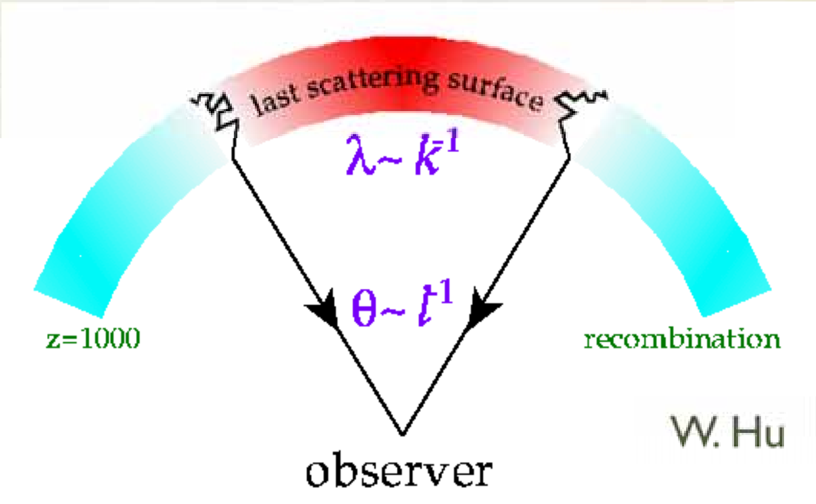
Jonathan Pritchard



THE COSMIC MICROWAVE BACKGROUND

- 400,000 years after the Big Bang, the temperature of the Universe was T~10,000 K
- Hot enough to keep hydrogen atoms *ionized* until this time
  - ***proton + electron → Hydrogen + photon*** $[p^+ + e^- \rightarrow H+\gamma]$
  - ***charged plasma → neutral gas***
- Photons (light) can't travel far in the presence of charged particles
  - ***Opaque → transparent***

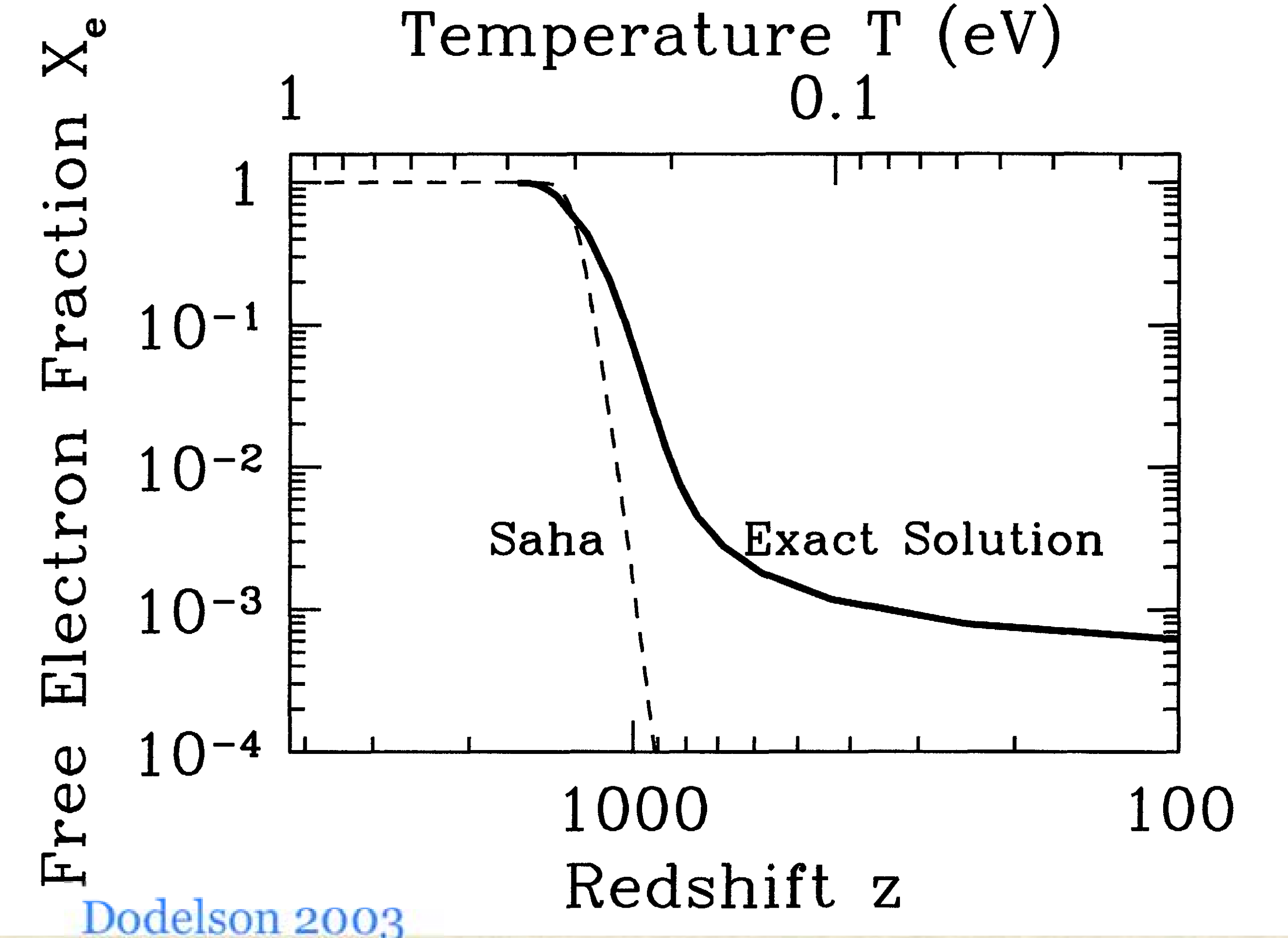




RECOMBINATION

Saha Equation

$$\frac{1-X_e}{X_e^2} = \frac{4\sqrt{2}\zeta(3)}{\sqrt{\pi}}\eta\left(\frac{kT}{m_ec^2}\right)^{3/2} e^{B/(kT)}$$



Dodelson 2003

Recombination

once T~0.3 eV

Meghnad Saha

DECOUPLING

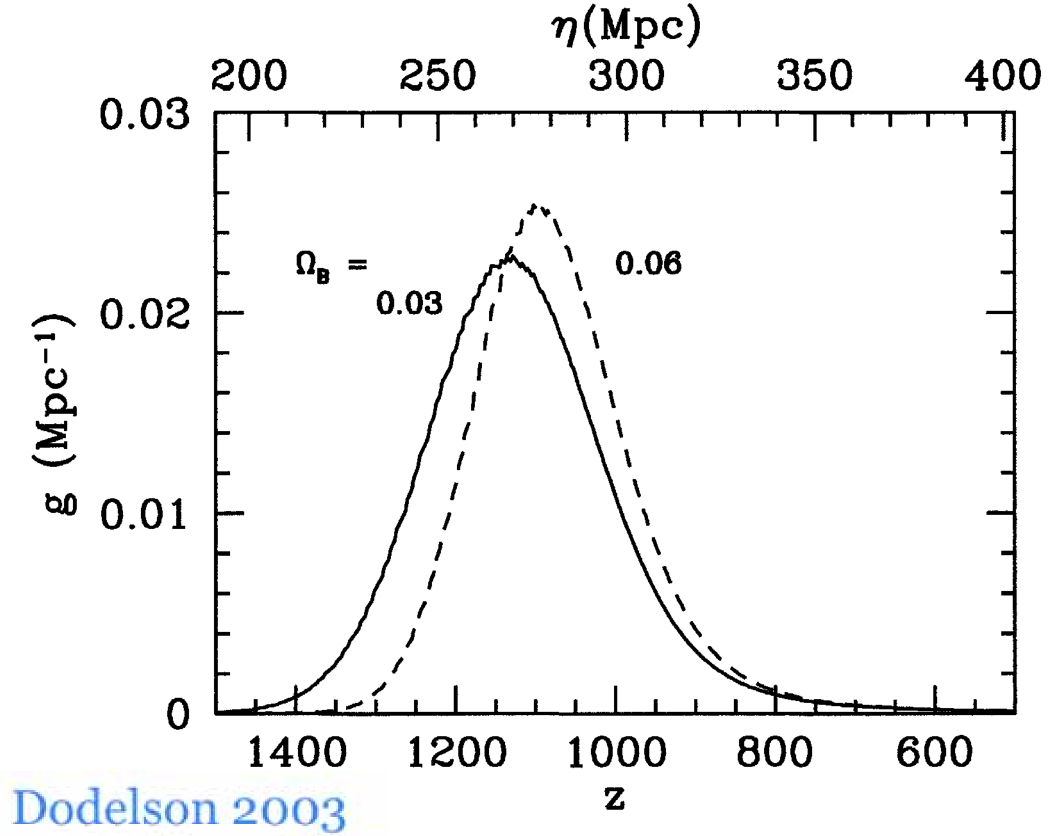
$$\tau = \int \sigma_T n_e(z) \mathrm{d}l$$

Optical depth

$$g(\eta) \equiv -\dot{\tau} e^{-\tau}$$

visibility function

$$\int_0^{\eta_0} d\eta g(\eta) = 1,$$



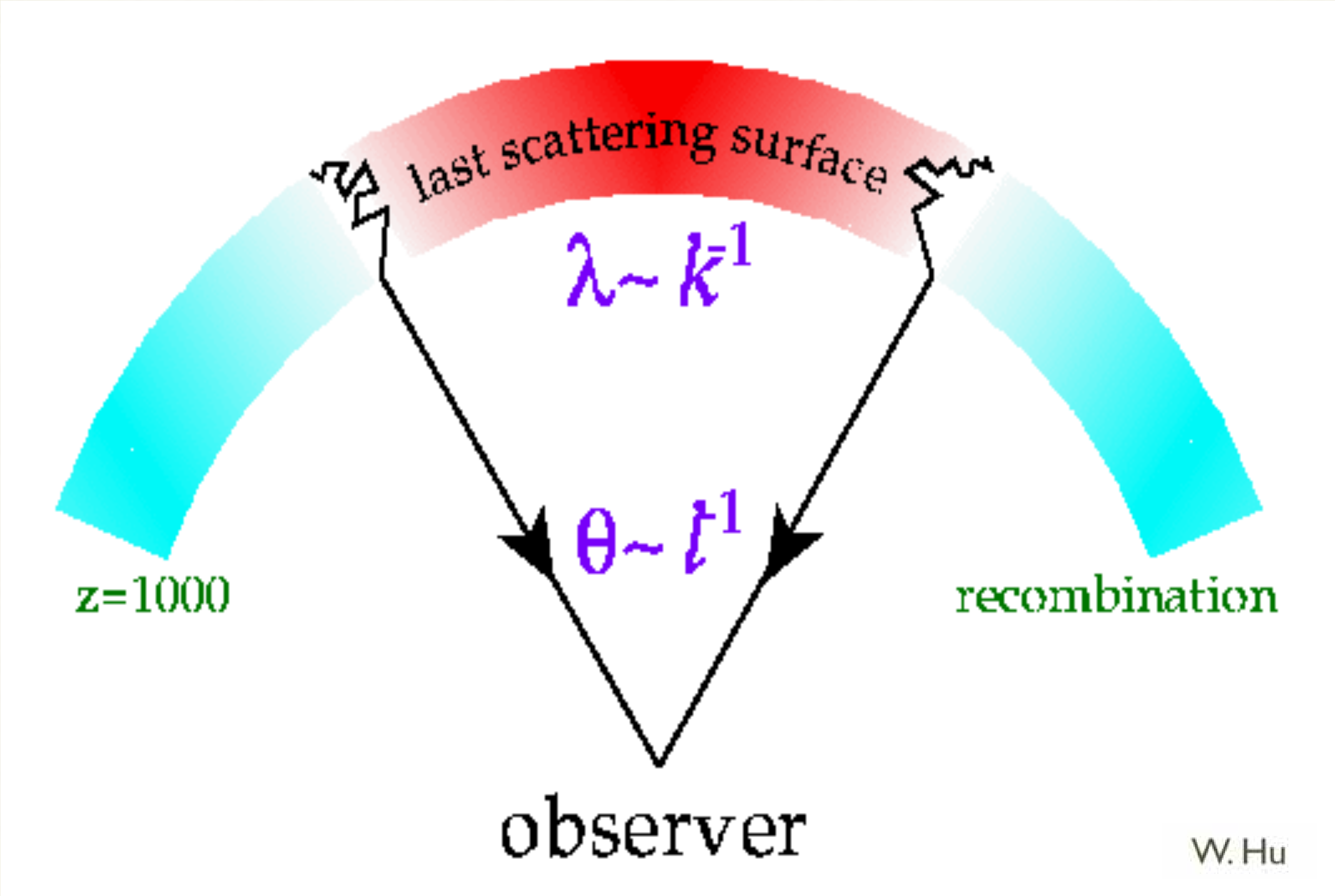
Dodelson 2003

Visibility defines the duration of decoupling

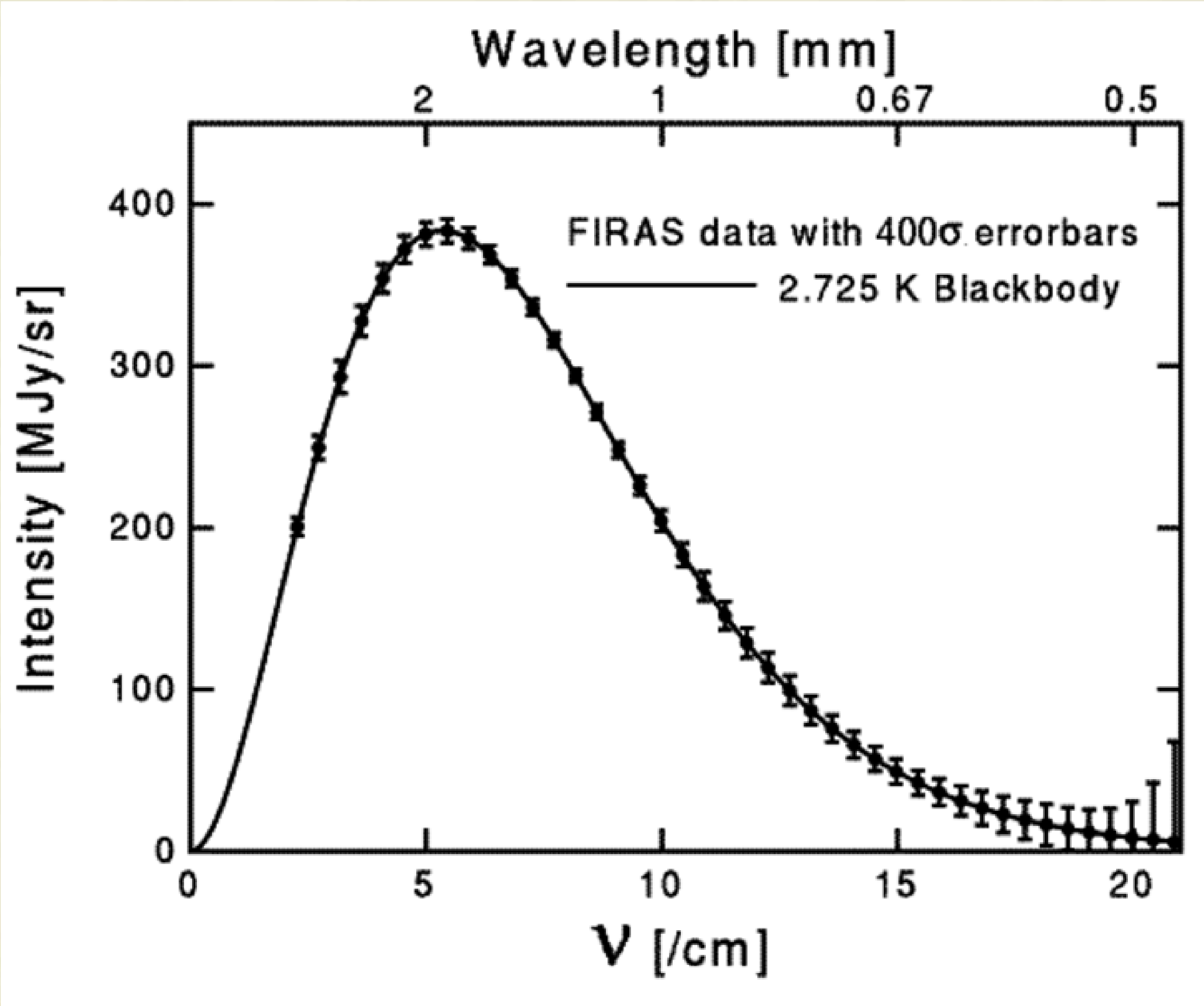
~PDF for last scattering

Peak at z~1100

SURFACE OF LAST SCATTERING



CMB BLACKBODY



COBE-FIRAS

(1994)

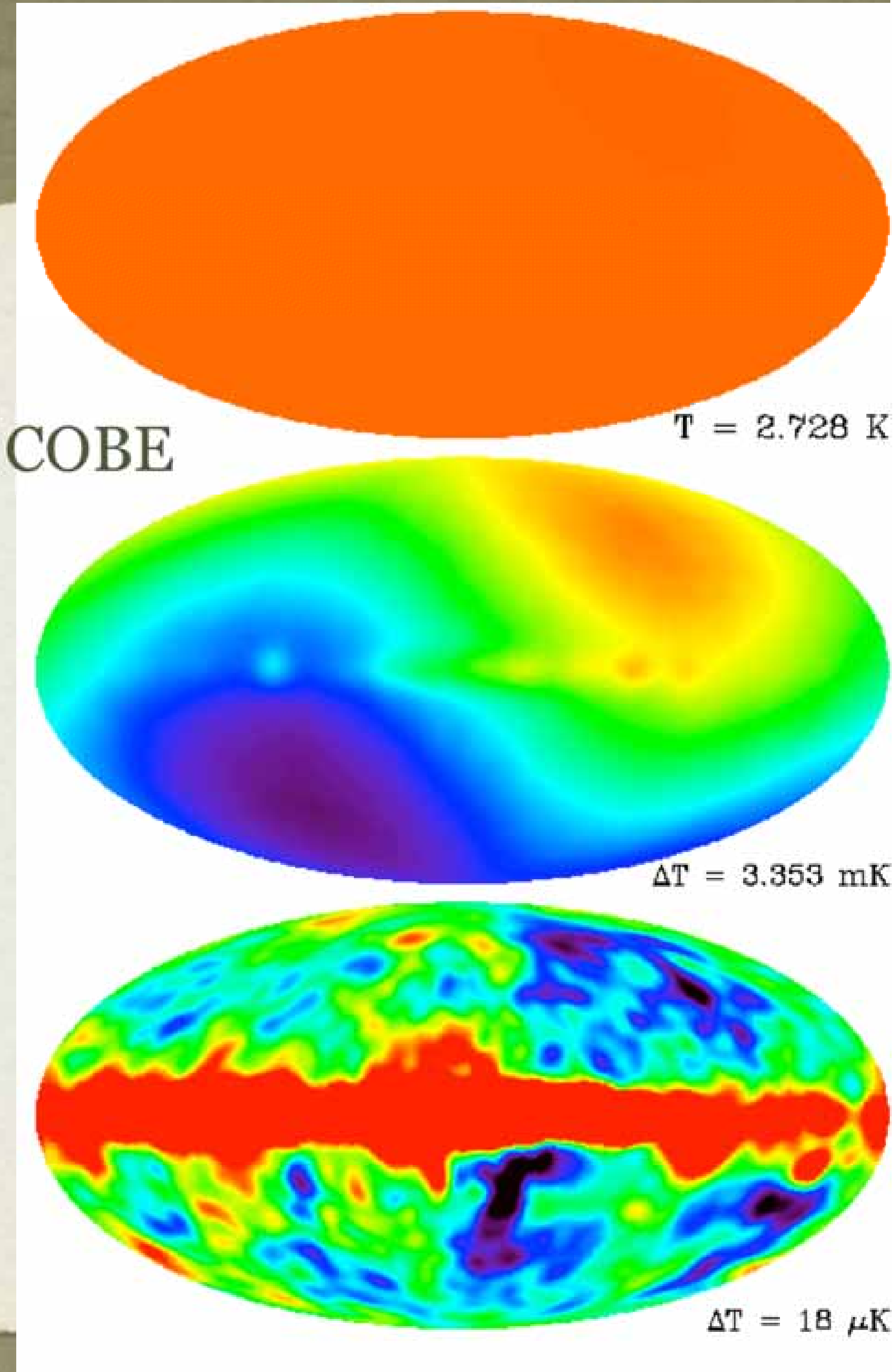
Strong evidence that Universe was thermalised at decoupling

CMB TEMPERATURE

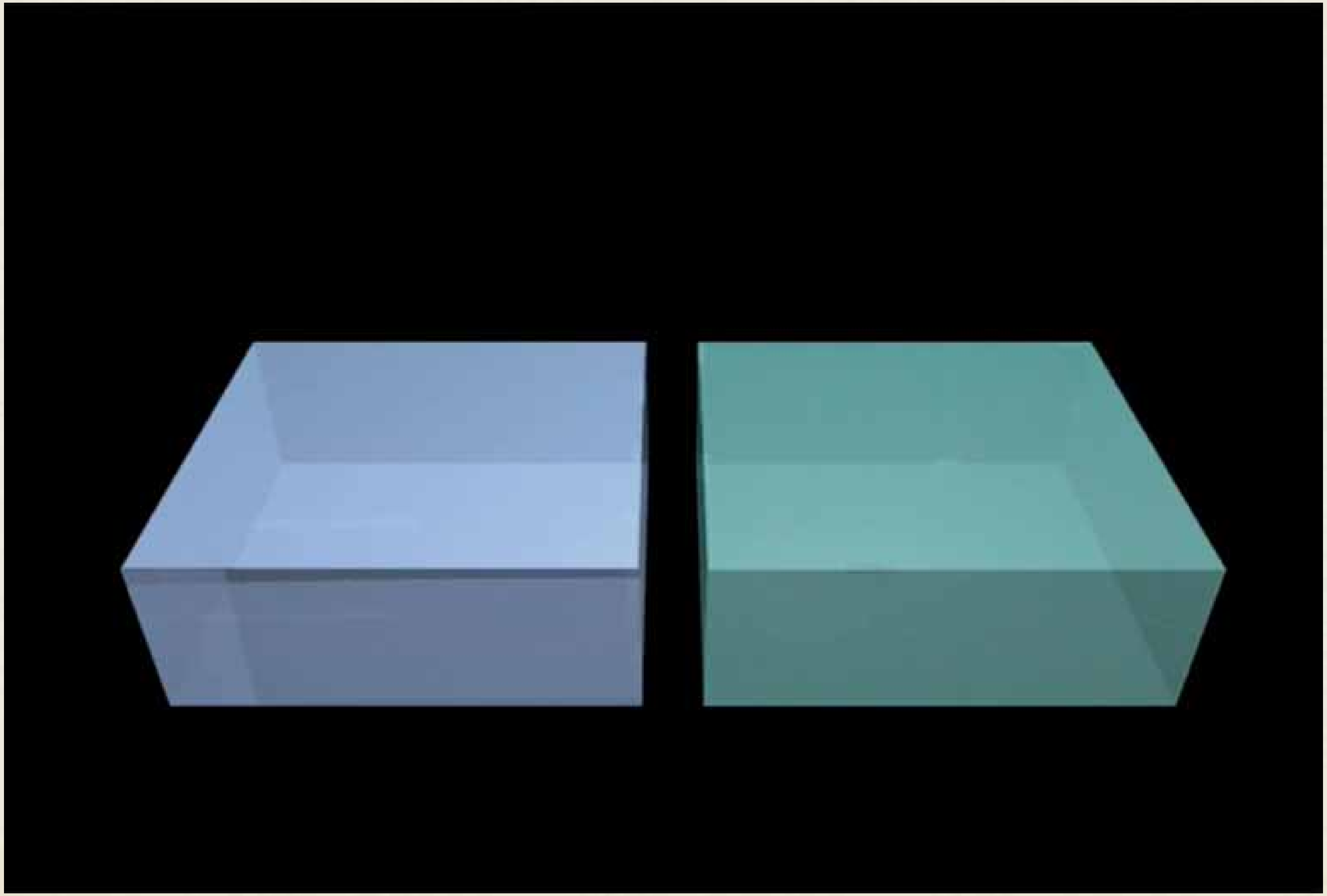
CMB temperature close to uniform

Motion relative to CMB rest frame leads to dipole pattern

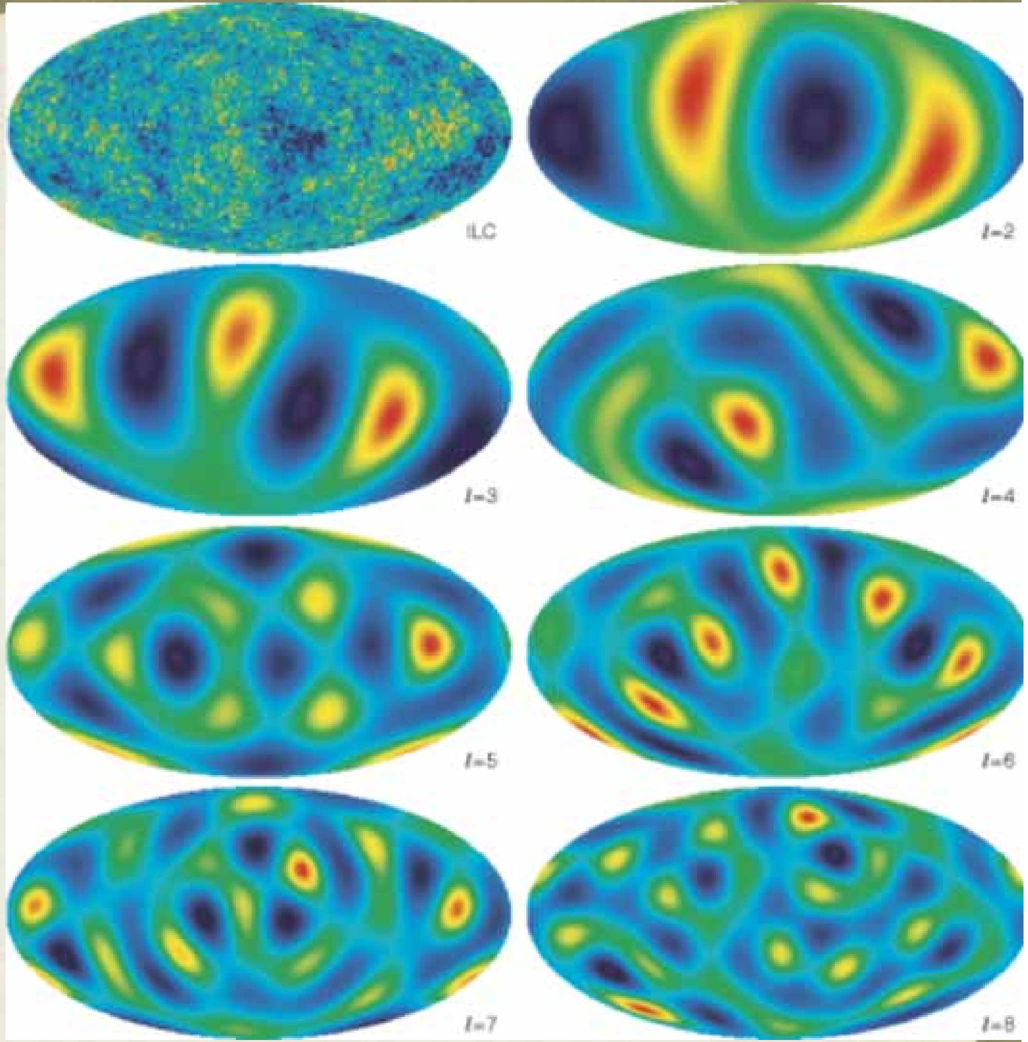
Temperature fluctuations at level of ~10 μK seen



TEMPERATURE FLUCTUATIONS



MULTIPOLE DECOMPOSITION



Natural to decompose temperature fluctuations in angular basis

$$\frac{T(\hat{x})-\bar{T}}{\bar{T}} \equiv \frac{\Delta T}{T}(\hat{x}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\hat{x})$$

Y_{lm} are spherical harmonics

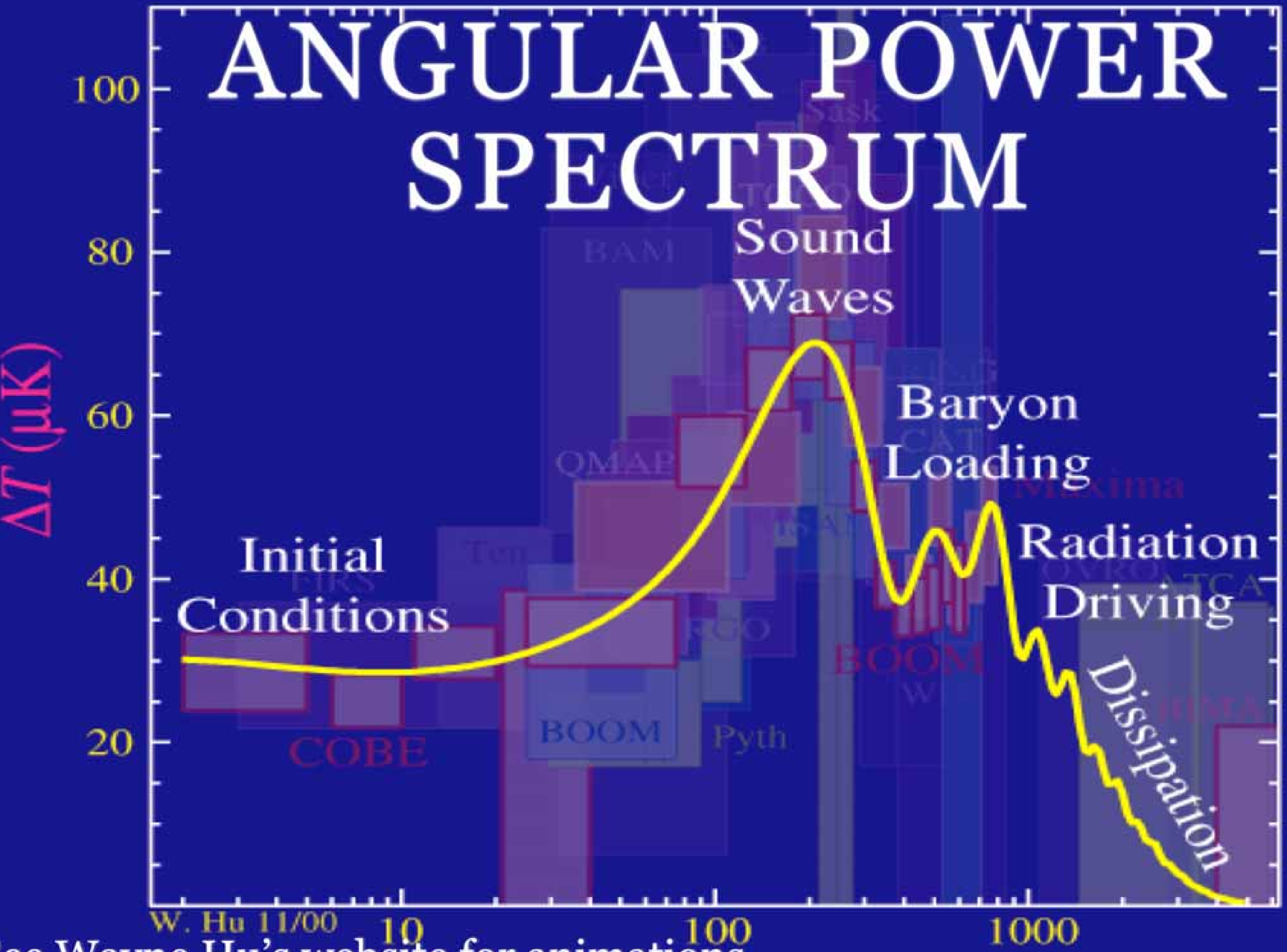
Angular multipole $l \sim \pi/\theta$

Power spectrum:

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

For Gaussian fluctuations, power spectrum contains all information

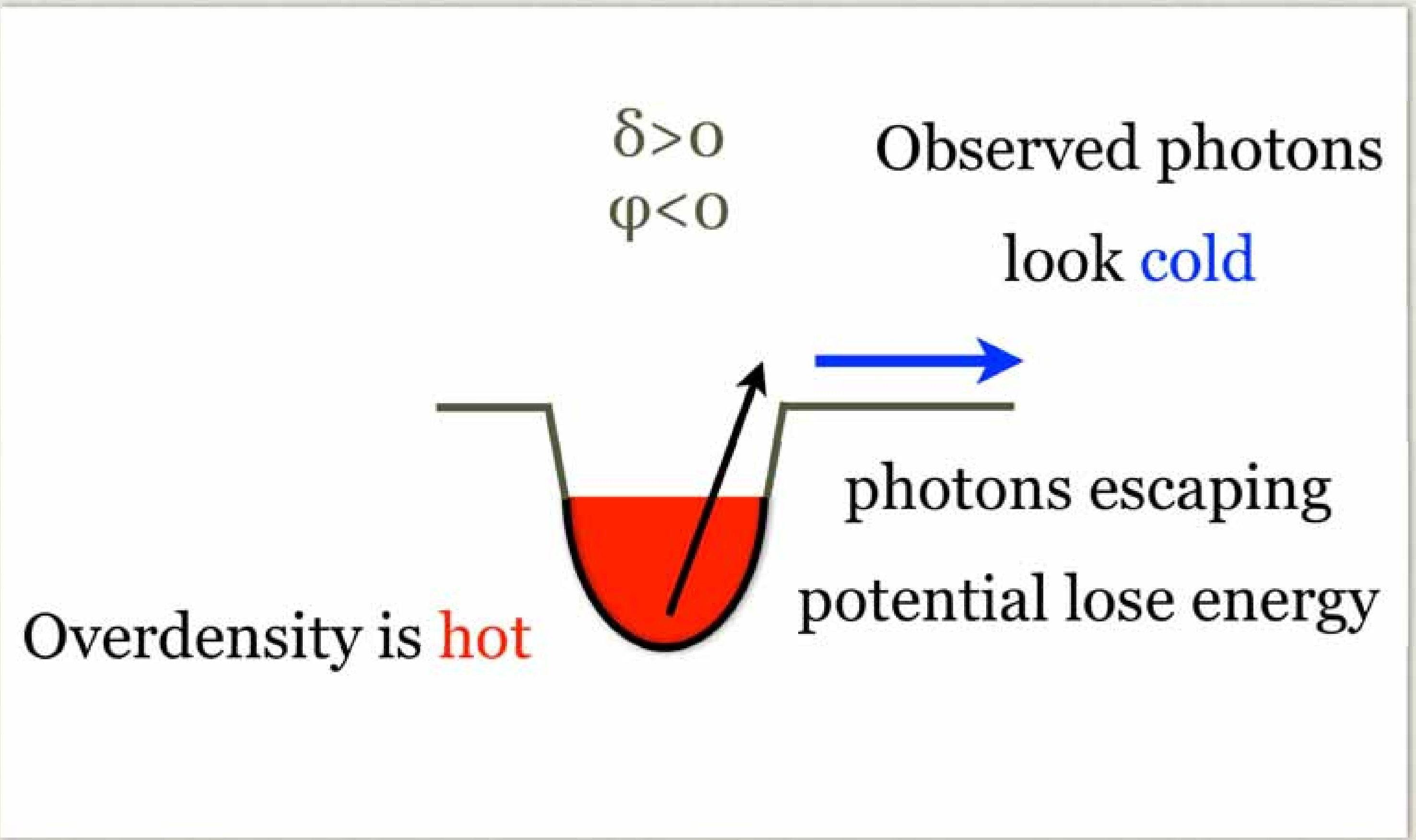
ANGULAR POWER SPECTRUM



See Wayne Hu's website for animations
http://background.uchicago.edu/index.html

SACHS-WOLFE EFFECT

- Overdense regions will be intrinsically hotter BUT
  See light after it escapes gravitational well



$\delta > 0$

$\varphi < 0$

Observed photons look cold

photons escaping potential lose energy

Overdensity is hot

- observed **cold** spots = **overdense** regions at last scattering
  observed **hot** spots = **underdense** regions at last scattering

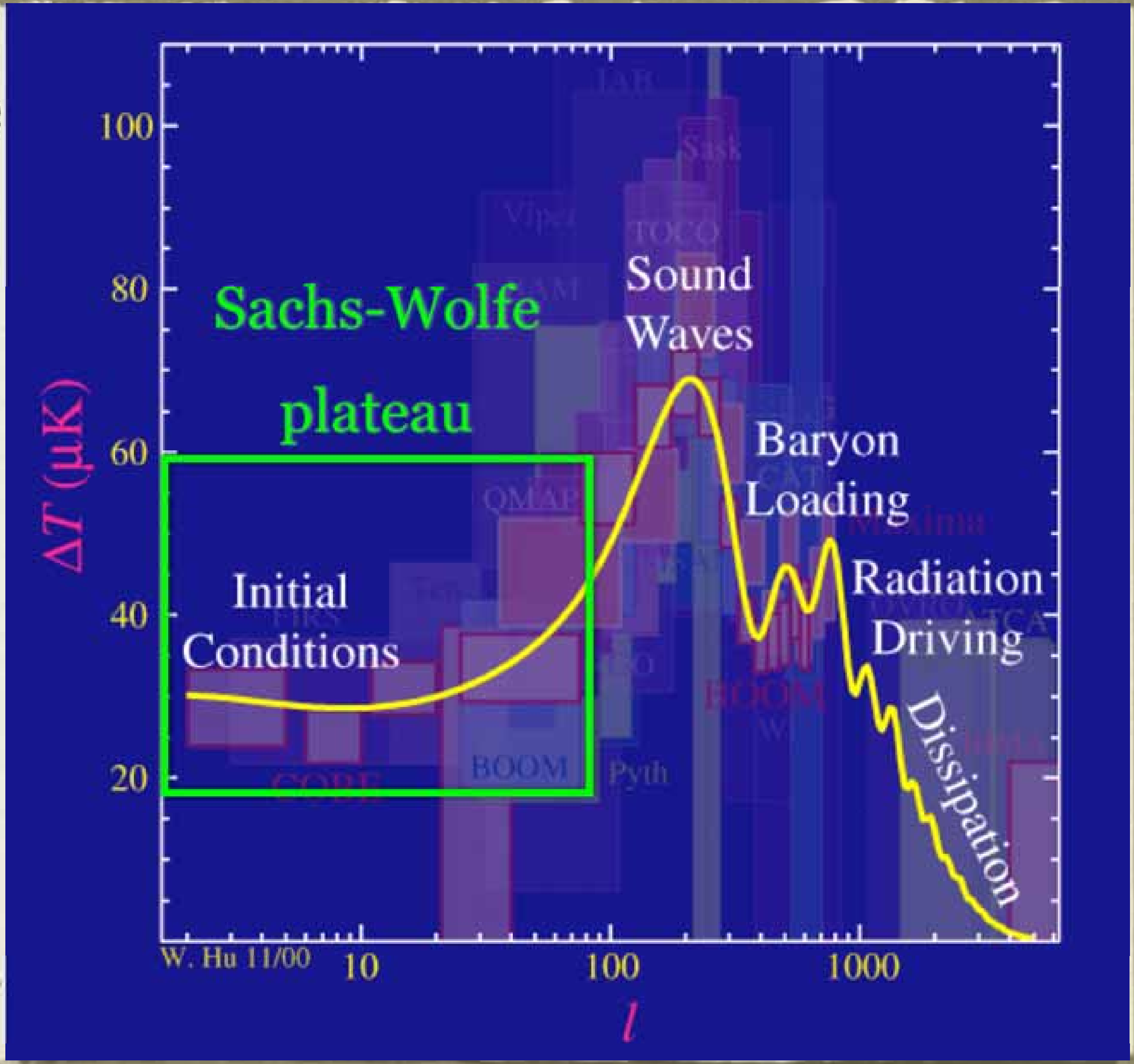
ANGULAR POWER SPECTRUM

Large scale modes are primordial i.e. ~scale free have grown beyond horizon

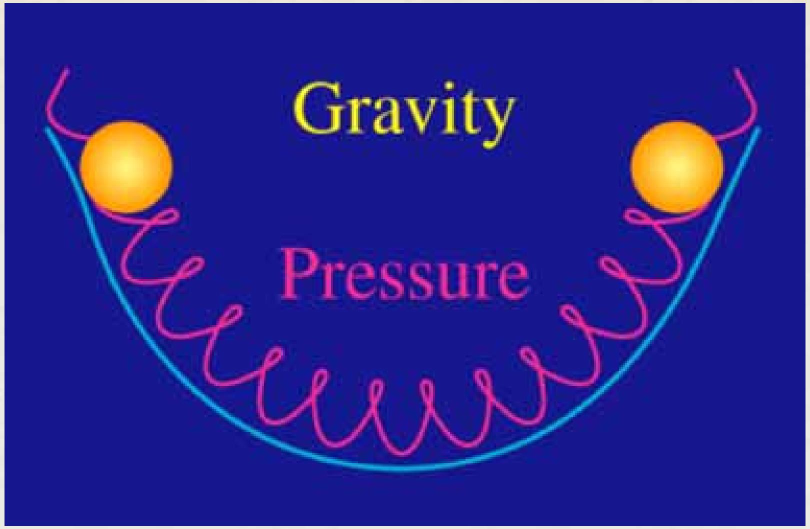
$$P_{\rm prim}(k) = A(k/k_0)^{n_s}$$

Sachs-Wolfe effect leads to constant fluctuations $l(l+1)C_l$~const

“Sachs-Wolfe plateau”



PRESSURE VS GRAVITY



- Scale outside horizon - growing under gravity
- On scales inside horizon - pressure balances gravity
  => oscillation
  => regions denser or less dense

Basic picture is that of forced harmonic oscillation

$$\ddot{x} + \frac{k}{m} x = \frac{F_0}{m}.$$

1) Evolving potentials act as forcing term

2) Baryon content determines "mass"

$$c_s \equiv \sqrt{\frac{1}{3(1+R)}}.$$

$$R = \frac{3\Omega_b h^2}{4\Omega_\gamma h^2}$$

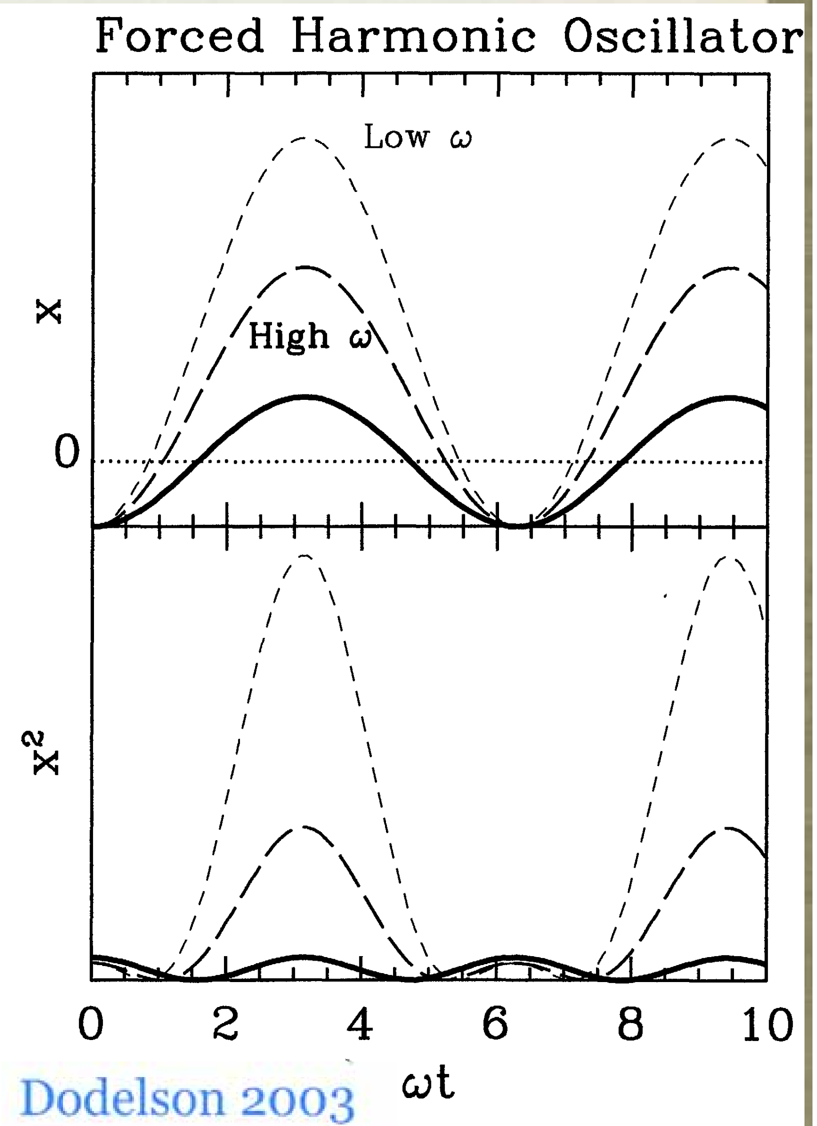
Solution:

$$x = A\cos(\omega t) + \frac{F_0}{m\omega^2}.$$

Power spectrum from a_{lm}^2

=> odd peaks (compression)

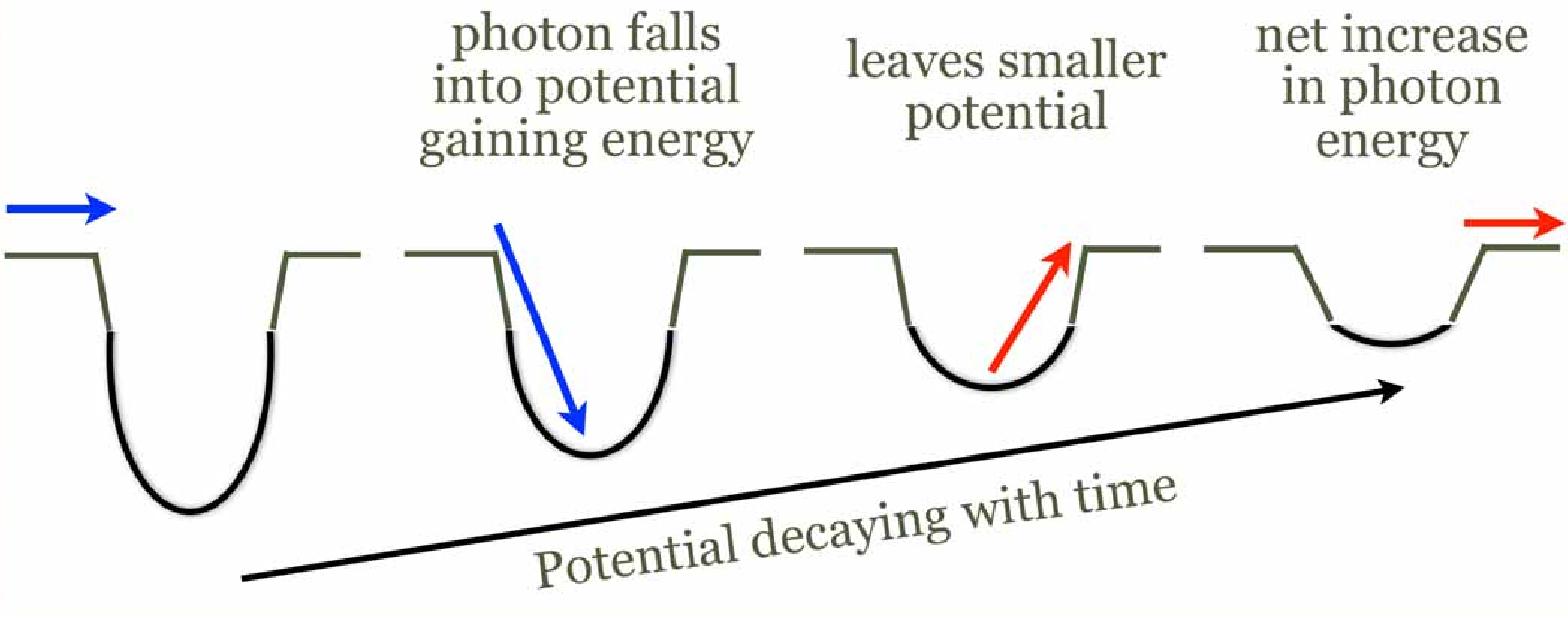
more enhanced than even (rarification)

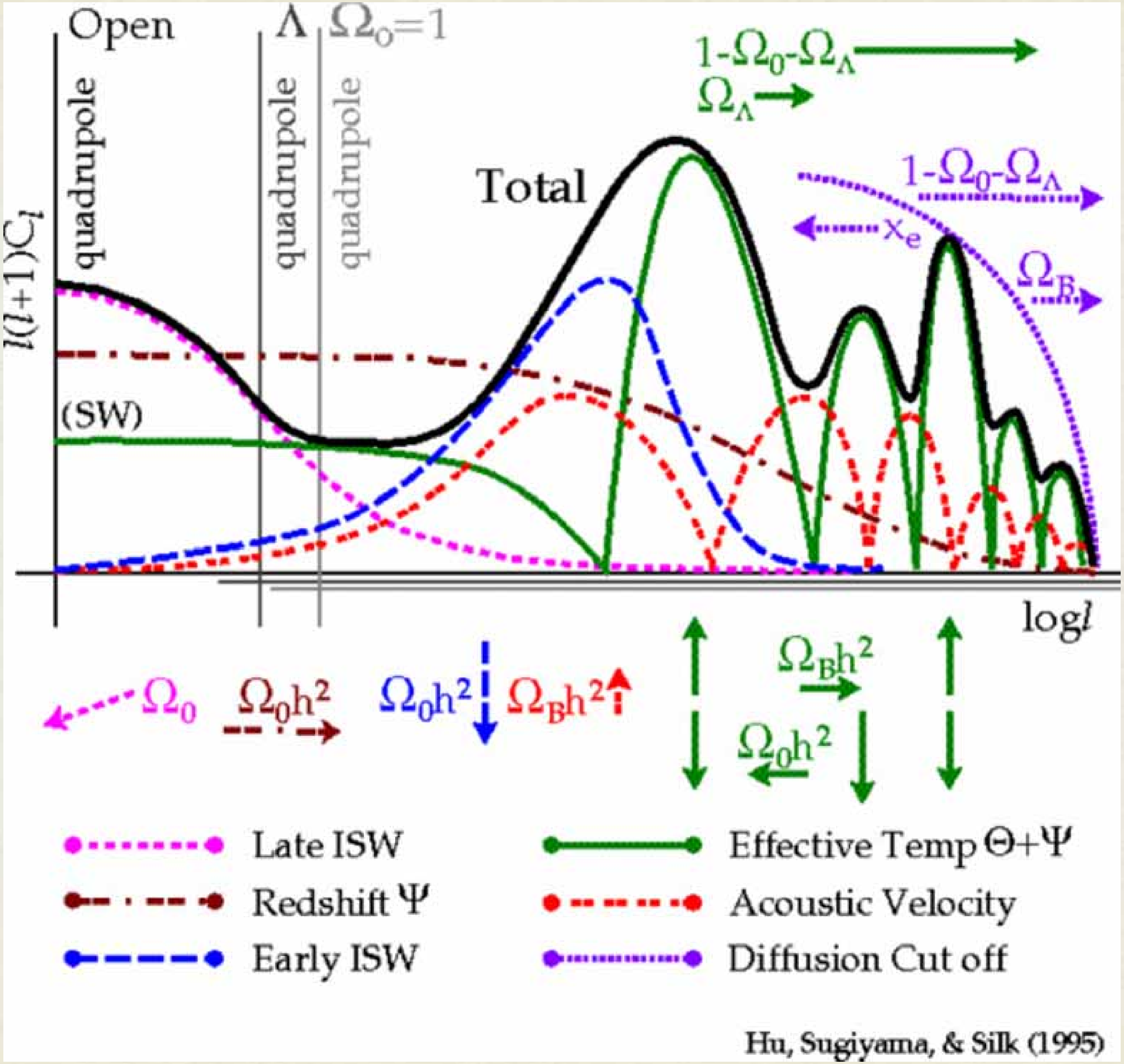


Dodelson 2003

INTEGRATED SACHS-WOLFE EFFECT

- A photon gains energy moving through a decaying potential
  => boost to height of first peak
- For later peaks oscillations average out gain in energy
- Early ISW as radiation domination ends and matter domination starts
  Late ISW effect when dark energy becomes important





Hu, Sugiyama, & Silk (1995)

ANGULAR POWER SPECTRUM

Scales inside horizon

are oscillating

=> peaks are different

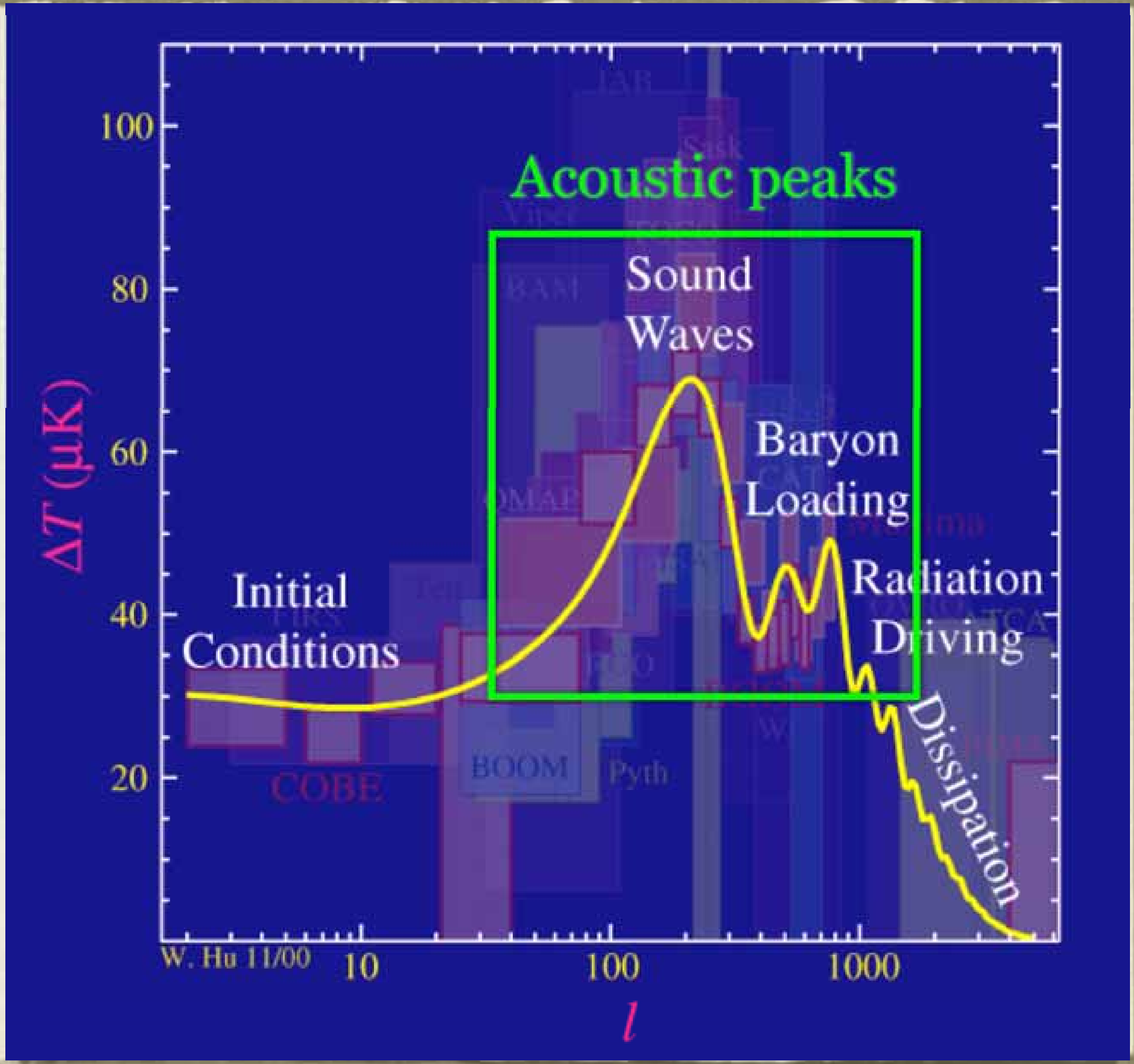
harmonics of oscillation

“Acoustic peaks”

More baryons

=>lower sound speed

=> higher third peak

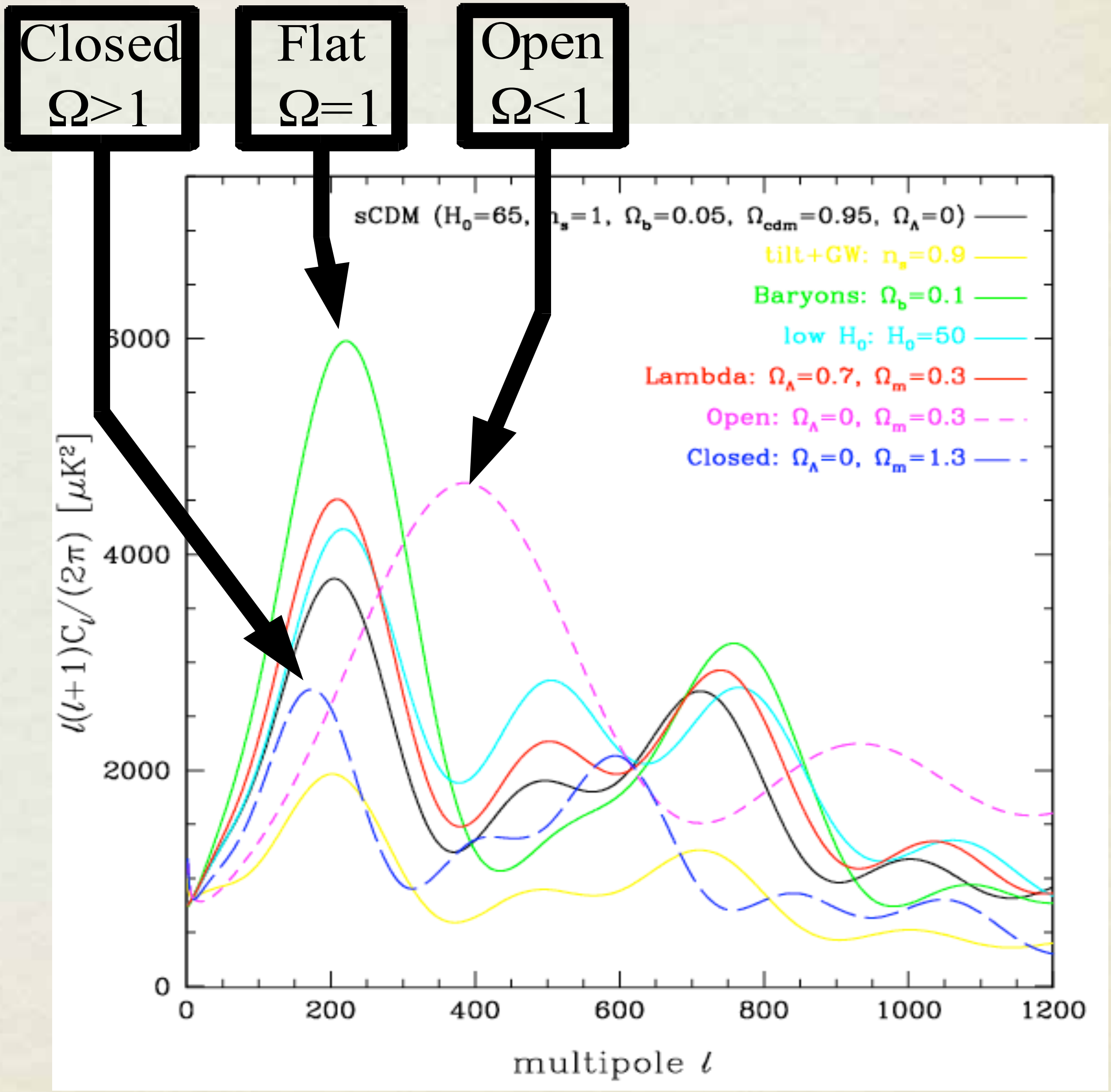


First peak and curvature

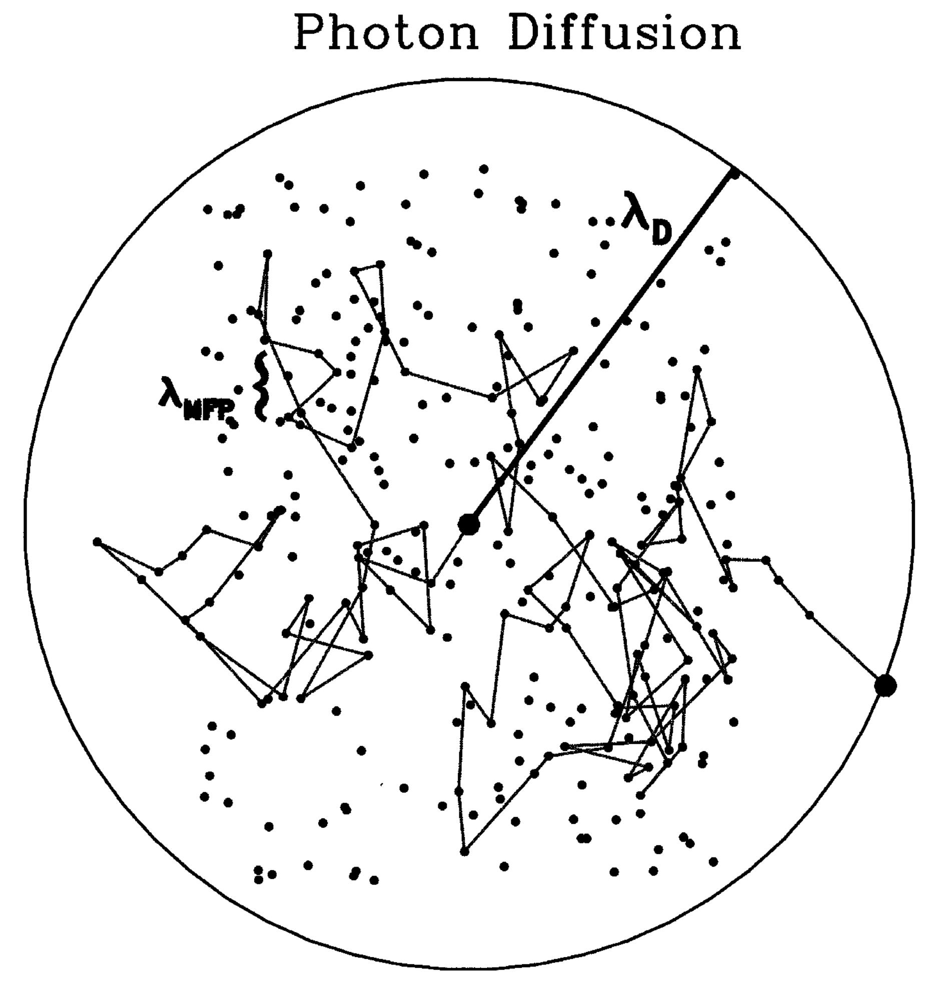
- $\ell_{\text{peak}} \sim \pi/\theta_{\text{fluc}}$
  - (Location of peak in C_ℓ) ~ (π/Angular scale of typical fluctuations)
- First peak at sound horizon/angular diameter distance

$$\theta_{\rm MC} \approx r_s(z_{\rm CMB})/D_A(z_{\rm CMB})$$

(Approximately) sensitive to *curvature*


Closed
$\Omega>1$
Flat
$\Omega=1$
Open
$\Omega<1$

DIFFUSION AND DAMPING



Recombination is not instantaneous => gives photons time to diffuse

$$\lambda_D \sim \lambda_{\rm MFP}\sqrt{n_e\sigma_T H^{-1}} = \frac{1}{\sqrt{n_e\sigma_T H}}$$

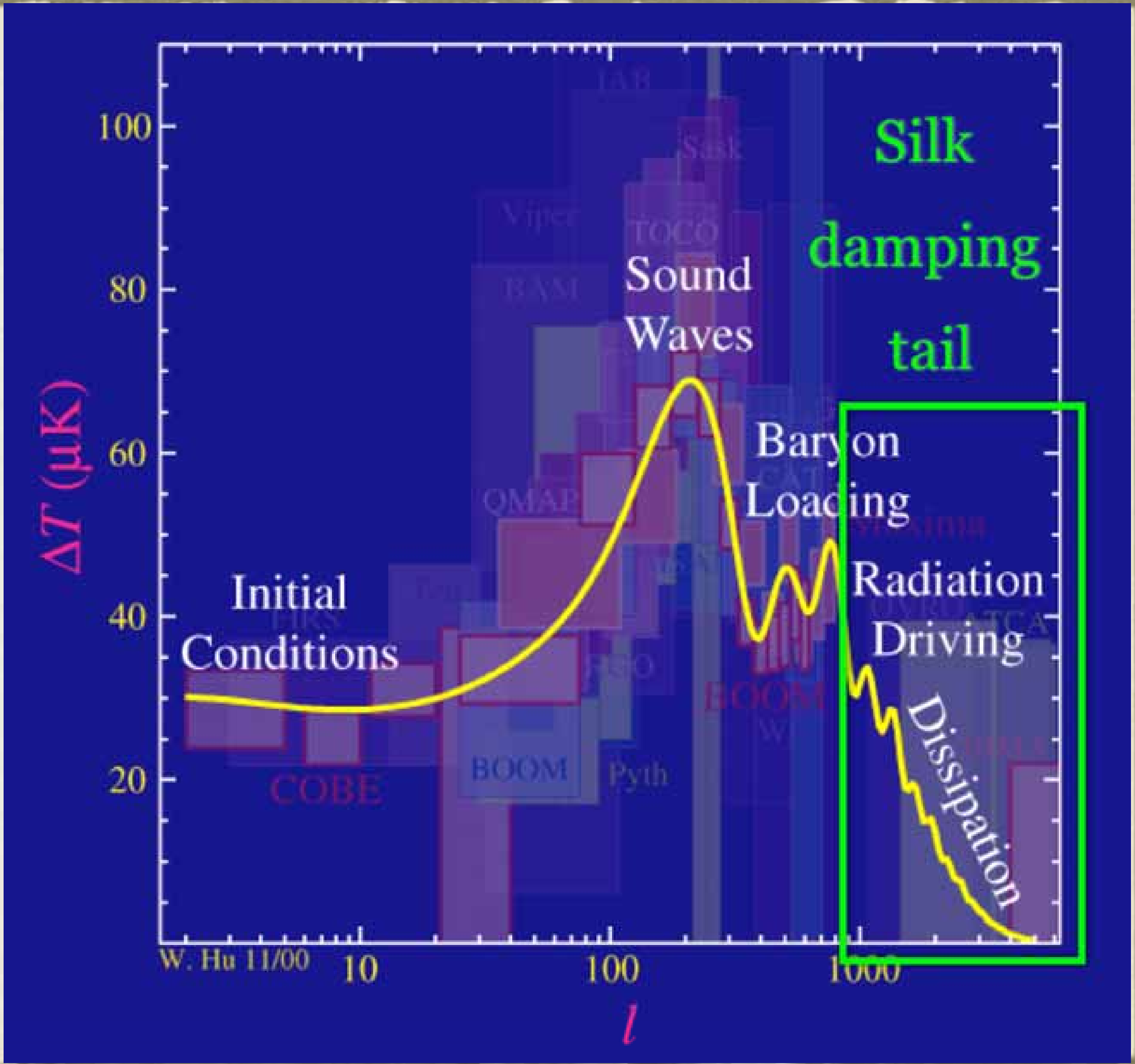
Photons move between hot and cold regions so fluctuations average out

ANGULAR POWER SPECTRUM

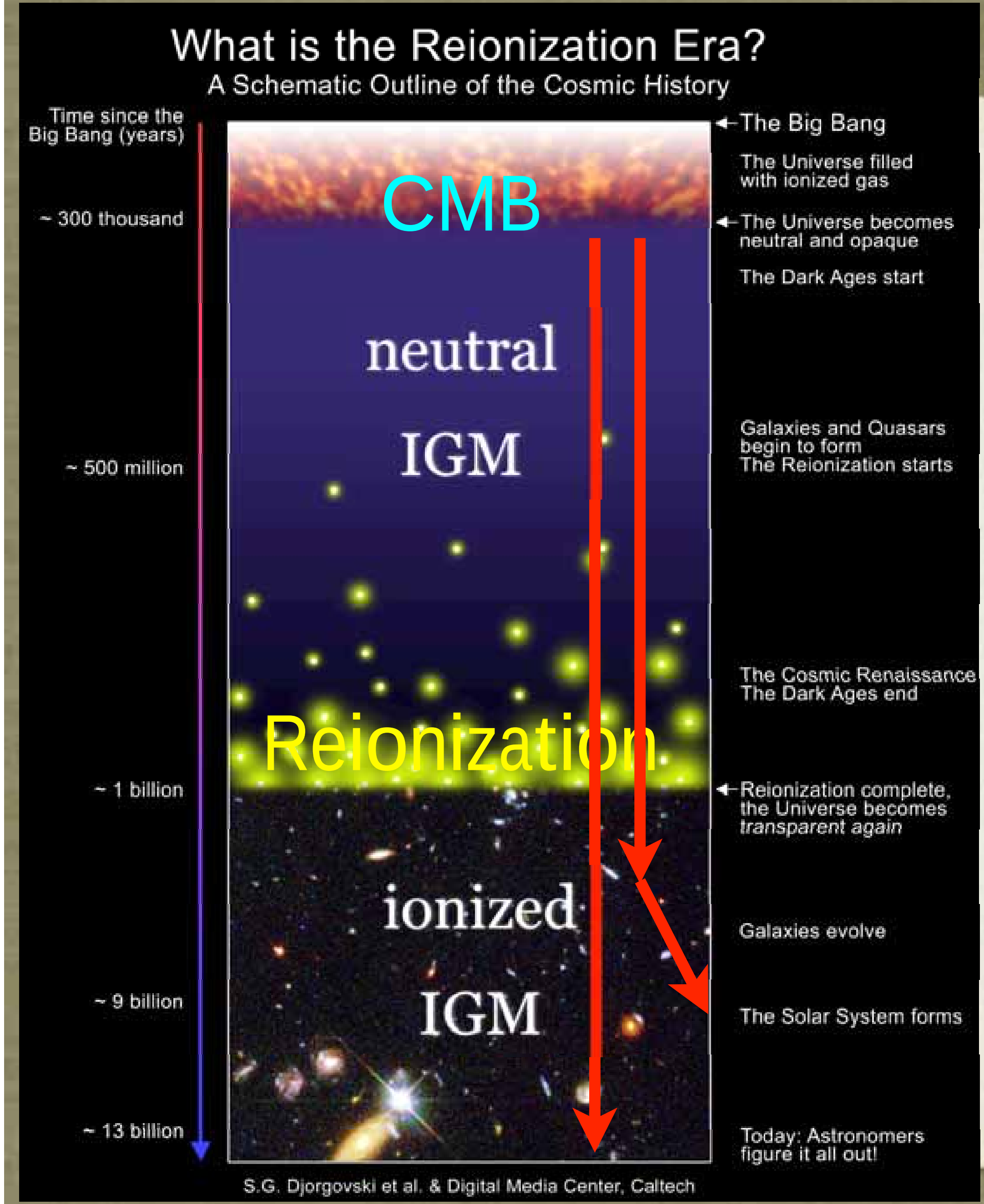
Scales smaller than diffusion scale are damped out

diffusion length sensitive to baryon density

“Silk damping tail”



REIONIZATION AKA FOG



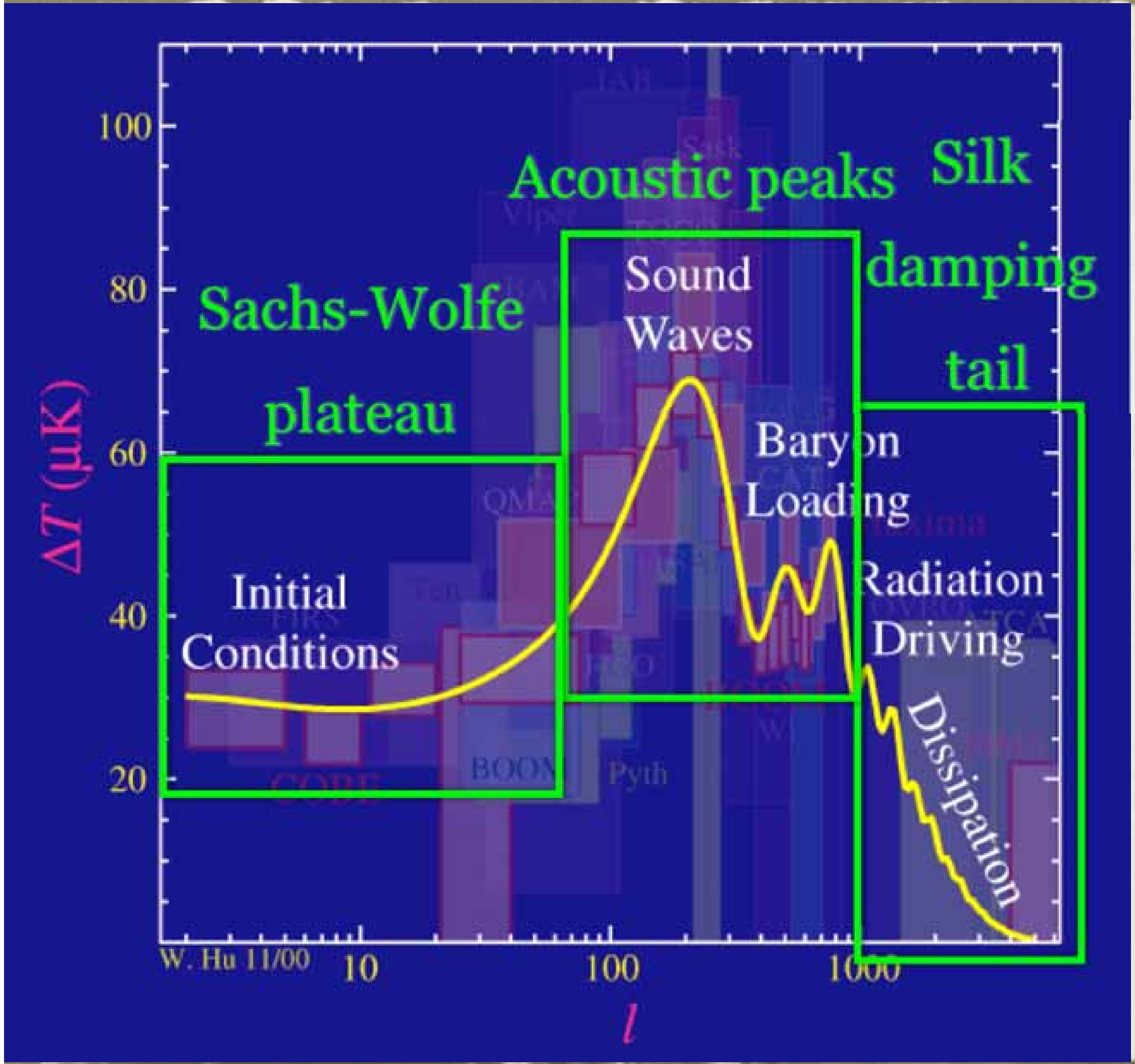
- Galaxies reionize the Universe at z<15
- Ionized IGM rescatters CMB photons
  => damps CMB anisotropies

$$C_l \rightarrow C_l e^{-2\tau}$$

- Optical depth to surface of last scattering tau~0.09

$$\tau = \int \sigma_T n_e(z) \mathrm{d}l$$

PRIMARY CMB PHYSICS



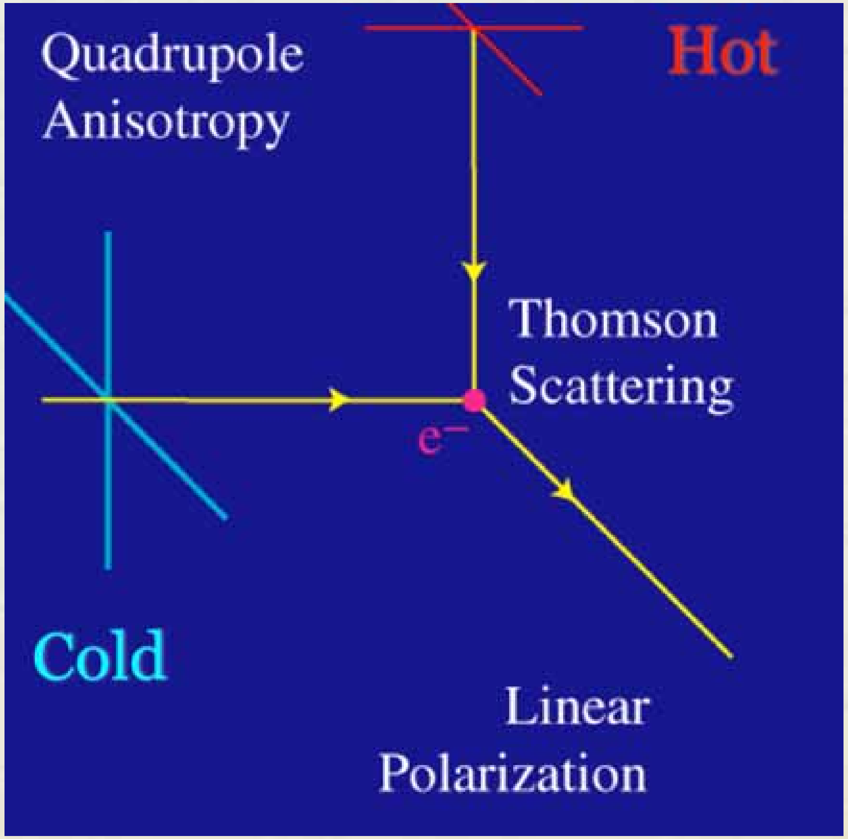
6 numbers to get CMB temperature C_l

	Planck	
Parameter	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068
τ	0.0925	0.097 ± 0.038
n_s	0.9624	0.9616 ± 0.0094
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072

POLARISATION

- Full description of CMB is intensity plus polarisation
- Polarisation originally dismissed as being too small to detect

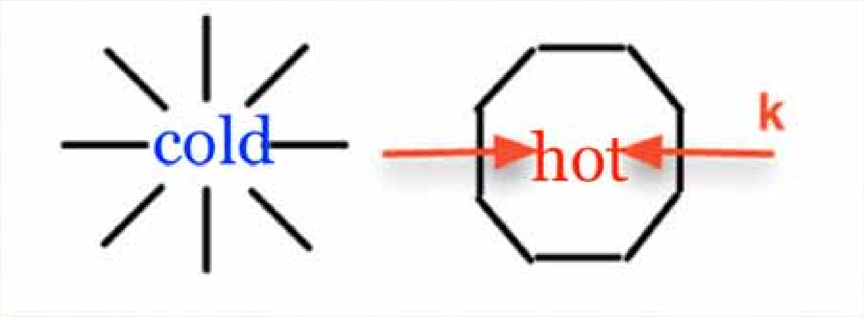
Thompson scattering of temperature quadrupole => linear polarisation



E- AND B-MODE POLARISATION

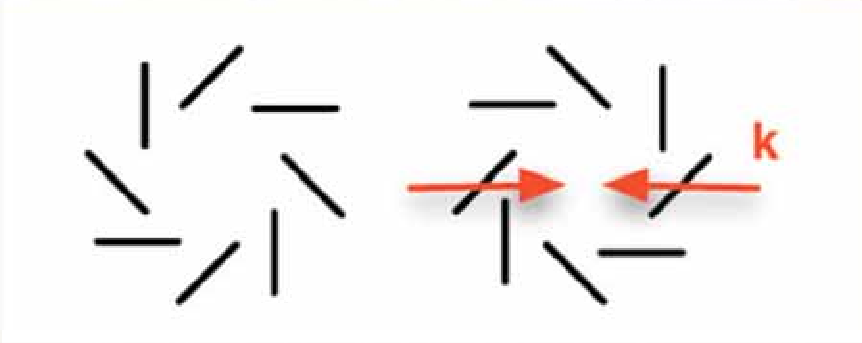
- Density (scalar) fluctuations lead to E-mode polarisation only
- Gravitational waves (tensor) fluctuations lead to B-mode polarisation
- Also get B-mode polarisation by lensing E-mode polarisation

E-mode (grad)

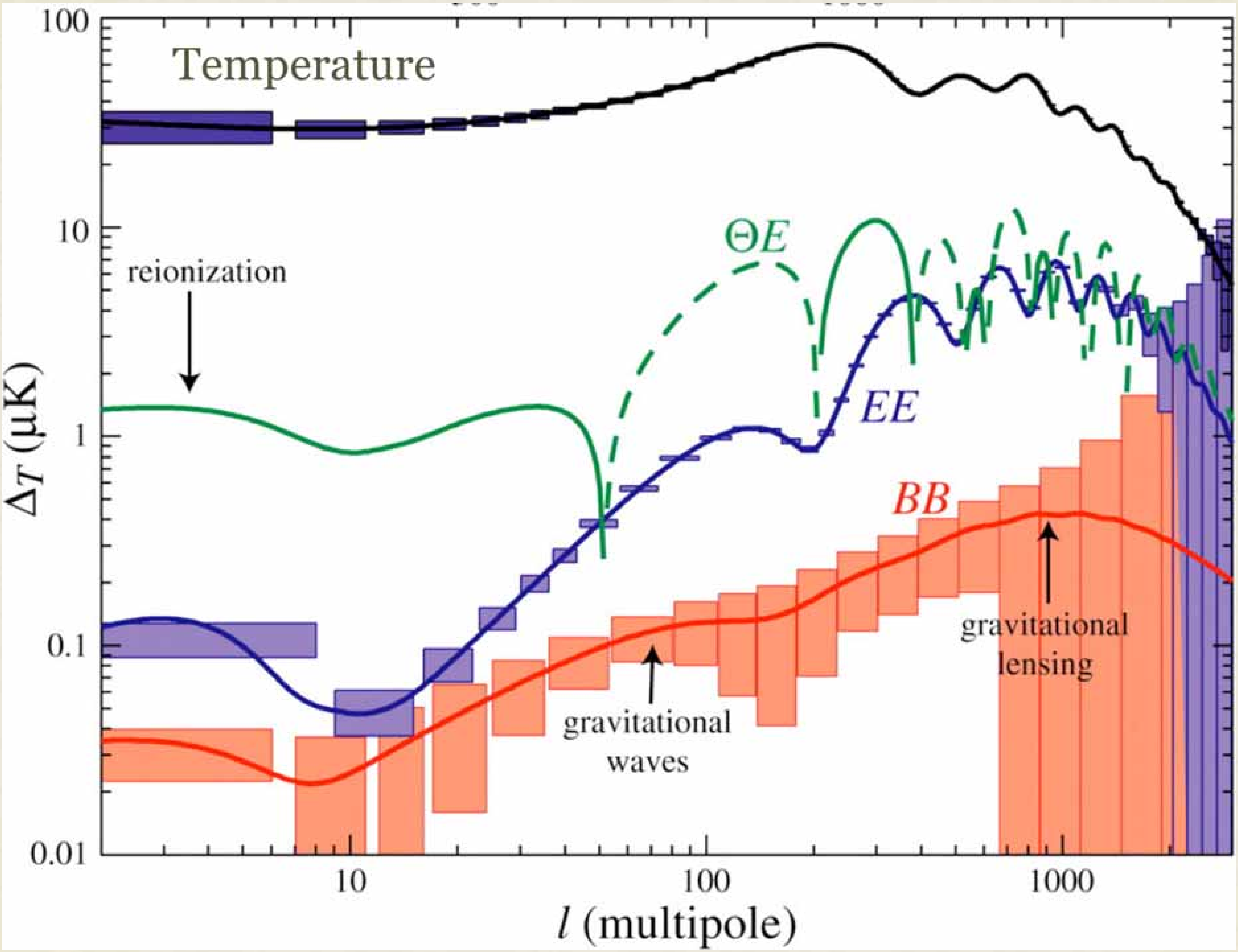


(parity symmetric
=no handedness)

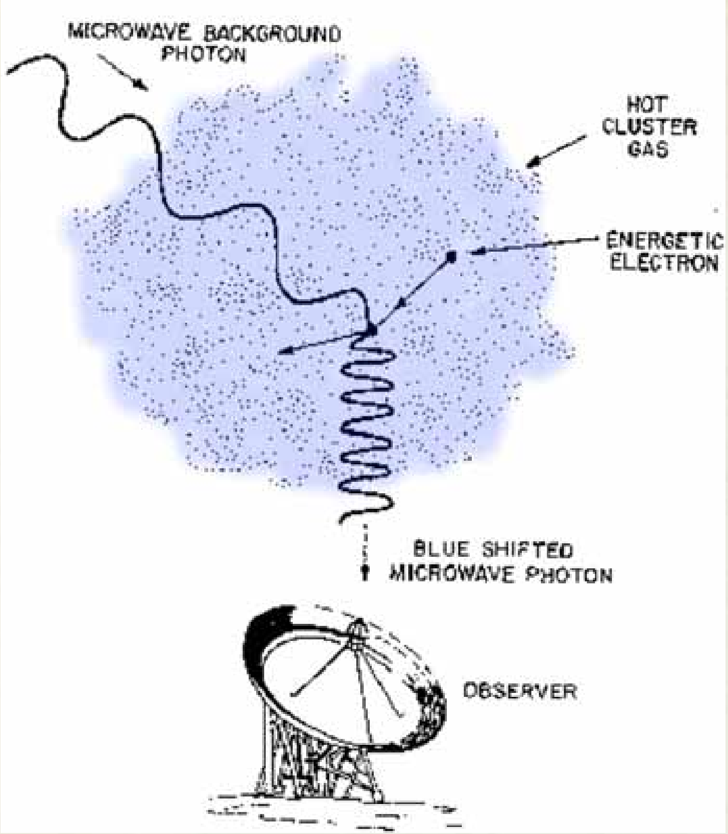
B-mode (curl)

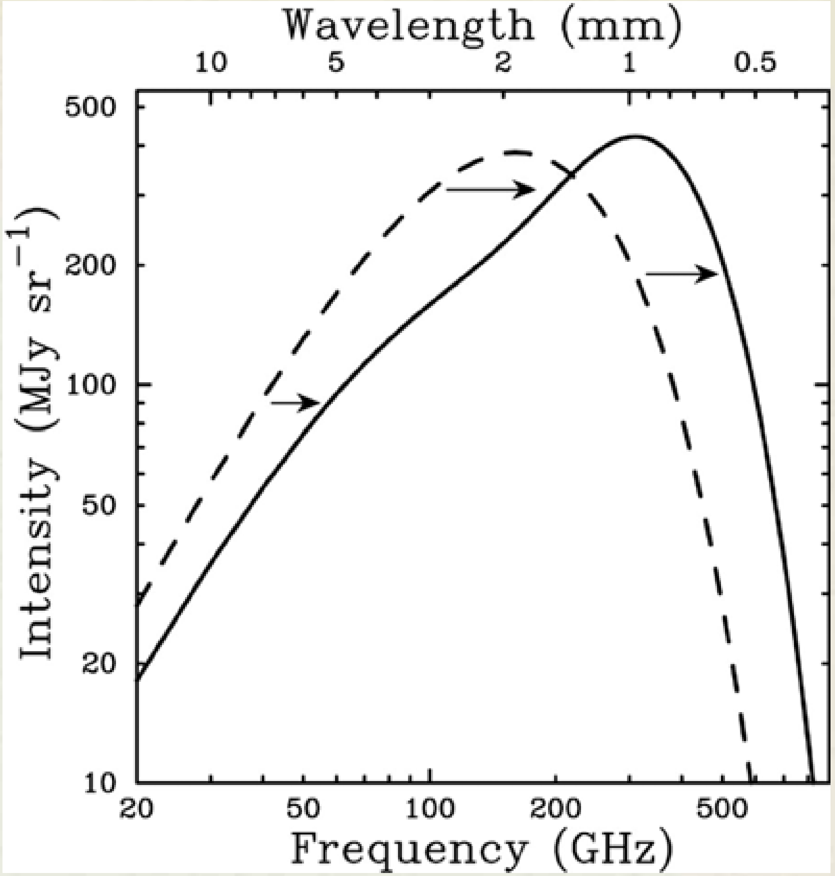


(parity inverted
=handedness)


Temperature
ΘE
EE
BB
reionization
gravitational waves
gravitational lensing
Δ_T (μK)
l (multipole)
100
10
1
0.1
0.01
10
100
1000

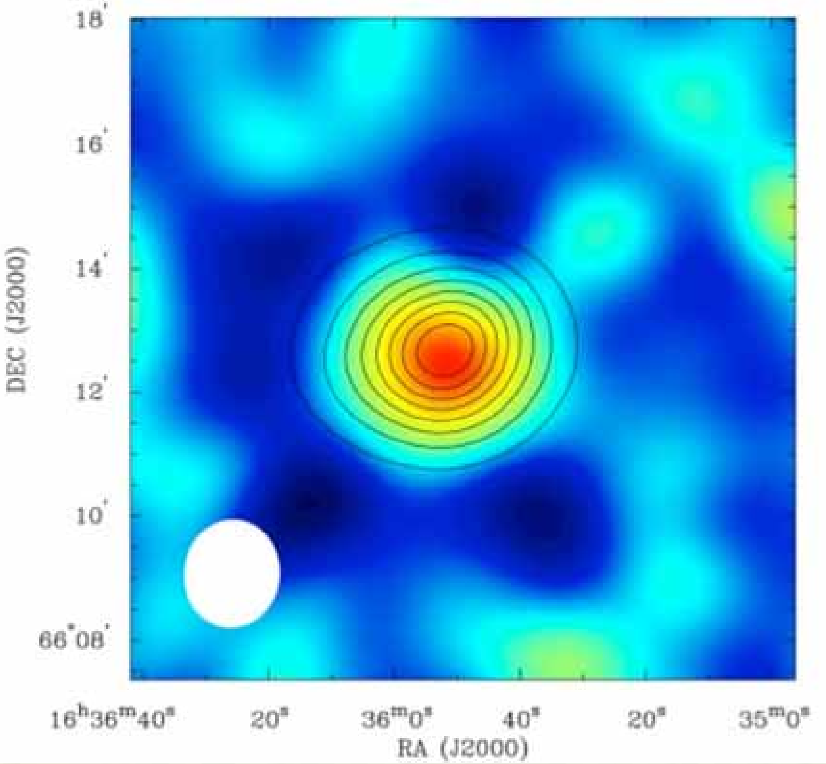
SUNYAEV-ZELDOVICH EFFECT





$$\frac{\Delta T}{T} \approx -2 \int \mathrm{d}\tau \, \frac{k_B T}{m_e c^2}$$

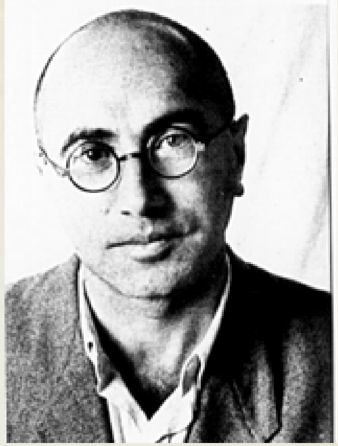
CLUSTERS



Abell 2218

Color: Sunyaev–Zeldovich Effect at 28.5 GHz (Chicago/MSFC S–Z group, BIMA Interferometer)

Contours: X–ray Emission (ROSAT PSPC imager)



Clusters are filled with hot (10^7-10^8K) gas

=> SZ effect makes them show up as small hot spots (~10arcsec)

TSZ VS KSZ

Thermal SZ

$$\frac{\Delta T}{T} \approx -2 \int \mathrm{d}\tau \, \frac{k_B T}{m_e c^2}$$

Thermal velocities

Frequency dependent

Kinetic SZ

$$\frac{\Delta T}{T} = \int \mathrm{d}\tau \, \frac{\mathbf{v} \cdot \hat{\mathbf{n}}}{c}$$

Bulk velocities

Frequency independent

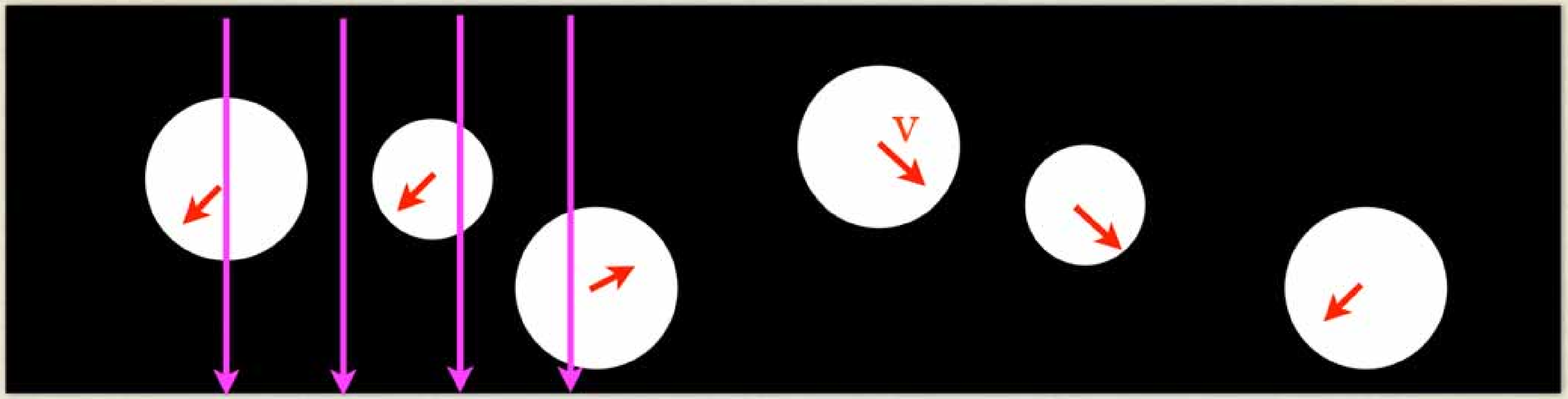
KSZ typically smaller $\frac{\Delta T_{\mathrm{KSZ}}}{\Delta T_{\mathrm{TSZ}}} \sim \frac{v_r/c}{\langle v_e^2 \rangle / c^2}$ ~1%

cluster peculiar velocity < 1000 km/s

electron thermal velocity ~10^4 km/s for 10^7K

Rapaeli 2005

PATCHY KSZ



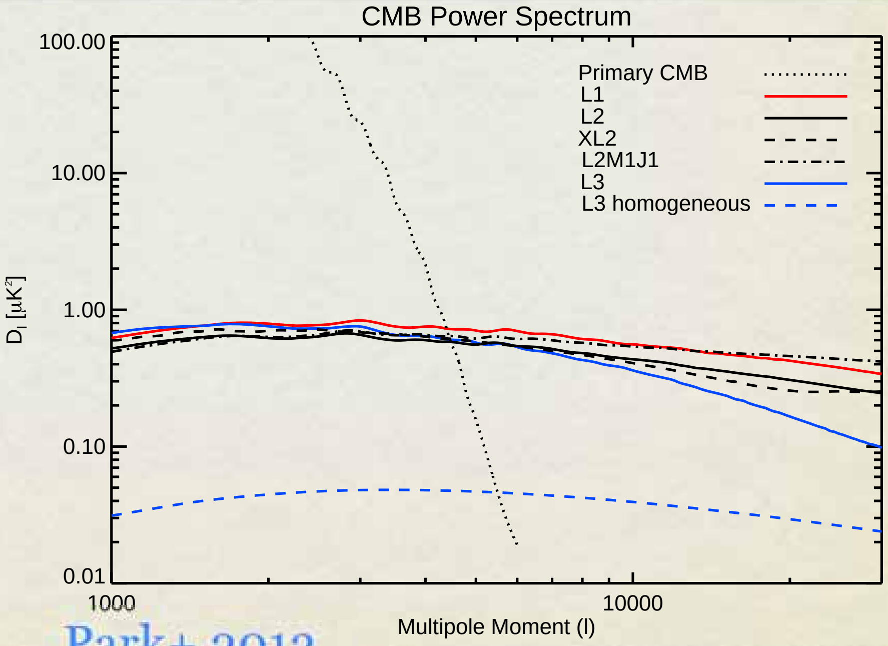
Bulk velocity of ionized bubbles

introduces patchy KSZ effect

=> probe of reionization

$$\frac{\Delta T_{\mathrm{kSZ}}}{T_{\mathrm{CMB}}}(\hat{\mathbf{n}}) = \frac{\sigma_T}{c}\int_{z_1}^{z_2}\frac{dx}{dz}\frac{dz}{(1+z)}\bar{n}_e(z)e^{-\tau(z)}\hat{\mathbf{n}}\cdot\mathbf{q},$$

$$\mathbf{q} = (1+\delta_x)\,(1+\delta_{\mathrm{b}})\,\mathbf{v}\,.$$



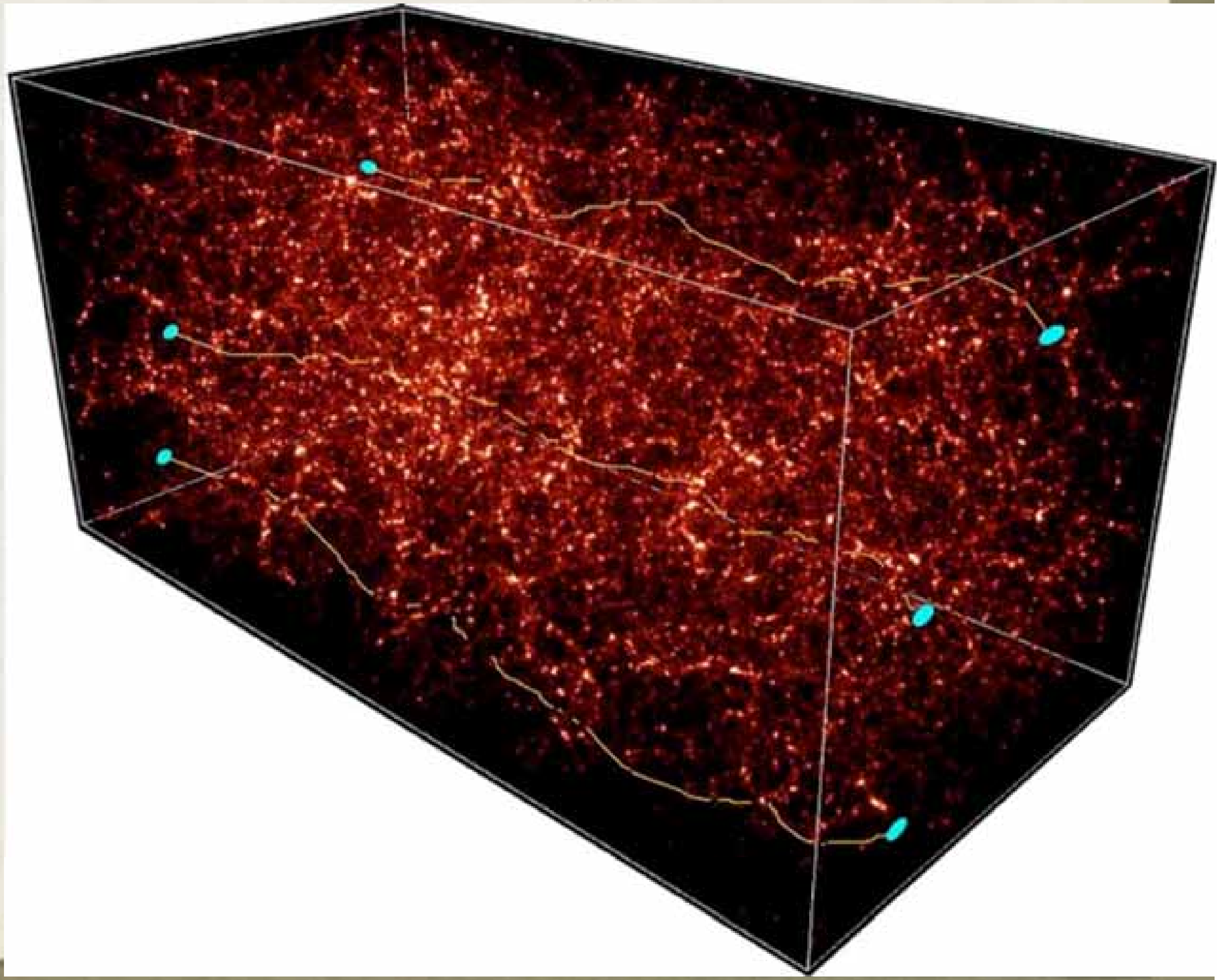
Park+ 2013

WEAK LENSING

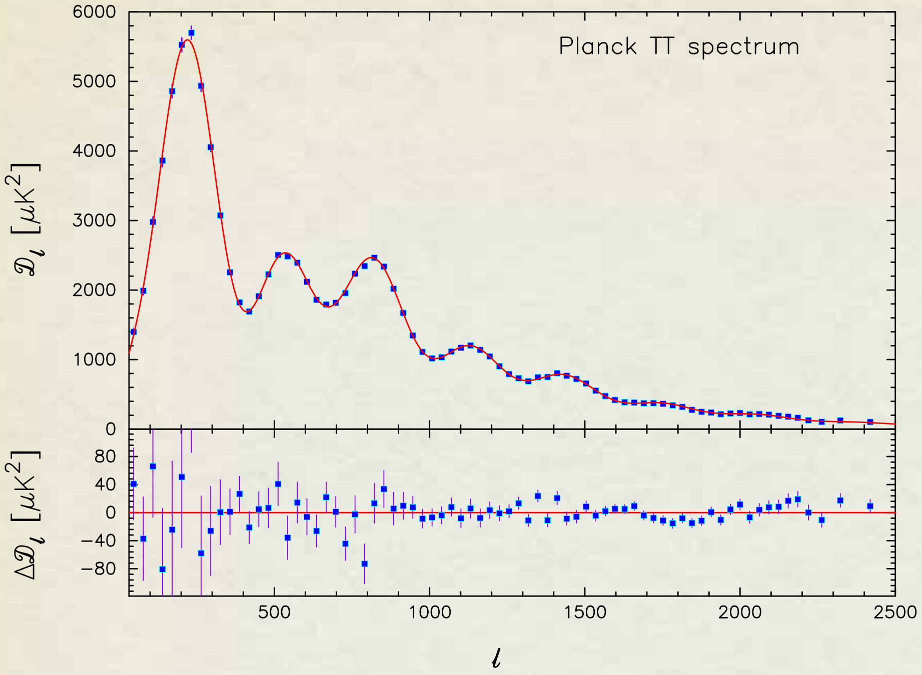
$$T_{\rm lensed}(\hat{n}') \approx T_{\rm unlensesd}(\hat{n}) + \alpha \cdot \nabla T_{\rm unlensesd}(\hat{n})$$

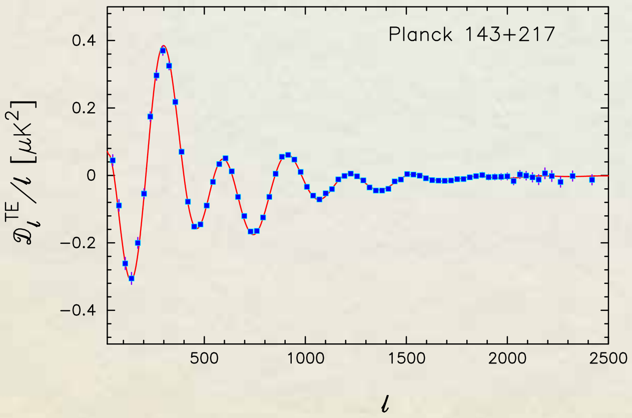
deflection angle $\alpha = \nabla\phi$

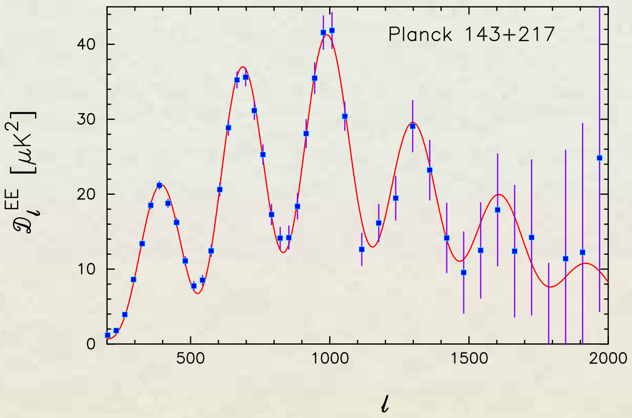
- Matter along line of sight to CMB will gravitationally lens temperature fluctuations
- 1) Mixes E<->B pol
  2) Adds Non-Gaussianity
- CMB a background screen to statistically probe large scale structure



PLANCK SPECTRA







PLANCK SCIENCE

- Independent check of WMAP observations
- Inflation models: scalar tilt + better B-mode constraints
- Bispectrum - Non-Gaussianity
- Weak lensing - map matter
- SZ effect - Clusters