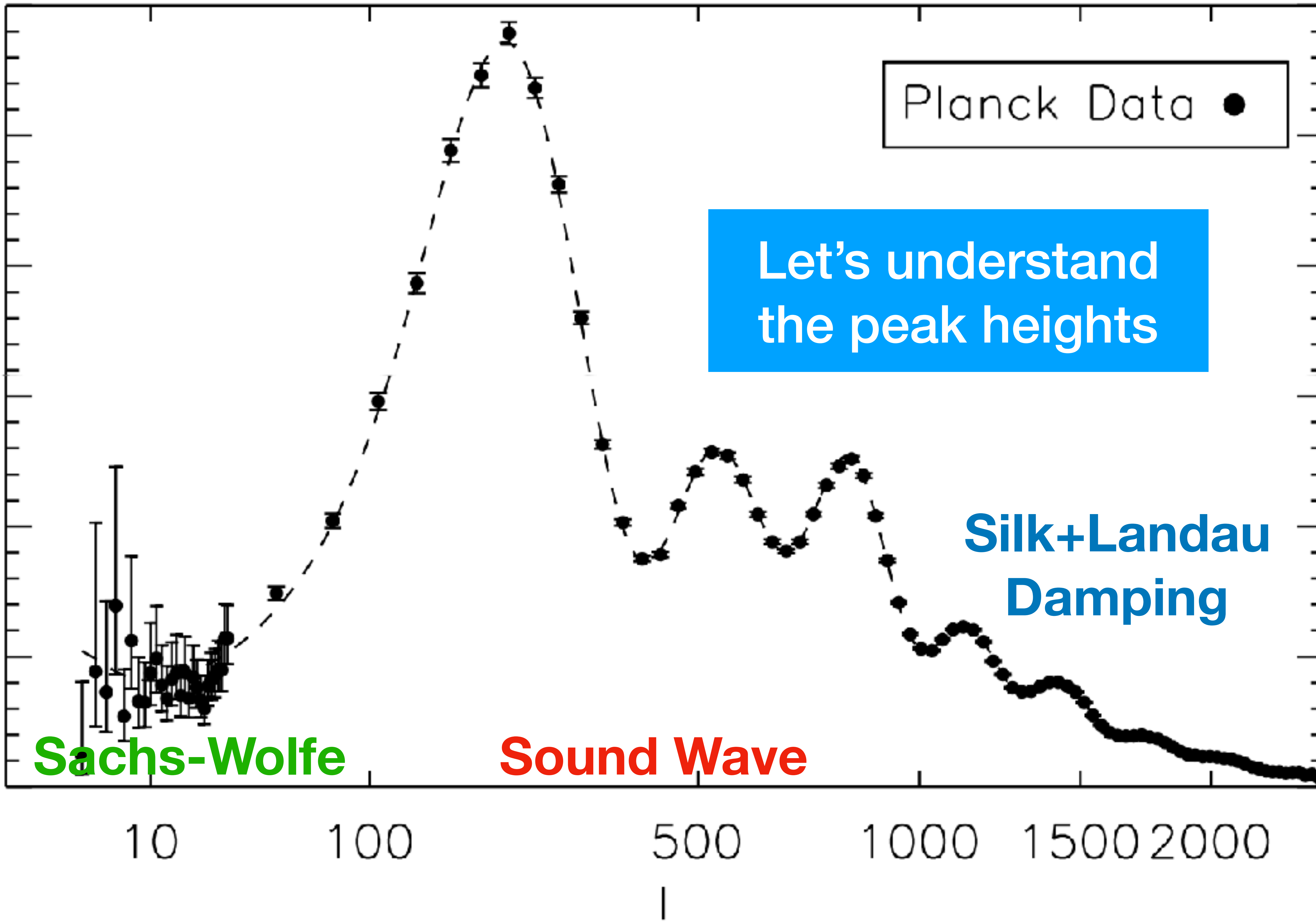
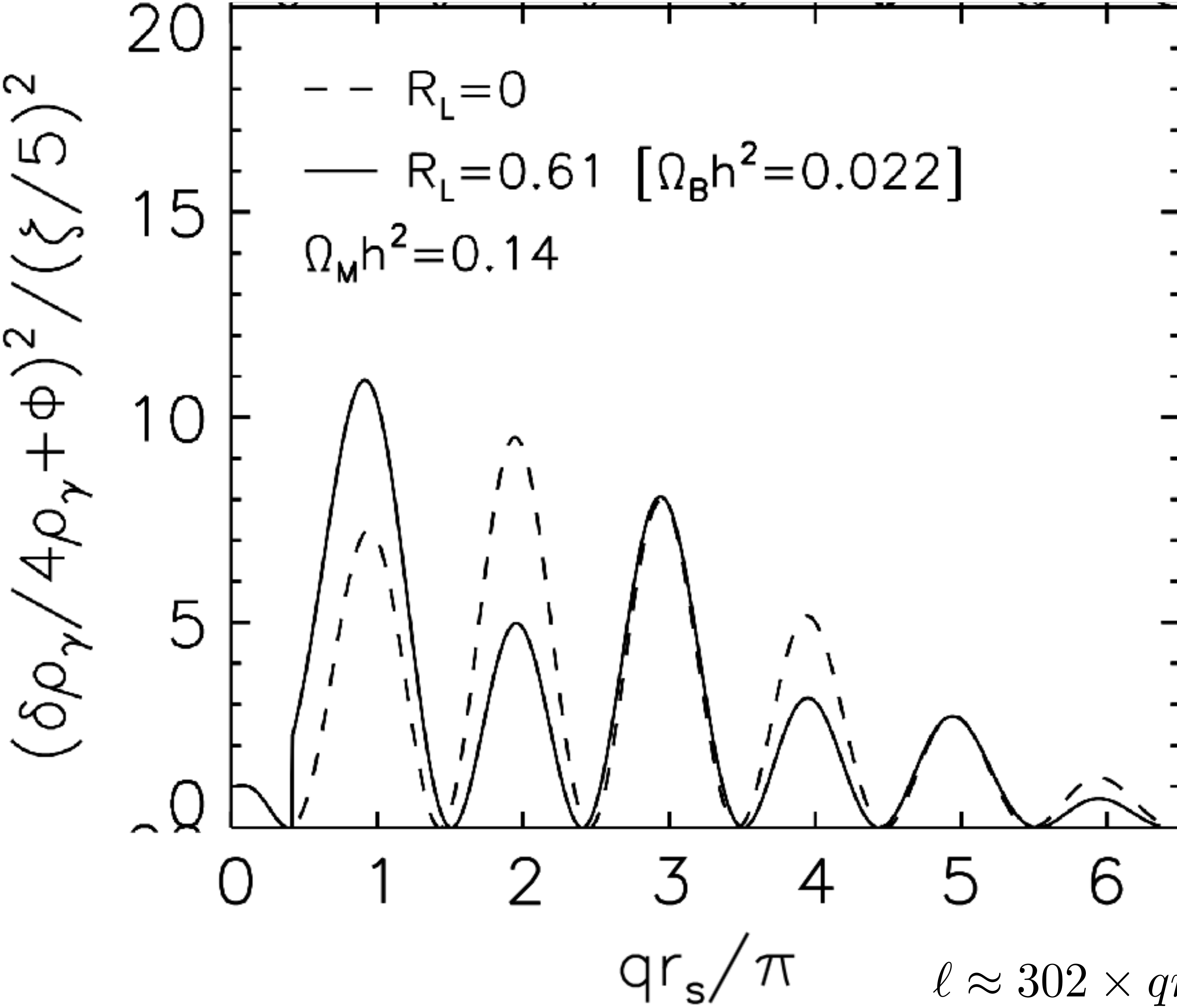
Lecture 4

- Cosmological parameter dependence of the temperature power spectrum (continued)

- Polarisation

Planck Collaboration (2016)





$\ell \approx 302 \times qr_s/\pi$

Not quite there yet…

- **The first peak is too low**
  - We need to include the “integrated Sachs-Wolfe effect”
- **How to fill zeros between the peaks?**
  - We need to include the Doppler shift of light

Doppler Shift of Light

$$\frac{\Delta T(\hat{n})}{T_0} = \frac{\delta\rho_\gamma(t_L, \hat{n}r_L)}{4\bar{\rho}_\gamma(t_L)} + \Phi(t_L, \hat{n}r_L) - \hat{n}\cdot\boldsymbol{v}_B(t_L, \hat{n}r_L)$$

V_B is the bulk velocity of a baryon fluid

- Using the velocity potential, we write $-\hat{n}\cdot\nabla\delta u_B/a$
- In tight coupling, $\delta u_B = \delta u_\gamma$
- Using energy conservation,

$$\delta u_\gamma = (3a^2/q^2)\partial(\delta\rho_\gamma/4\bar{\rho}_\gamma)/\partial t$$

Line-of-sight direction

$$\hat{n}^i = -\gamma^i$$

Coming distance (r)

$$x^i = \hat{n}^i r$$

$$r(t) = \int_t^{t_0} \frac{dt'}{a(t')}$$

Doppler Shift of Light

$$\frac{\Delta T(\hat{n})}{T_0} = \frac{\delta\rho_\gamma(t_L, \hat{n}r_L)}{4\bar{\rho}_\gamma(t_L)} + \Phi(t_L, \hat{n}r_L) - \hat{n}\cdot \boldsymbol{v}_B(t_L, \hat{n}r_L)$$

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- Using energy conservation,

$$\delta u_\gamma = (3a^2/q^2)\partial(\delta\rho_\gamma/4\bar{\rho}_\gamma)/\partial t$$

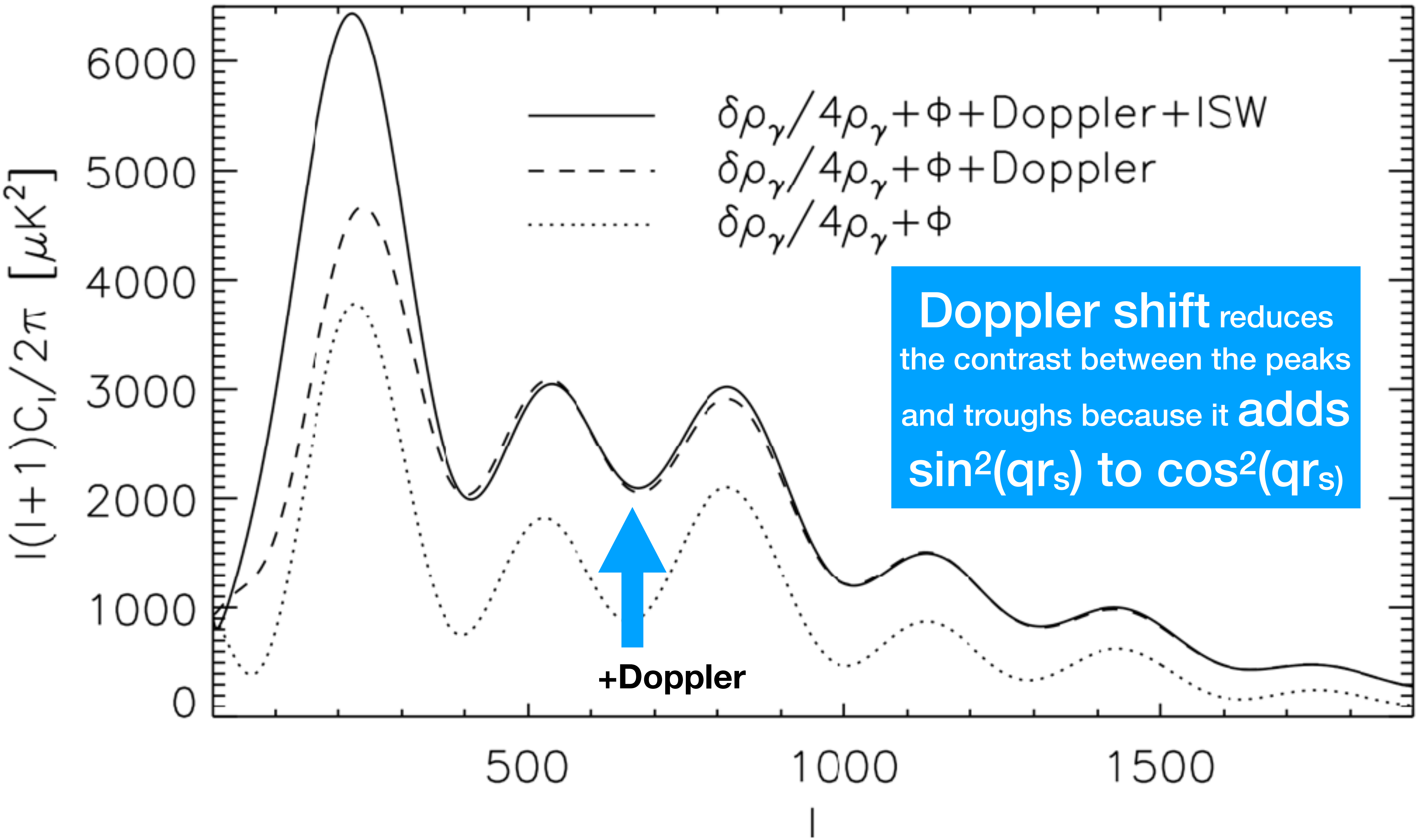
Velocity potential is a **time-derivative** of the energy density: **cos(qr$_s$) becomes sin(qr$_s$)!**

Temperature Anisotropy from Doppler Shift

$$\frac{q}{a}\delta u_\gamma = \frac{\sqrt{3}\zeta}{5}(1+R)^{-3/4}\mathcal{S}(\kappa)\sin[qr_s + \theta(\kappa)]$$

- To this, we should multiply the damping factor

$$\exp(-q^2/q^2_{\text{Damp}})$$



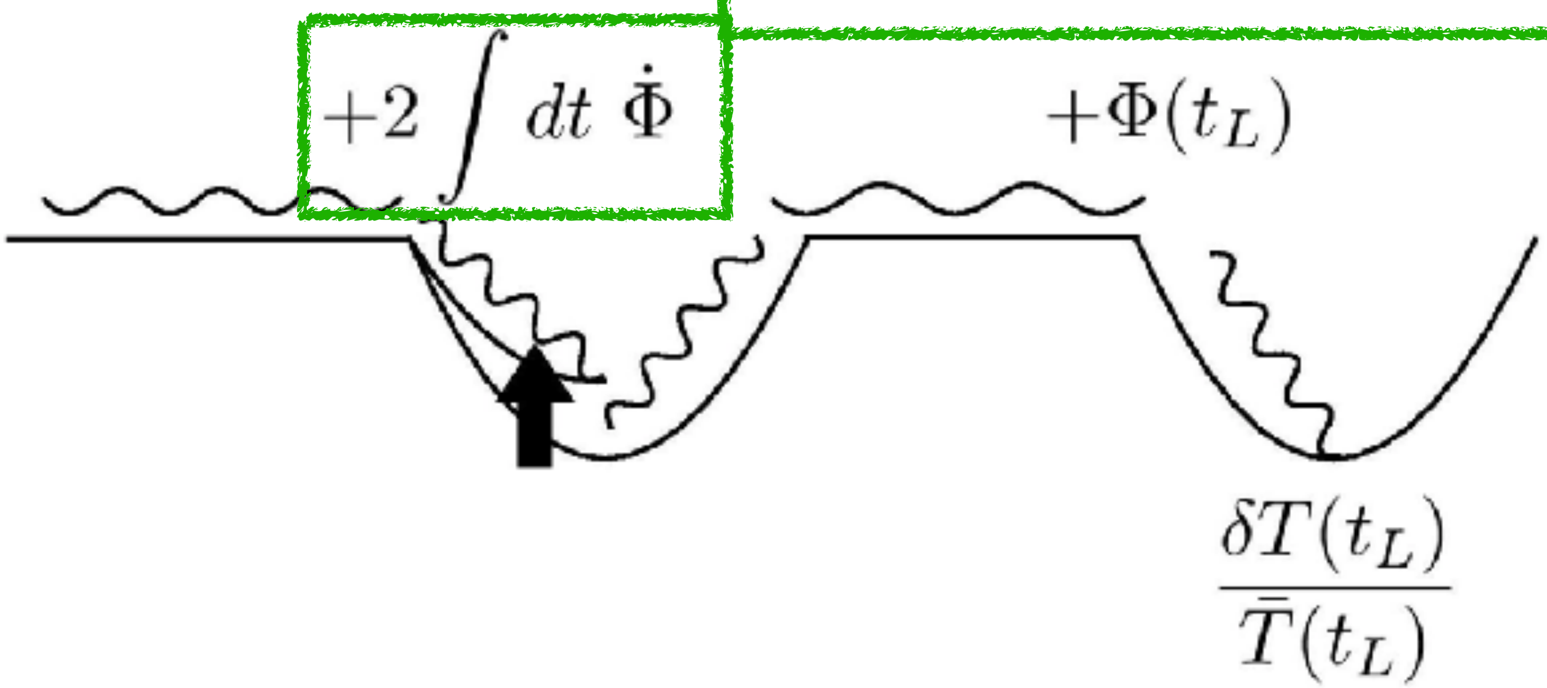
6000
5000
4000
3000
2000
1000
0
500
1000
1500
l
l(l+1)C_l/2π [μK²]
δρ_γ/4ρ_γ+Φ+Doppler+ISW
δρ_γ/4ρ_γ+Φ+Doppler
δρ_γ/4ρ_γ+Φ
+Doppler
Doppler shift reduces the contrast between the peaks and troughs because it adds sin²(qr_s) to cos²(qr_s)

Hu & Sugiyama (1996)

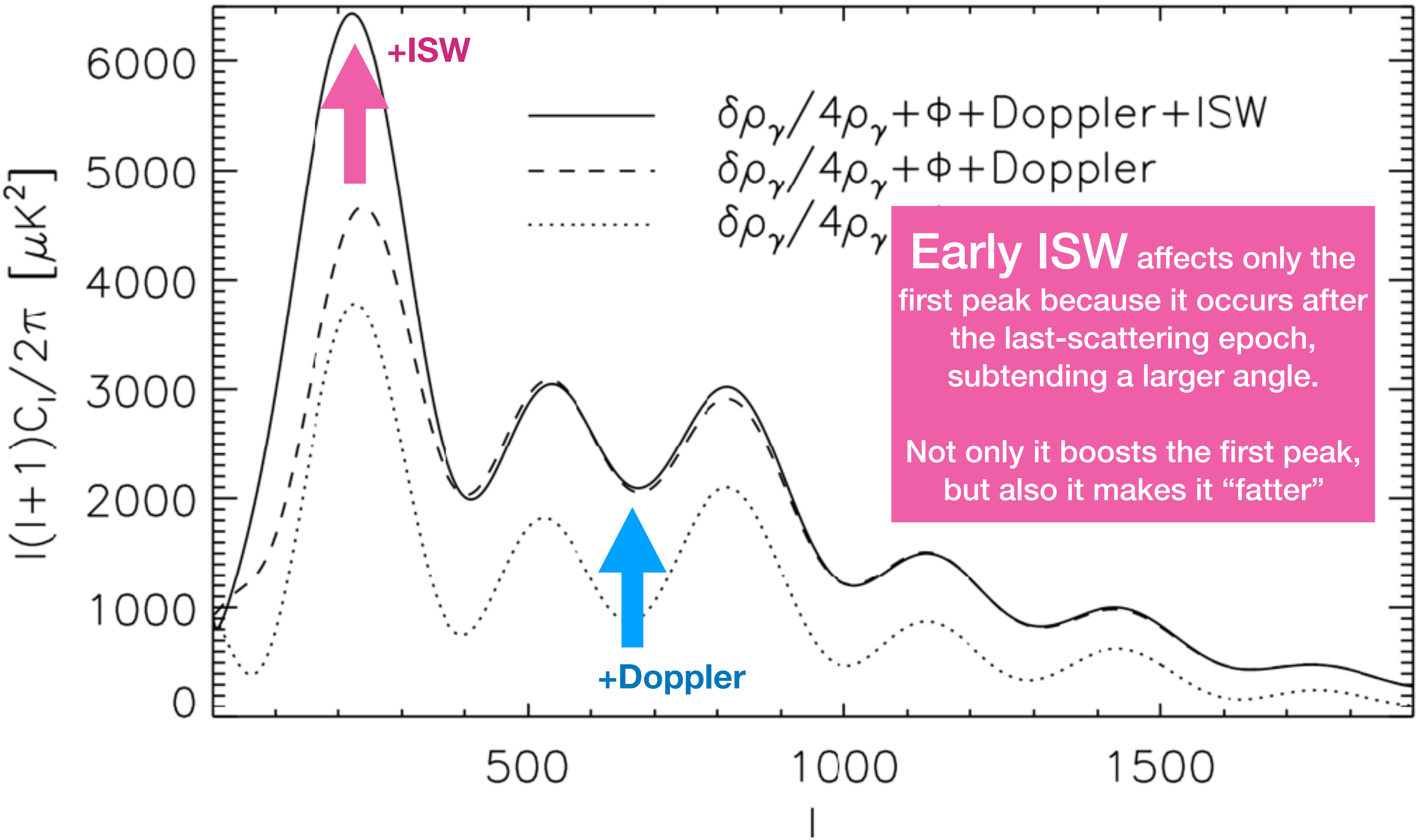
(Early) ISW

$$\frac{\Delta T(\hat{n})}{T_0} = \frac{\delta T(t_L, \hat{n} r_L)}{\bar{T}(t_L)} + \Phi(t_L, \hat{n} r_L) - \Phi(t_0, 0) + \int_{t_L}^{t_0} dt \; (\dot{\Phi} + \dot{\Psi})(t, \hat{n} r)$$

"integrated Sachs-Wolfe" (ISW) effect

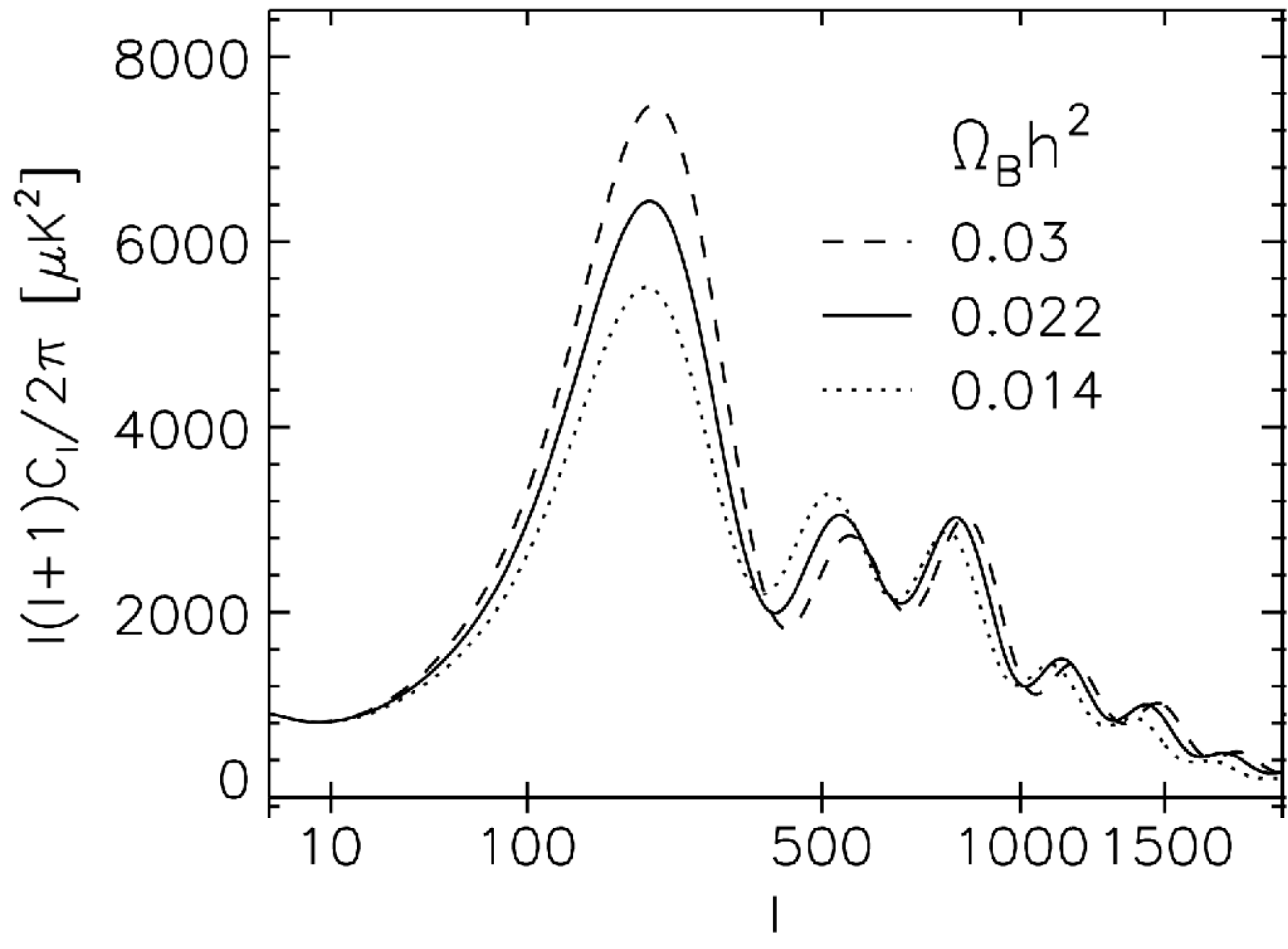


Gravitational potentials still decay after last-scattering because the Universe then was not completely matter-dominated yet

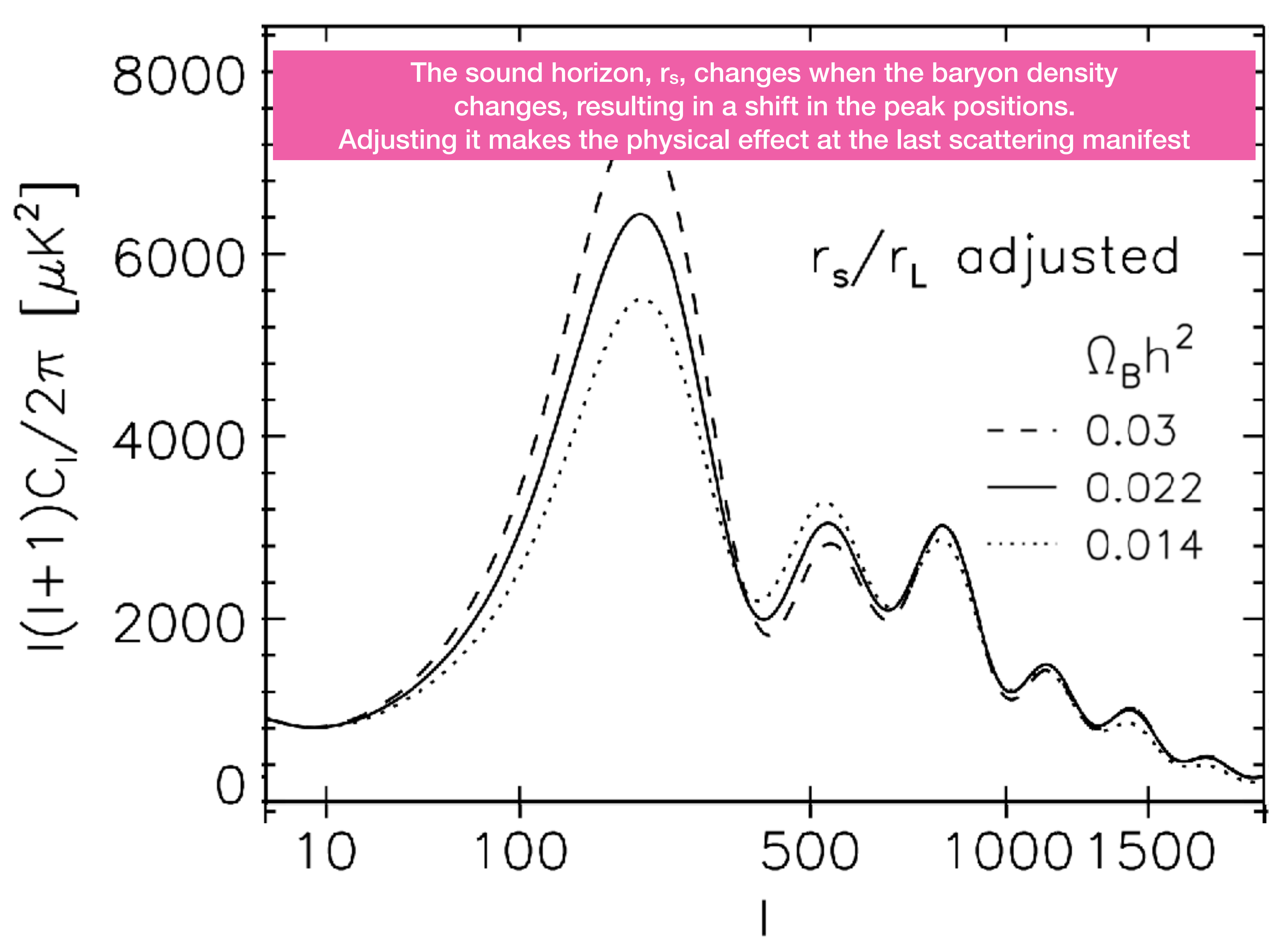

+ISW
δρ_γ/4ρ_γ+Φ+Doppler+ISW
δρ_γ/4ρ_γ+Φ+Doppler
δρ_γ/4ρ_γ
Early ISW affects only the first peak because it occurs after the last-scattering epoch, subtending a larger angle.
Not only it boosts the first peak, but also it makes it "fatter"
+Doppler
l(l+1)C_l/2π [μK²]
l
0
1000
2000
3000
4000
5000
6000
500
1000
1500

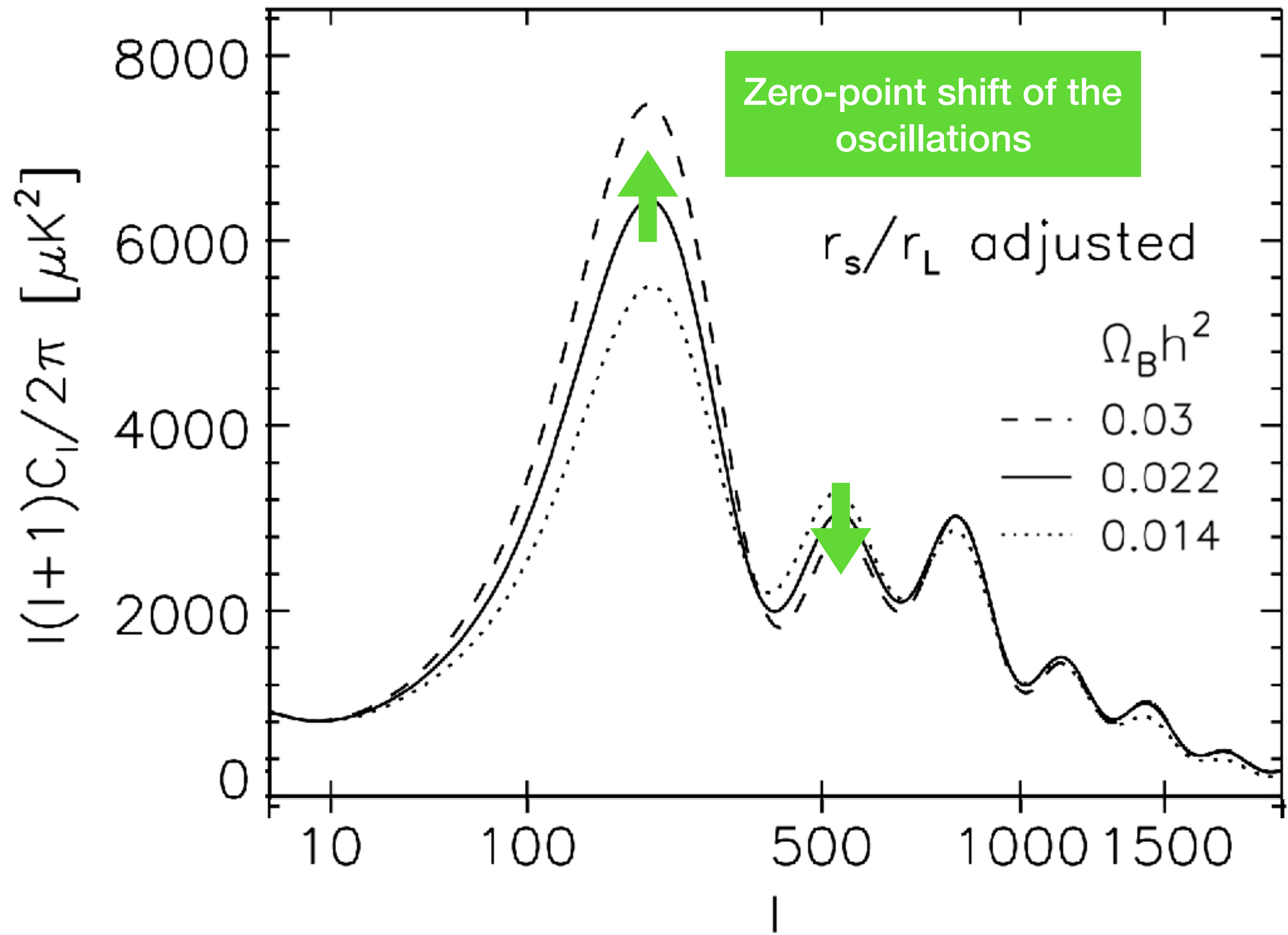
We are ready!

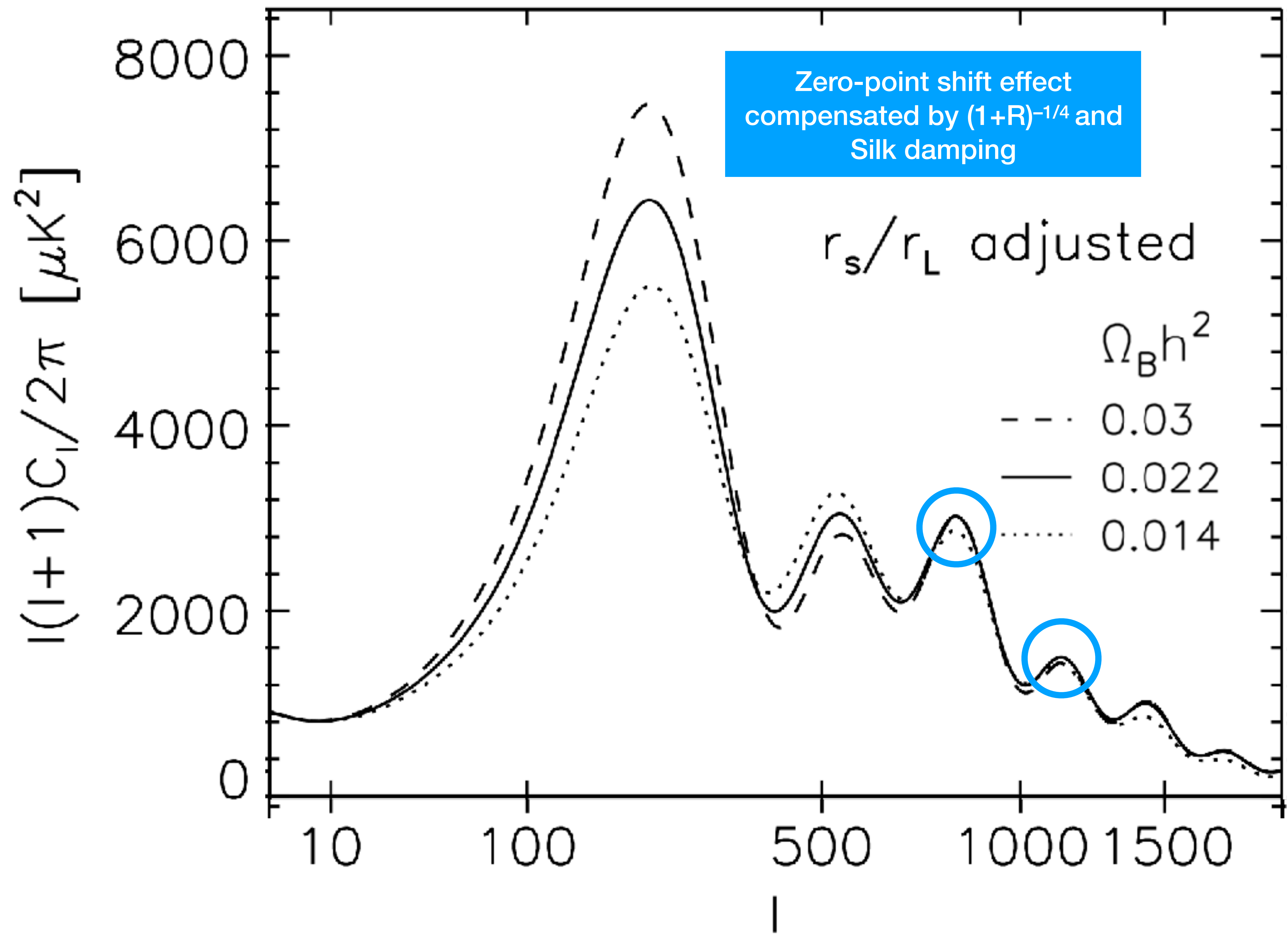
- We are ready to understand the effects of all the cosmological parameters.
- Let's start with the baryon density



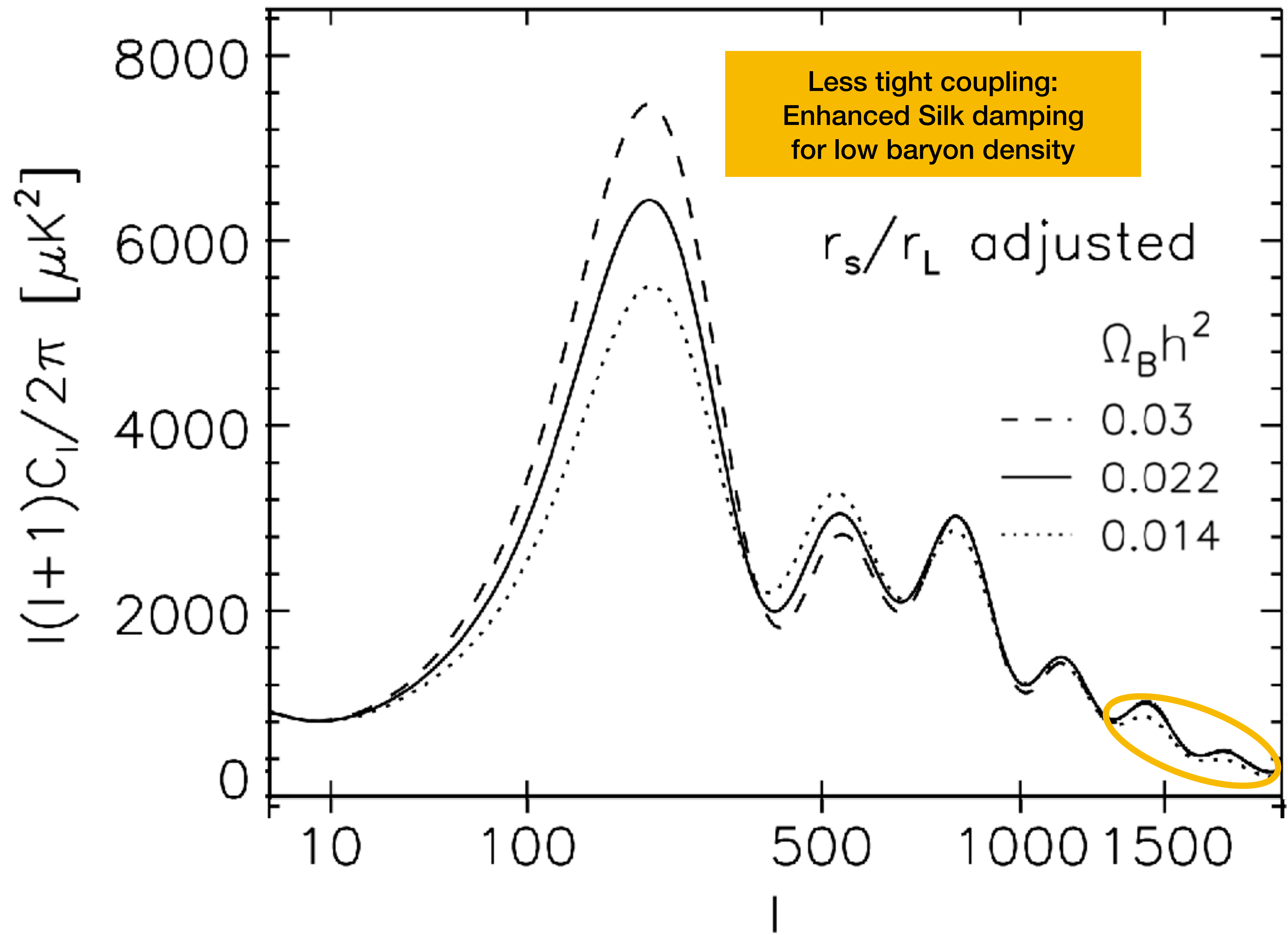
8000
6000
4000
2000
0
10
100
500
1000
1500
l
l(l+1)C_l/2π [μK^2]
Ω_B h^2
0.03
0.022
0.014


The sound horizon, r_s, changes when the baryon density changes, resulting in a shift in the peak positions.
Adjusting it makes the physical effect at the last scattering manifest
r_s/r_L adjusted
$\Omega_B h^2$
0.03
0.022
0.014
8000
6000
4000
2000
0
10
100
500
1000
1500
l
$l(l+1)C_l/2\pi$ [μK^2]

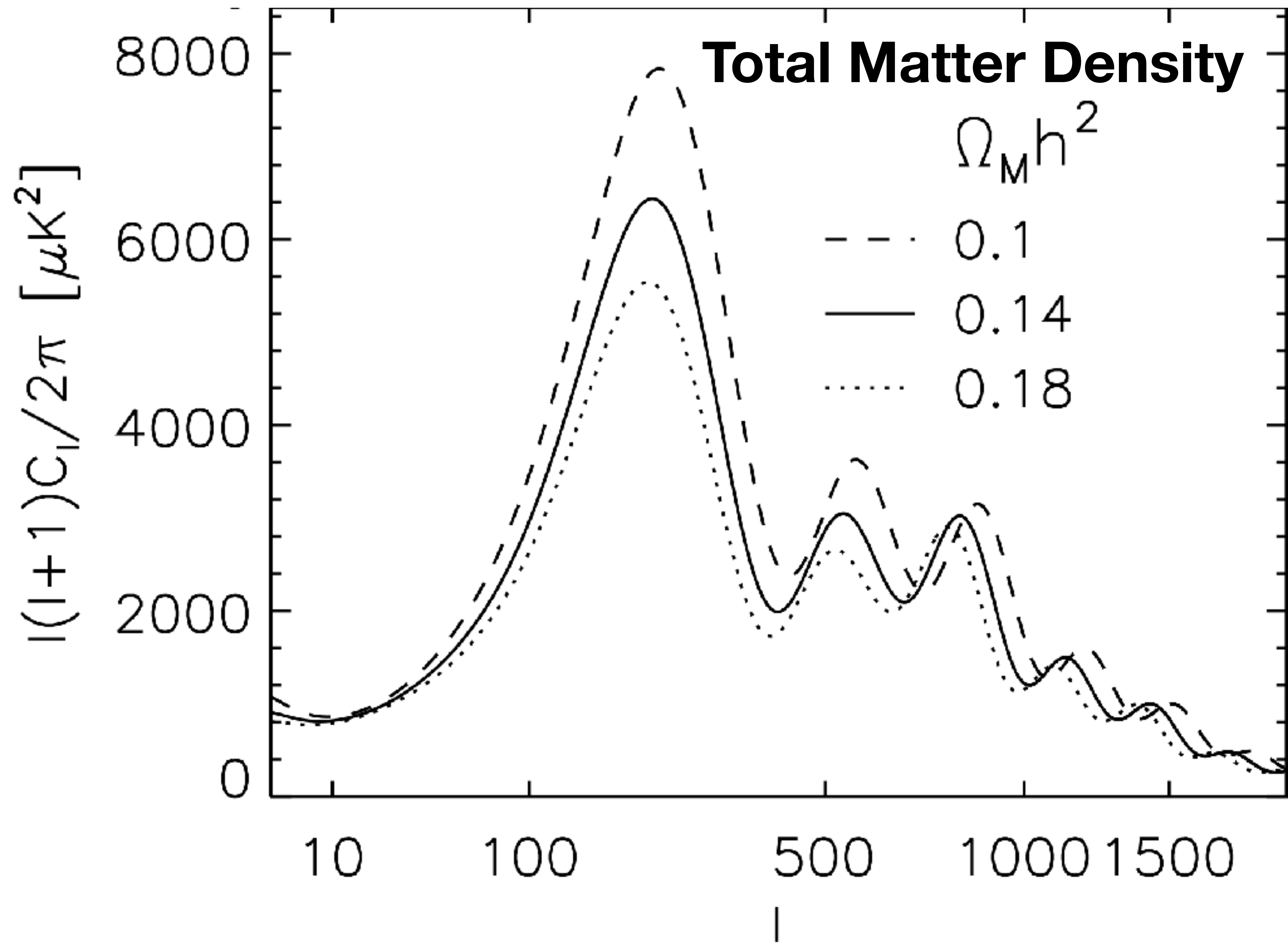

8000
6000
4000
2000
0
$l(l+1)C_l/2\pi$ [μK^2]
Zero-point shift of the oscillations
r_s/r_L adjusted
$\Omega_B h^2$
0.03
0.022
0.014
10
100
500
1000
1500
l



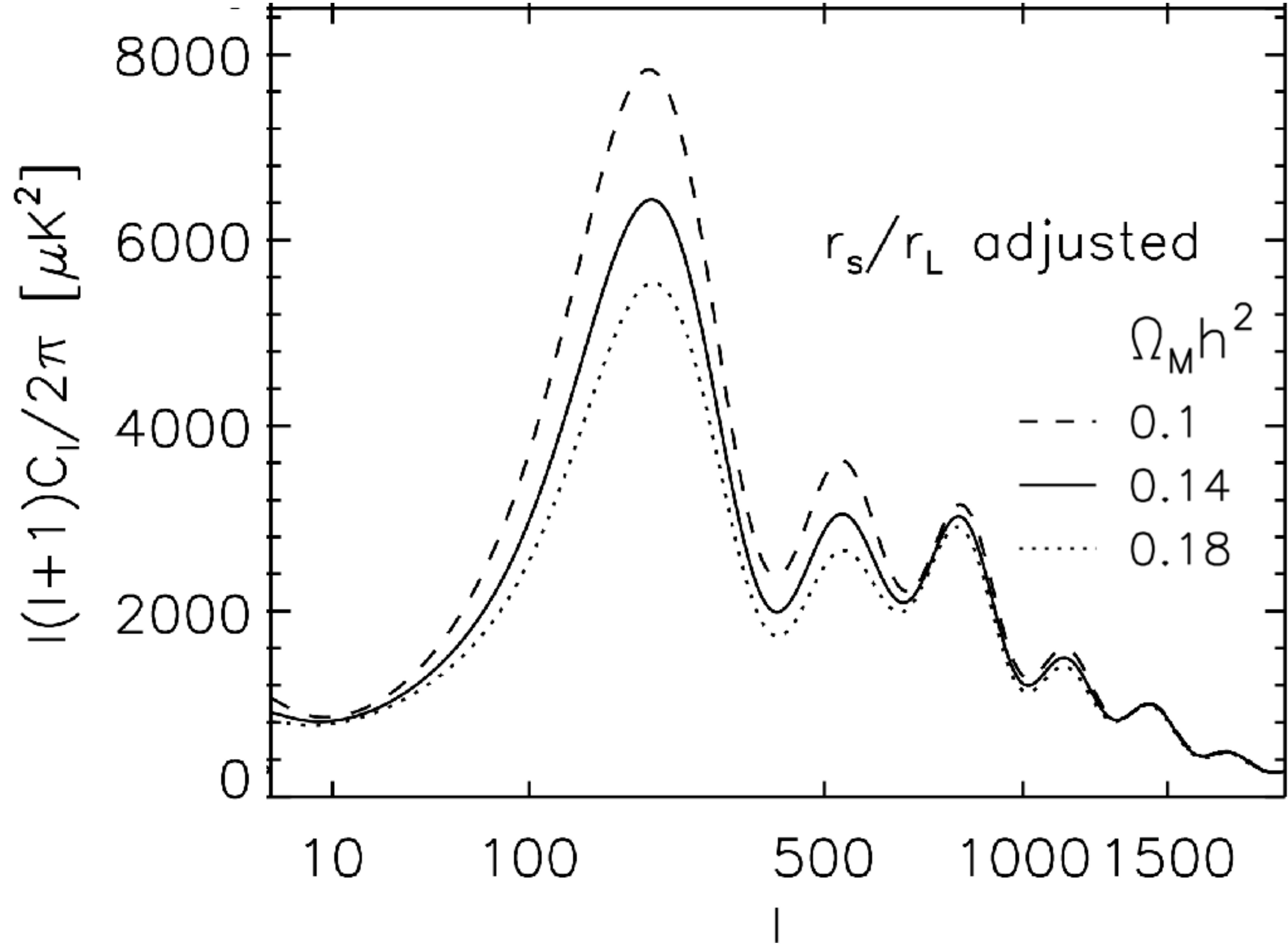
Zero-point shift effect compensated by (1+R)−1/4 and Silk damping
rs/rL adjusted
ΩBh2
0.03
0.022
0.014
l(l+1)Cl/2π [μK2]
8000
6000
4000
2000
0
10
100
500
1000
1500
l



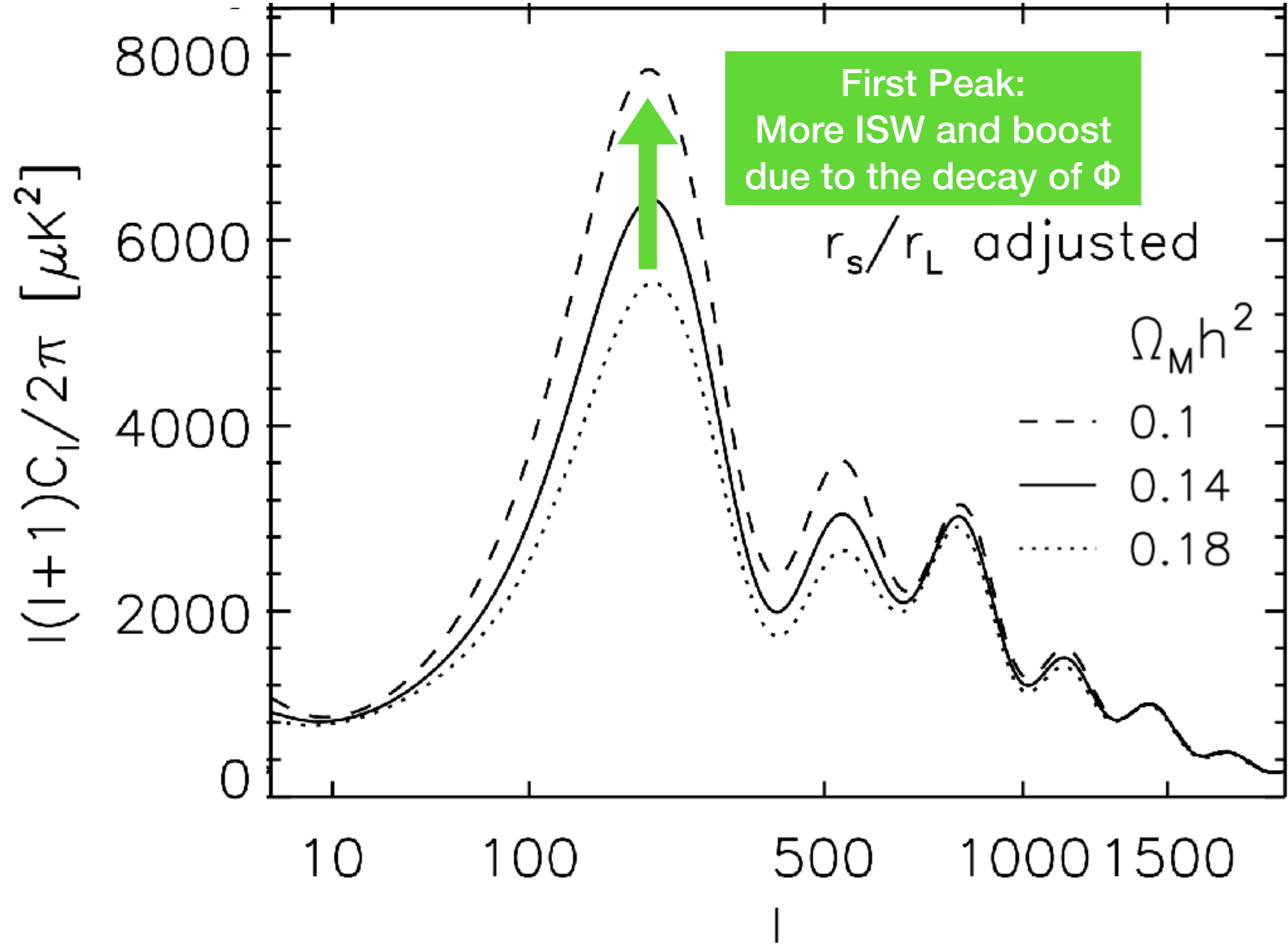
Less tight coupling:
Enhanced Silk damping
for low baryon density
r_s/r_L adjusted
Ω_B h^2
0.03
0.022
0.014
l(l+1)C_l/2π [μK^2]
8000
6000
4000
2000
0
10
100
500
1000
1500
l

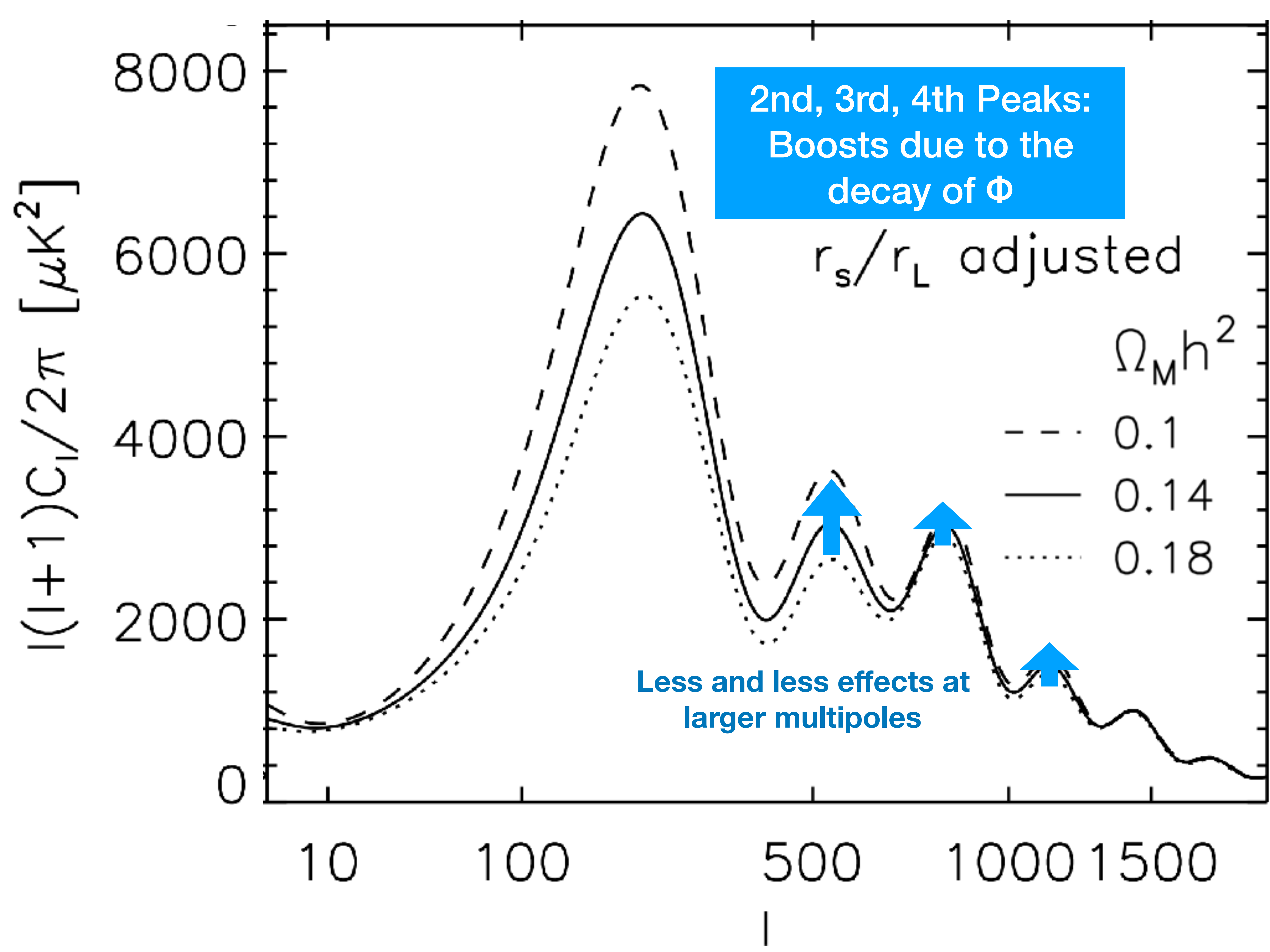


Total Matter Density
$\Omega_M h^2$
0.1
0.14
0.18
8000
6000
4000
2000
0
10
100
500
1000
1500
$l(l+1)C_l/2\pi$ [μK^2]
l



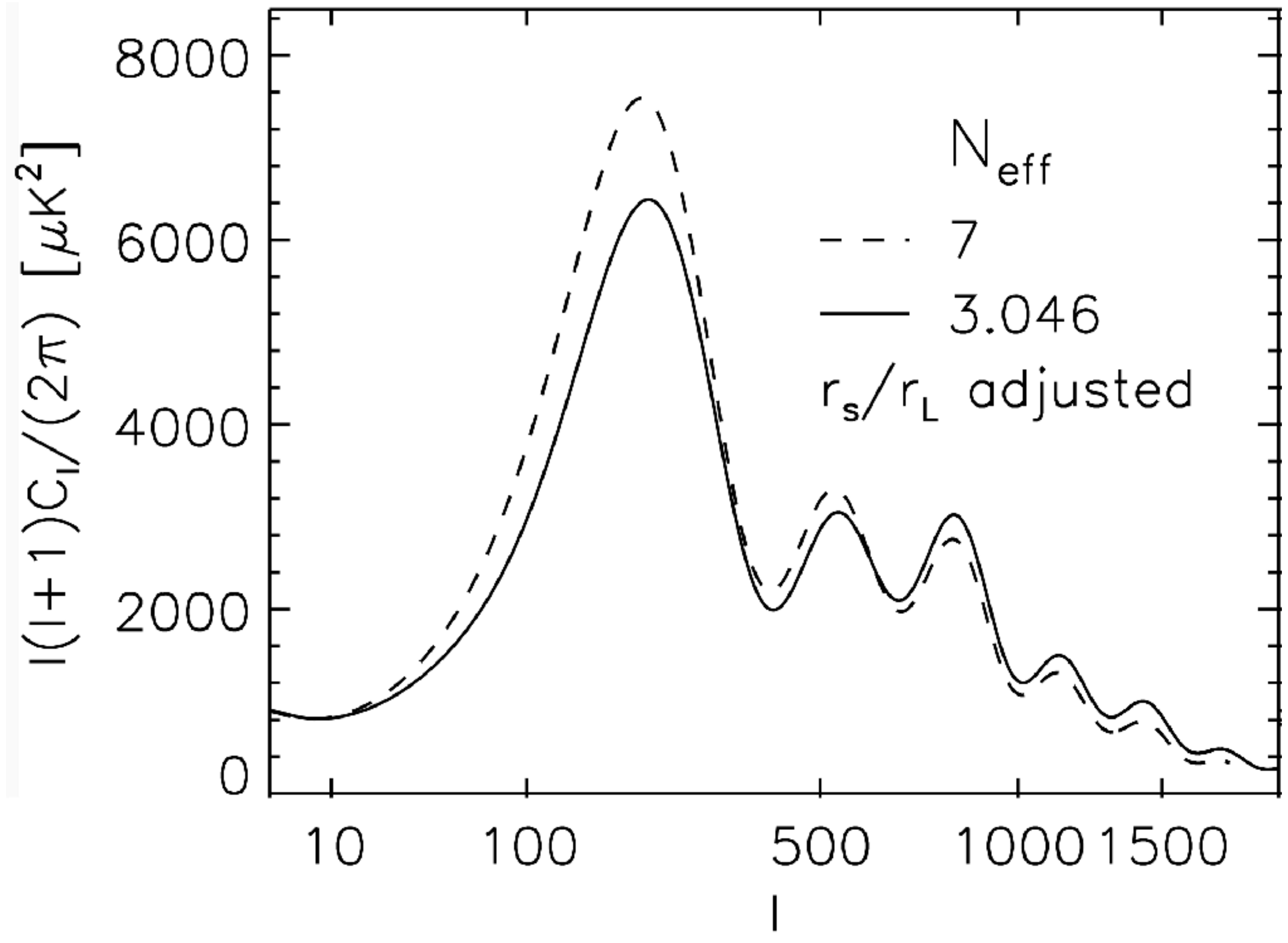
8000
6000
4000
2000
0
l(l+1)C_l/2π [μK²]
r_s/r_L adjusted
Ω_M h²
0.1
0.14
0.18
10
100
500
1000
1500
l


First Peak:
More ISW and boost
due to the decay of Φ
r_s/r_L adjusted
$\Omega_M h^2$
0.1
0.14
0.18
8000
6000
4000
2000
0
$l(l+1)C_l/2\pi$ [μK^2]
10
100
500
1000
1500
l

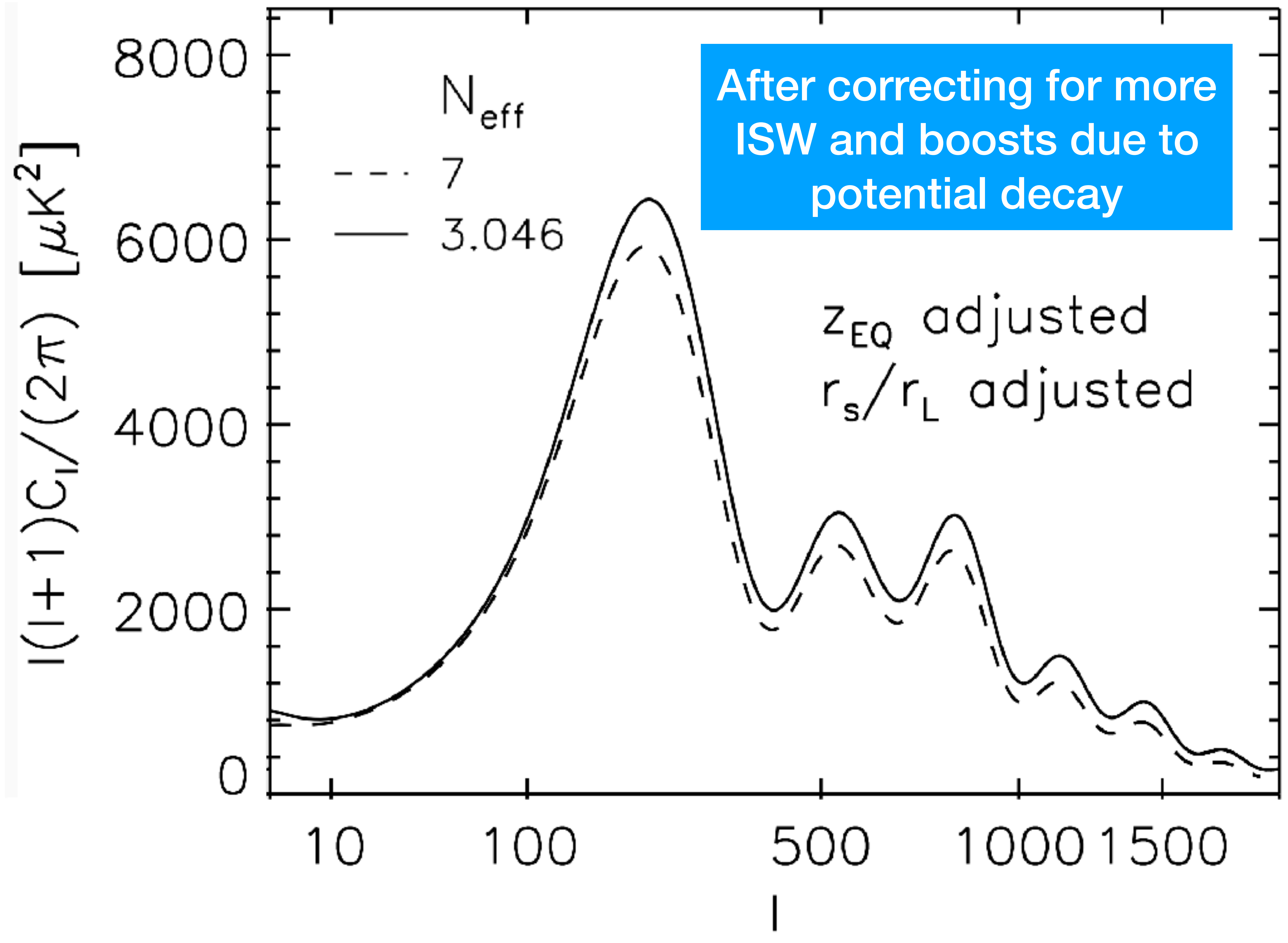

2nd, 3rd, 4th Peaks:
Boosts due to the
decay of Φ
r_s/r_L adjusted
Ω_M h^2
0.1
0.14
0.18
Less and less effects at
larger multipoles
l(l+1)C_l/2π [μK^2]
8000
6000
4000
2000
0
10
100
500
1000
1500
l

Effects of Relativistic Neutrinos

- To see the effects of relativistic neutrinos, we **artificially increase the number of neutrino species from 3 to 7**
  - Great energy density in neutrinos, i.e., greater energy density in radiation
  - **(1)** Longer radiation domination -> More ISW and boosts due to potential decay



8000
6000
4000
2000
0
l(l+1)C_l/(2π) [μK^2]
N_eff
7
3.046
r_s/r_L adjusted
10
100
500
1000
1500
l



After correcting for more ISW and boosts due to potential decay
N_eff
7
3.046
z_EQ adjusted
r_s/r_L adjusted
8000
6000
4000
2000
0
10
100
500
1000
1500
l
l(l+1)C_l/(2π) [μK^2]

(2): Viscosity Effect on the Amplitude of Sound Waves

The solution is

$$X = -C\cos(\varphi + \theta)$$

$$R_\nu \equiv \bar{\rho}_\nu/(\bar{\rho}_\gamma + \bar{\rho}_\nu) \approx 0.409$$

where

$$C \equiv \sqrt{(-\zeta + \Delta A_\nu)^2 + \Delta B_\nu^2}$$

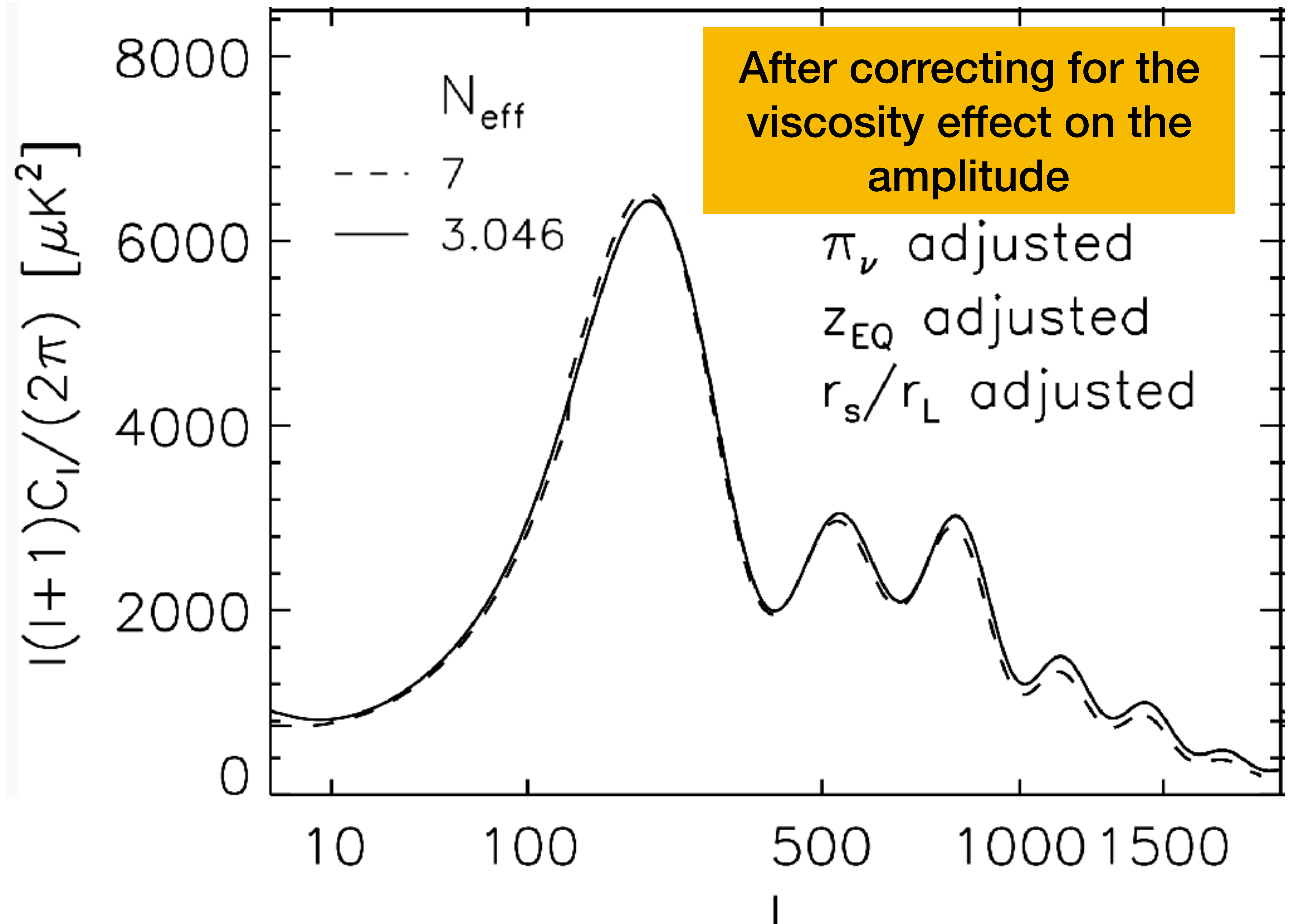
$$\approx \zeta(1 + 4R_\nu/15)^{-1}$$

Hu & Sugiyama (1996)

$$\tan\theta = -\frac{\Delta B_\nu}{-\zeta + \Delta A_\nu} \approx 0.063\pi$$

Phase shift!

Bashinsky & Seljak (2004)

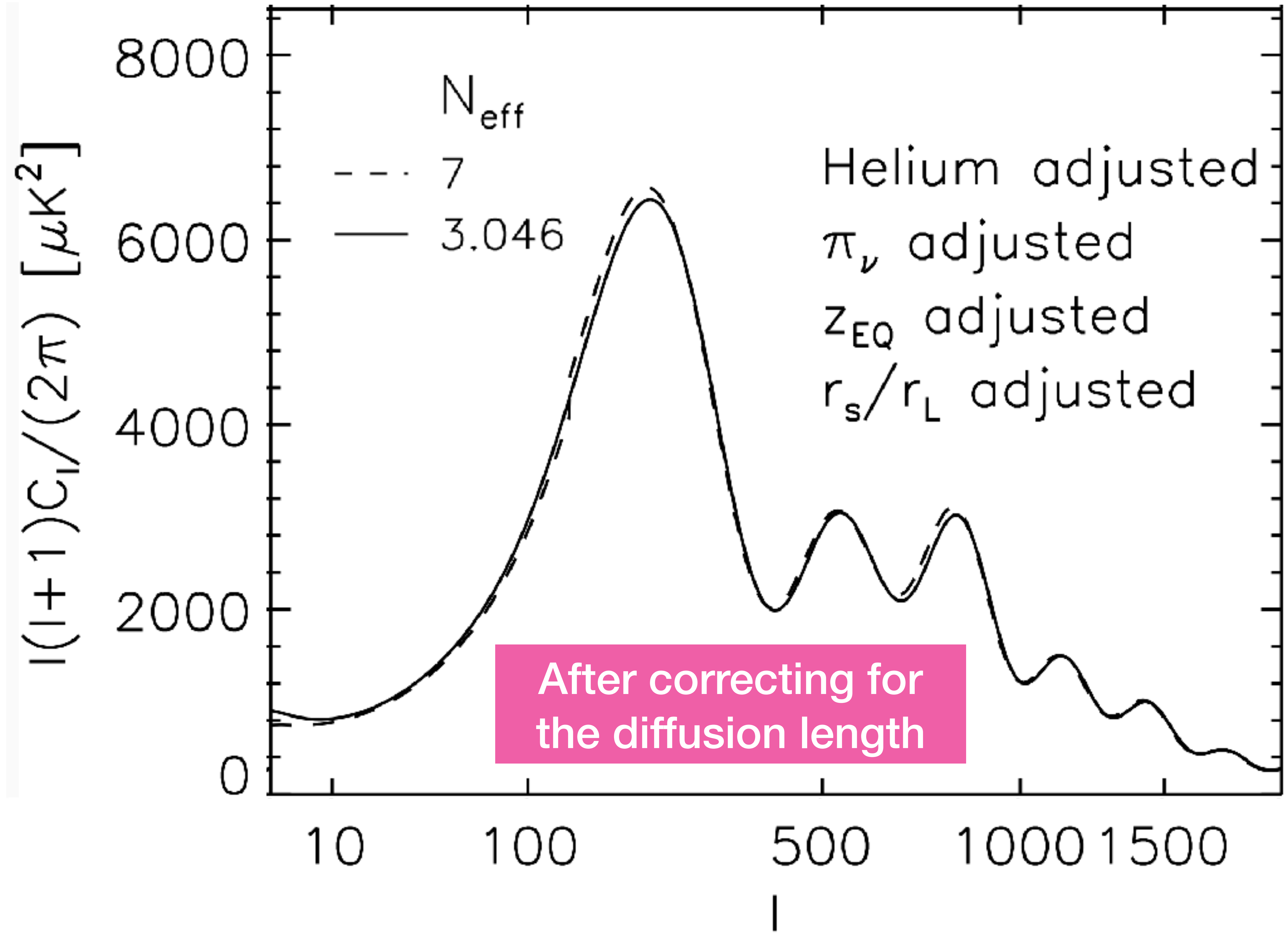


After correcting for the viscosity effect on the amplitude
N_{eff}
7
3.046
π_ν adjusted
z_{EQ} adjusted
r_s/r_L adjusted
$l(l+1)C_l/(2\pi)$ [μK^2]
8000
6000
4000
2000
0
10
100
500
1000
1500
l

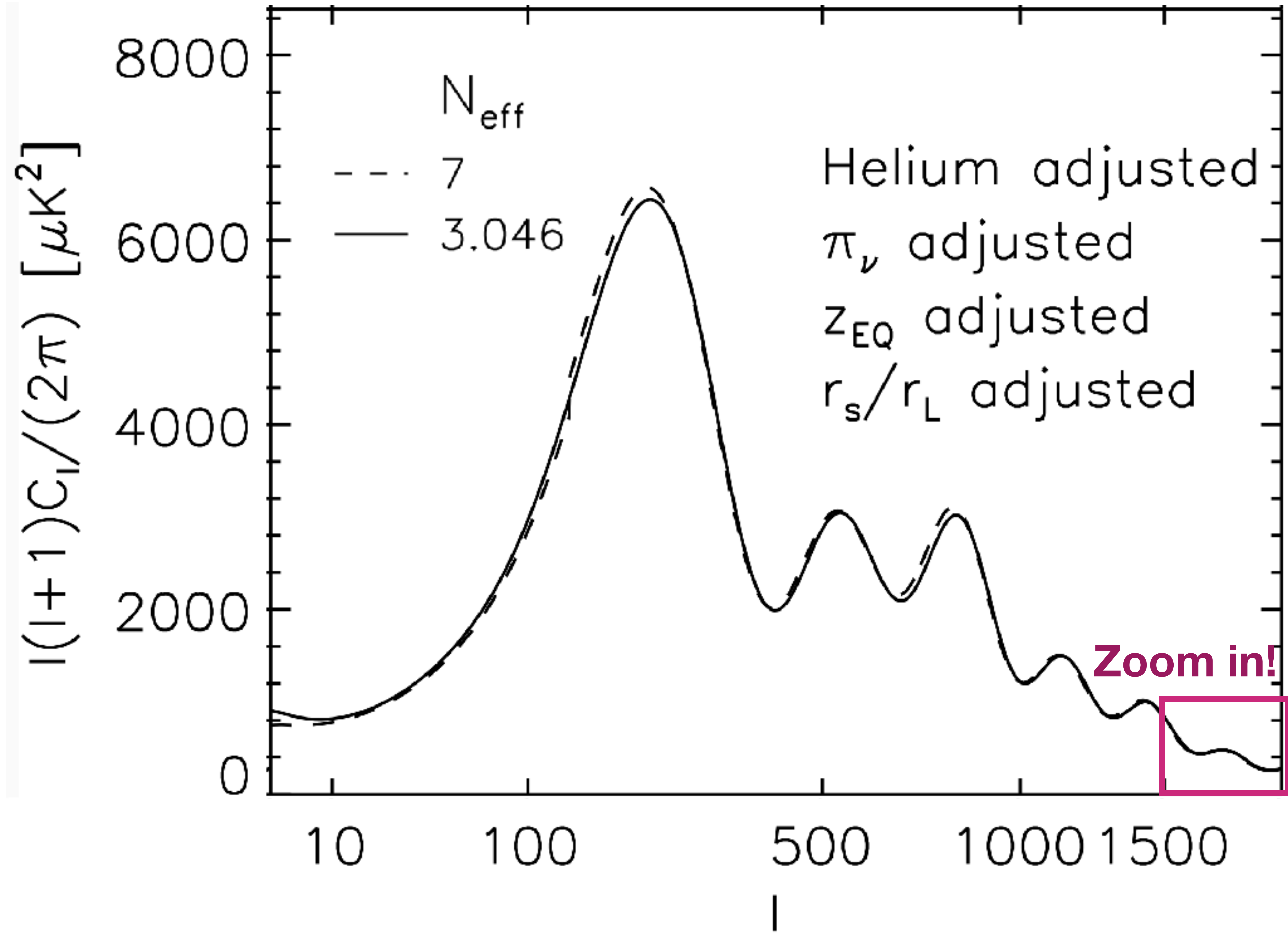
Bashinsky & Seljak (2004)

(3): Change in the Silk Damping

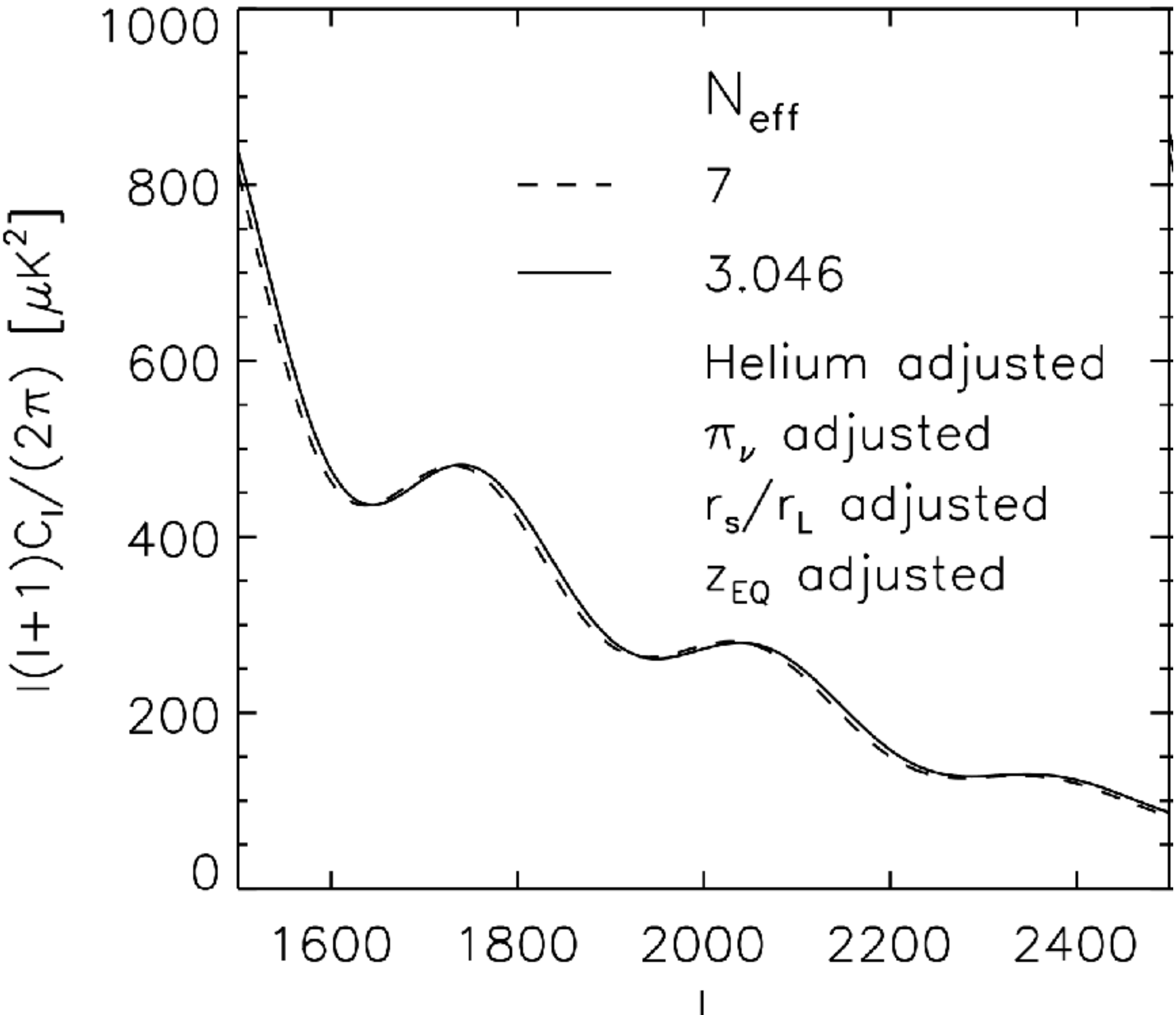
- Greater neutrino energy density implies greater Hubble expansion rate, $H^2=8\pi G\sum\rho_\alpha/3$
- This **reduces** the sound horizon in proportion to H^{-1}, as $r_s \sim c_s H^{-1}$
- This also reduces the diffusion length, but in proportional to $H^{-1/2}$, as $a/q_{silk} \sim (\sigma_T n_e H)^{-1/2}$ **Consequence of the random walk!**
- As a result, l_{silk} **decreases relative to the first peak position**, enhancing the Silk damping



N_{eff}
7
3.046
Helium adjusted
π_ν adjusted
z_{EQ} adjusted
r_s/r_L adjusted
After correcting for the diffusion length
$l(l+1)C_l/(2\pi)$ $[\mu K^2]$
8000
6000
4000
2000
0
10
100
500
1000
1500
l



8000
6000
4000
2000
0
$l(l+1)C_l/(2\pi)$ [μK^2]
N_{eff}
7
3.046
Helium adjusted
π_ν adjusted
z_{EQ} adjusted
r_s/r_L adjusted
Zoom in!
10
100
500
1000
1500
l



1000
800
600
400
200
0
1600
1800
2000
2200
2400
l
l(l+1)C_l/(2π) [μK^2]
N_eff
7
3.046
Helium adjusted
π_ν adjusted
r_s/r_L adjusted
z_EQ adjusted

(4): Viscosity Effect on the Phase of Sound Waves

The solution is

$$X = -C\cos(\varphi + \theta)$$

where

$$R_\nu \equiv \bar{\rho}_\nu/(\bar{\rho}_\gamma + \bar{\rho}_\nu) \approx 0.409$$

$$C \equiv \sqrt{(-\zeta + \Delta A_\nu)^2 + \Delta B_\nu^2}$$

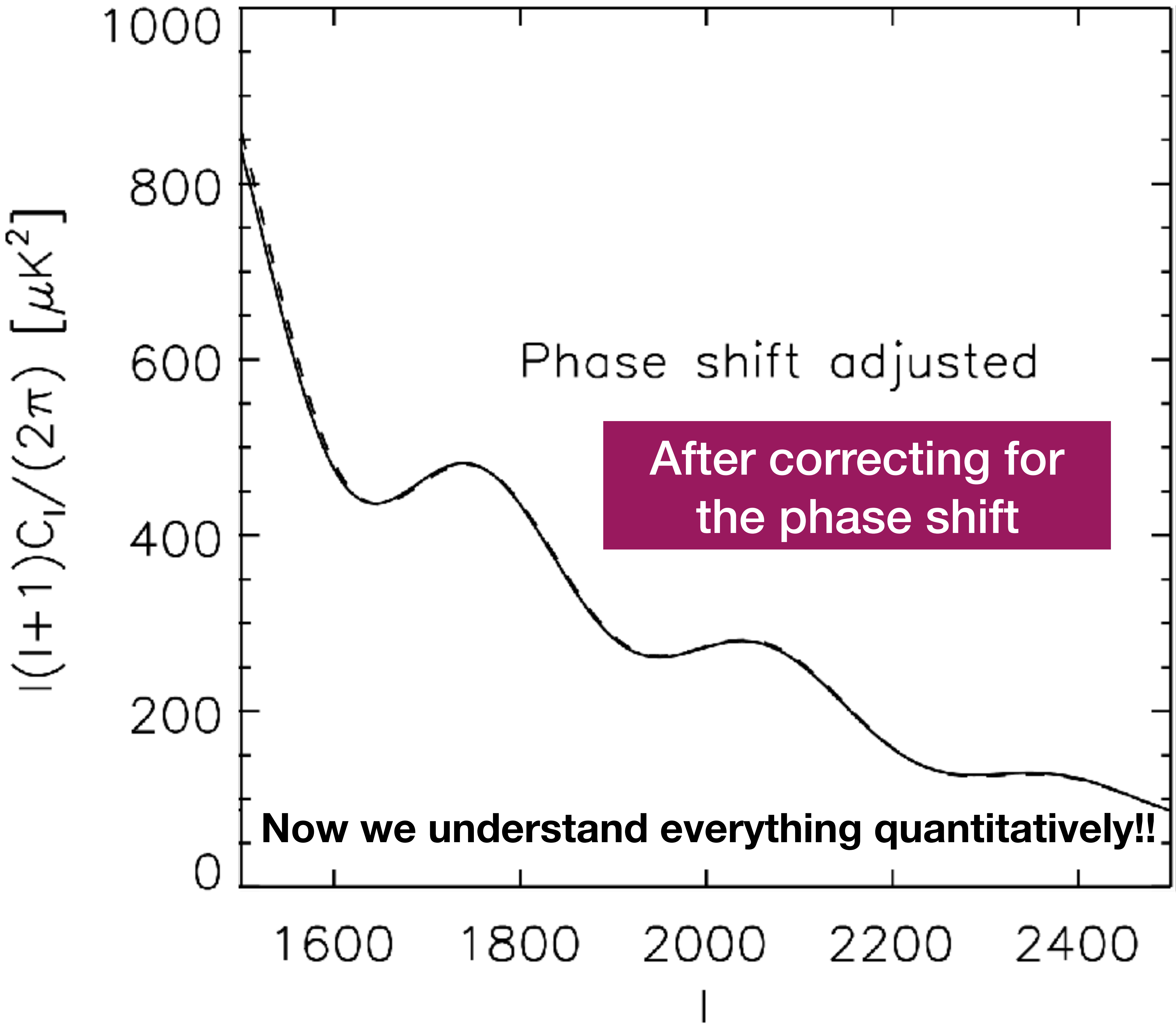
$$\approx \zeta(1 + 4R_\nu/15)^{-1}$$

Hu & Sugiyama (1996)

$$\tan\theta = -\frac{\Delta B_\nu}{-\zeta + \Delta A_\nu} \approx 0.063\pi$$

Phase shift!

Bashinsky & Seljak (2004)


Phase shift adjusted
After correcting for the phase shift
Now we understand everything quantitatively!!
l(l+1)C_l/(2π) [μK^2]
1000
800
600
400
200
0
1600
1800
2000
2200
2400
l

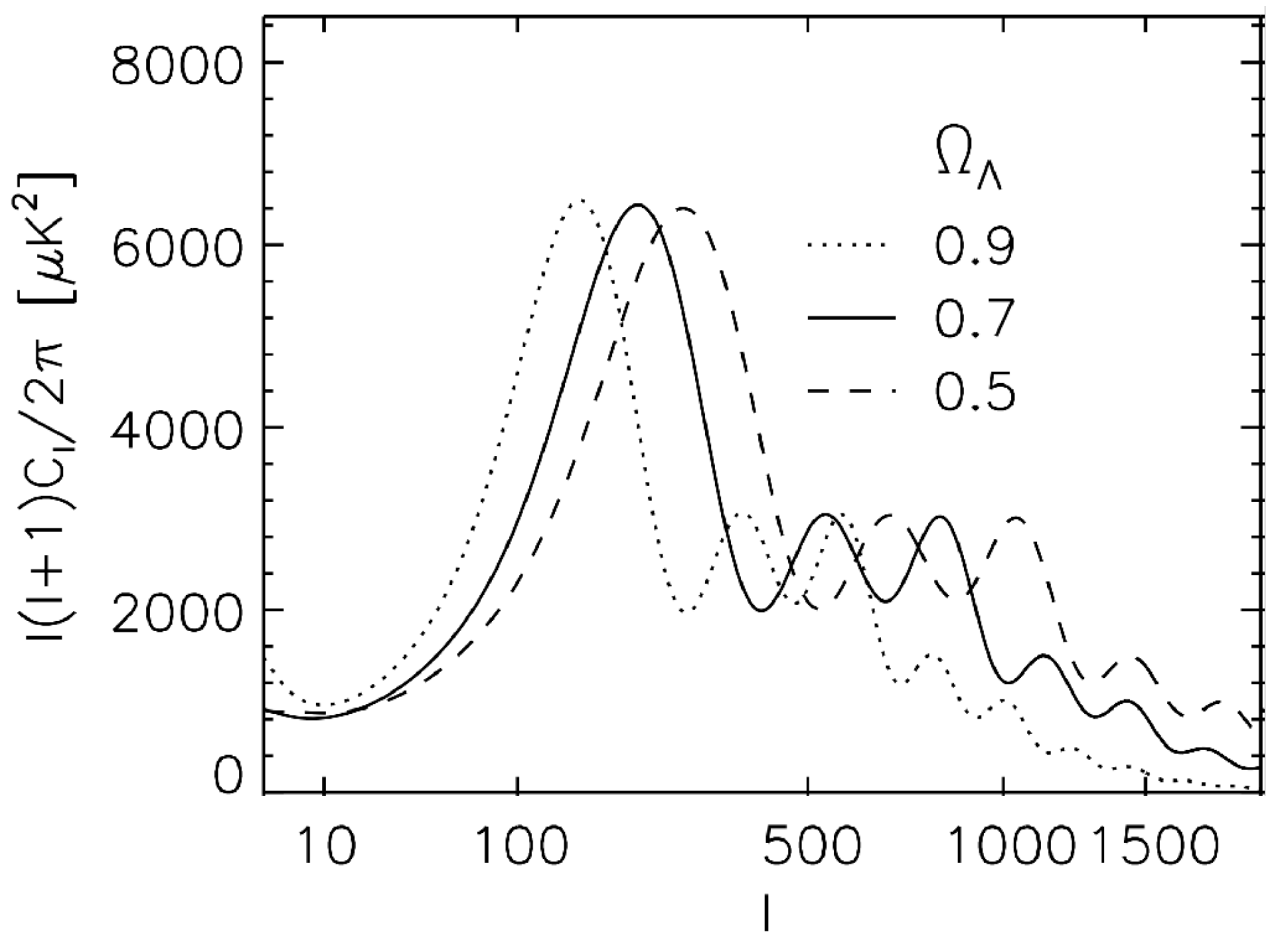
Two Other Effects

- **Spatial curvature**
  - We have been assuming spatially-flat Universe with zero curvature (i.e., Euclidean space). What if it is curved?
- **Optical depth to Thomson scattering in a low-redshift Universe**
  - We have been assuming that the Universe is transparent to photons since the last scattering at $z=1090$. What if there is an extra scattering in a low-redshift Universe?

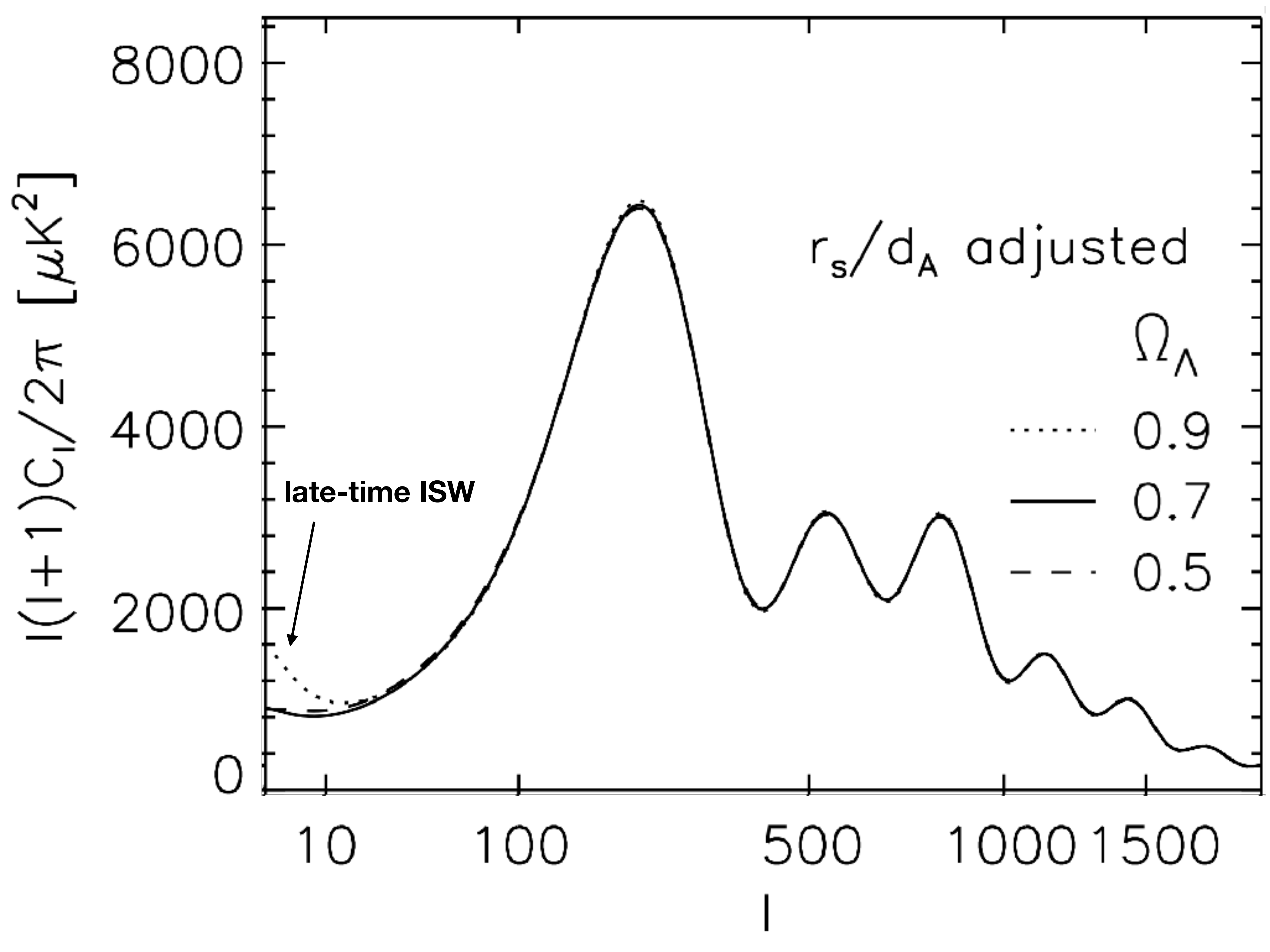
Spatial Curvature

- It changes the angular diameter distance, d_A, to the last scattering surface; namely,
  - $r_L \rightarrow d_A = R\,\mathit{sin}(r_L/R) = r_L(1 - r_L^2/6R^2) + \ldots$ for positively-curved space
  - $r_L \rightarrow d_A = R\,\mathit{sinh}(r_L/R) = r_L(1 + r_L^2/6R^2) + \ldots$ for negatively-curved space

Smaller angles (larger multipoles) for a negatively curved Universe



l(l+1)C$_l$/2π [μK^2]
8000
6000
4000
2000
0
10
100
500
1000
1500
l
Ω$_Λ$
0.9
0.7
0.5



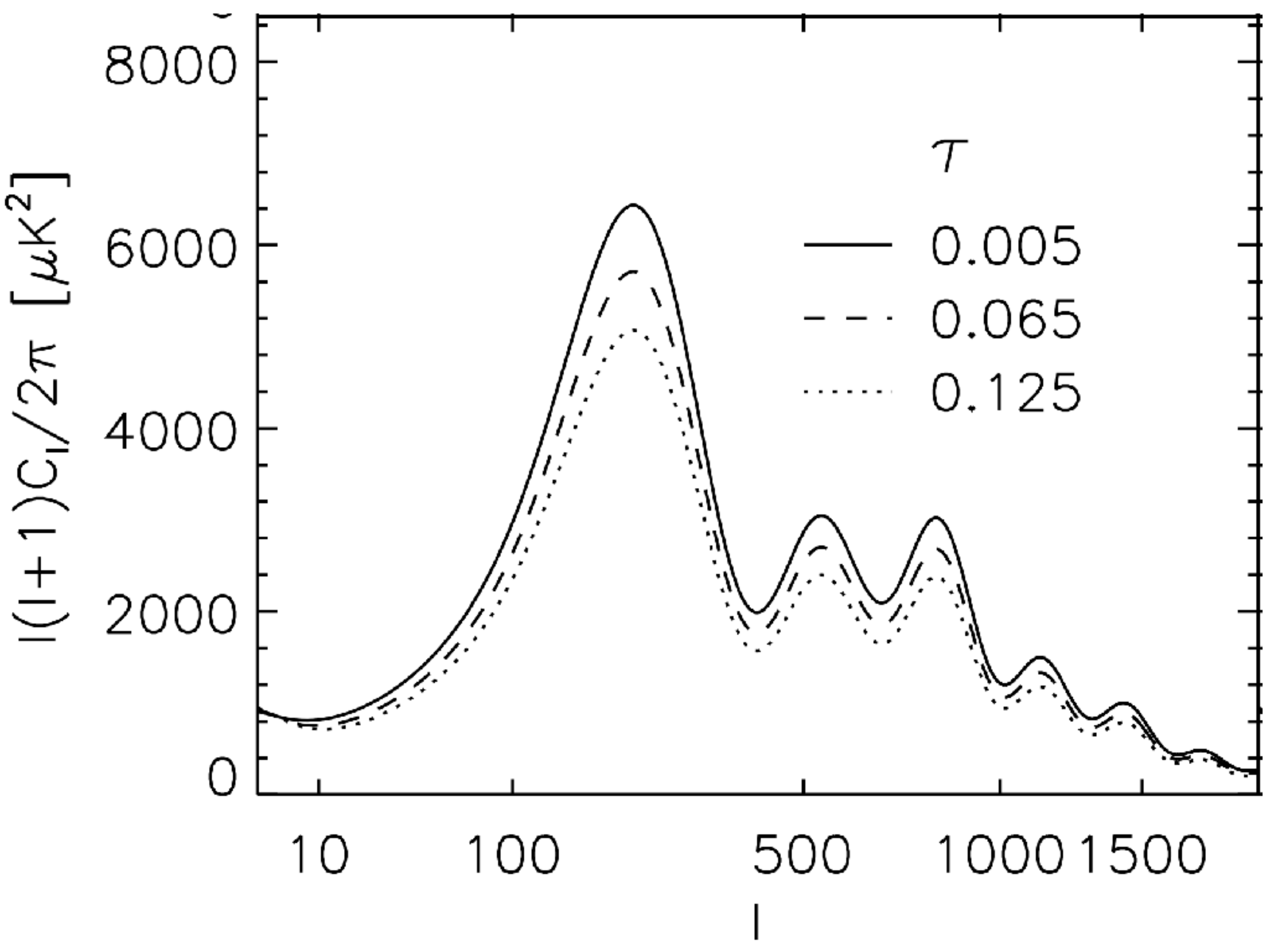
8000
6000
4000
2000
0
l(l+1)C_l/2π [μK^2]
10
100
500
1000
1500
l
r_s/d_A adjusted
Ω_Λ
0.9
0.7
0.5
late-time ISW

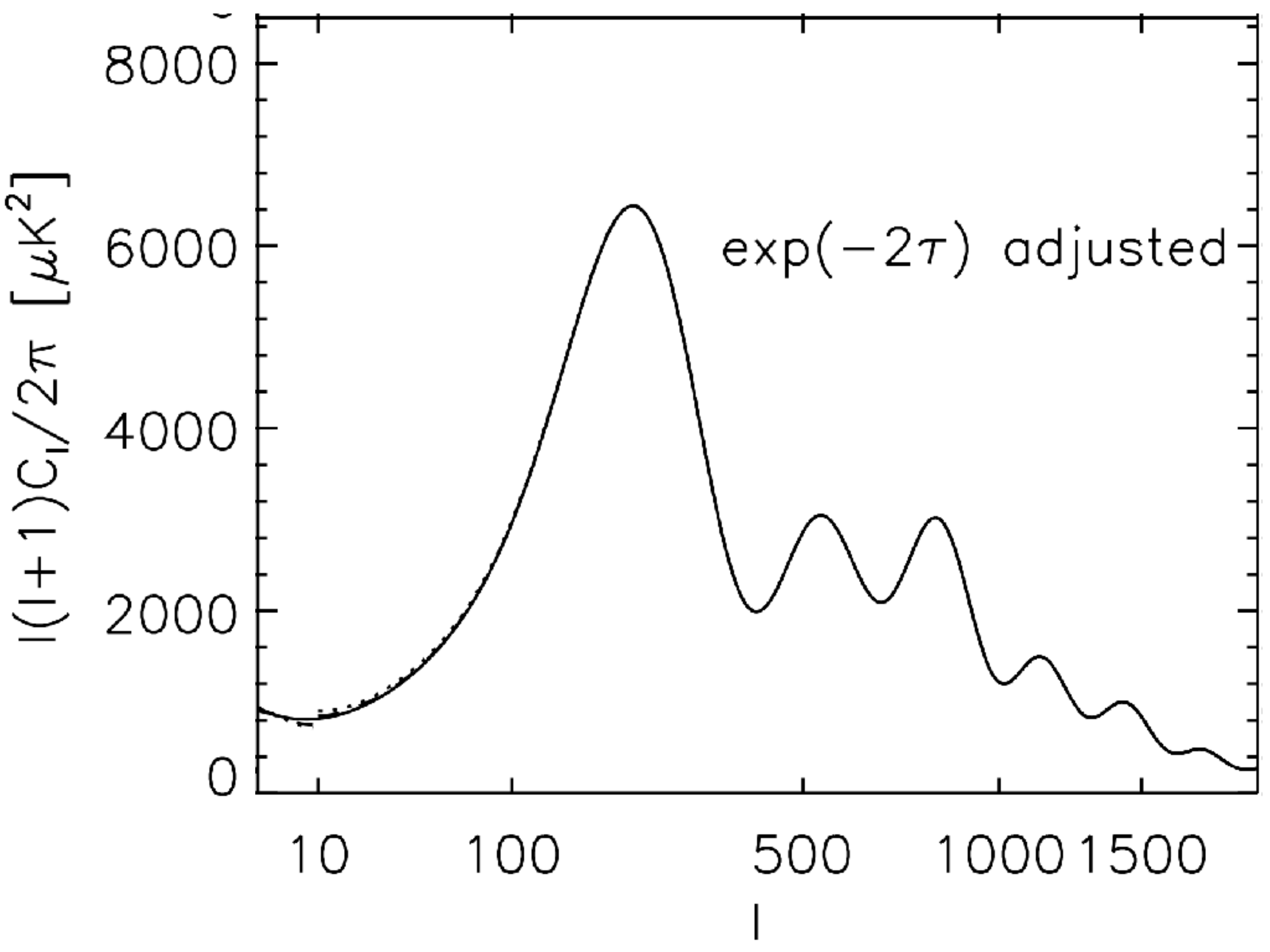
Optical Depth

- Extra scattering by electrons in a low-redshift Universe damps temperature anisotropy

- $C_l \to C_l \exp(-2\tau)$ at $l \gtrsim 10$
  - where τ is the optical depth

$$\tau = c\sigma_T \int_{t_{\text{re-ionisation}}}^{t_0} dt \; \bar{n}_e$$


8000
6000
4000
2000
0
l(l+1)C$_l$/2π [μK^2]
τ
0.005
0.065
0.125
10
100
500
1000
1500
l



8000
6000
4000
2000
0
l(l+1)C_l/2π [μK^2]
exp(−2τ) adjusted
10
100
500
1000
1500
l

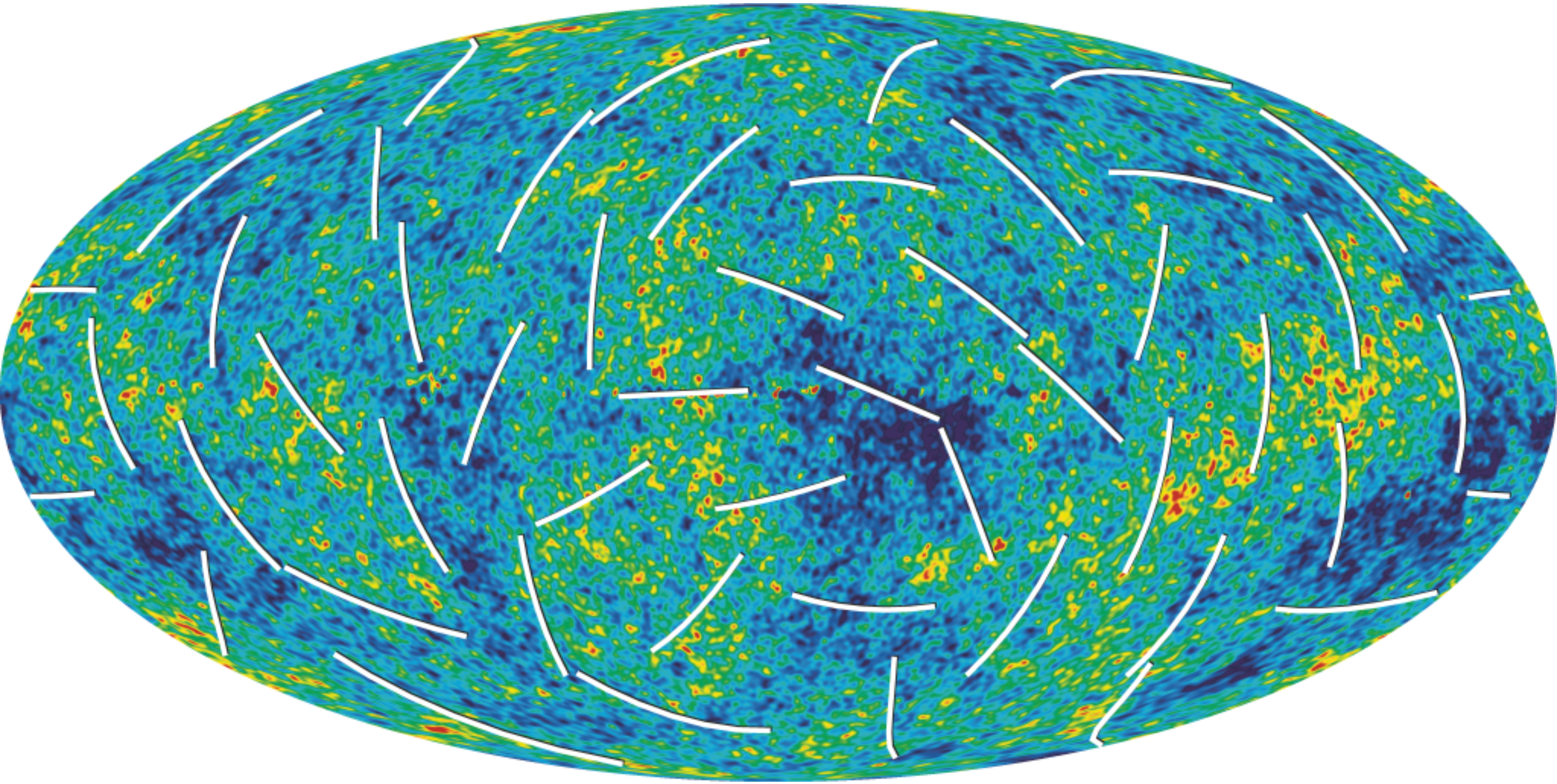
Important consequence of the optical depth

- Since the power spectrum is uniformly suppressed by $\exp(-2\tau)$ at $l>\sim 10$, we cannot determine the amplitude of the power spectrum of the gravitational potential, $P_\Phi(q)$, independently of τ.
  - Namely, what we constrain is the combination:
    $$\exp(-2\tau)P_\Phi(q) \propto \exp(-2\tau)A_s$$
- Breaking this degeneracy requires an independent determination of the optical depth. This requires **POLARISATION** of the CMB.

Cosmological Parameters Derived from the Power Spectrum

	WMAP	Planck	+CMB Lensing
$100\Omega_B h^2$	2.264 ± 0.050	2.222 ± 0.023	2.226 ± 0.023
$\Omega_D h^2$	0.1138 ± 0.0045	0.1197 ± 0.0022	0.1186 ± 0.0020
Ω_Λ	0.721 ± 0.025	0.685 ± 0.013	0.692 ± 0.012
n	0.972 ± 0.013	0.9655 ± 0.0062	0.9677 ± 0.0060
$10^9 A_s$	2.203 ± 0.067	$2.198^{+0.076}_{-0.085}$	2.139 ± 0.063
τ	0.089 ± 0.014	0.078 ± 0.019	0.066 ± 0.016
t_0 [100 Myr]	137.4 ± 1.1	138.13 ± 0.38	137.99 ± 0.38
H_0	70.0 ± 2.2	67.31 ± 0.96	67.81 ± 0.92
$\Omega_M h^2$	0.1364 ± 0.0044	0.1426 ± 0.0020	0.1415 ± 0.0019
$10^9 A_s e^{-2\tau}$	1.844 ± 0.031	1.880 ± 0.014	1.874 ± 0.013
σ_8	0.821 ± 0.023	0.829 ± 0.014	0.8149 ± 0.0093

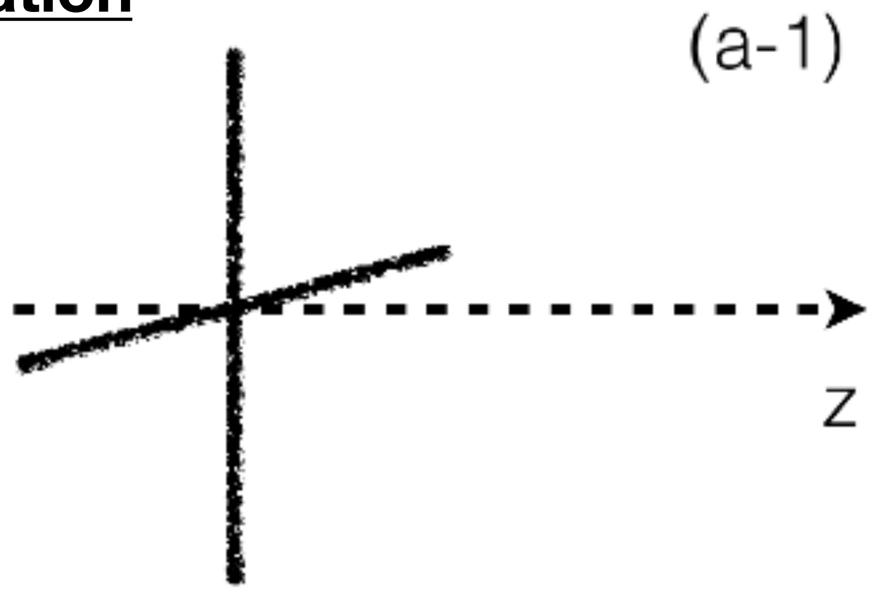
CMB Polarisation

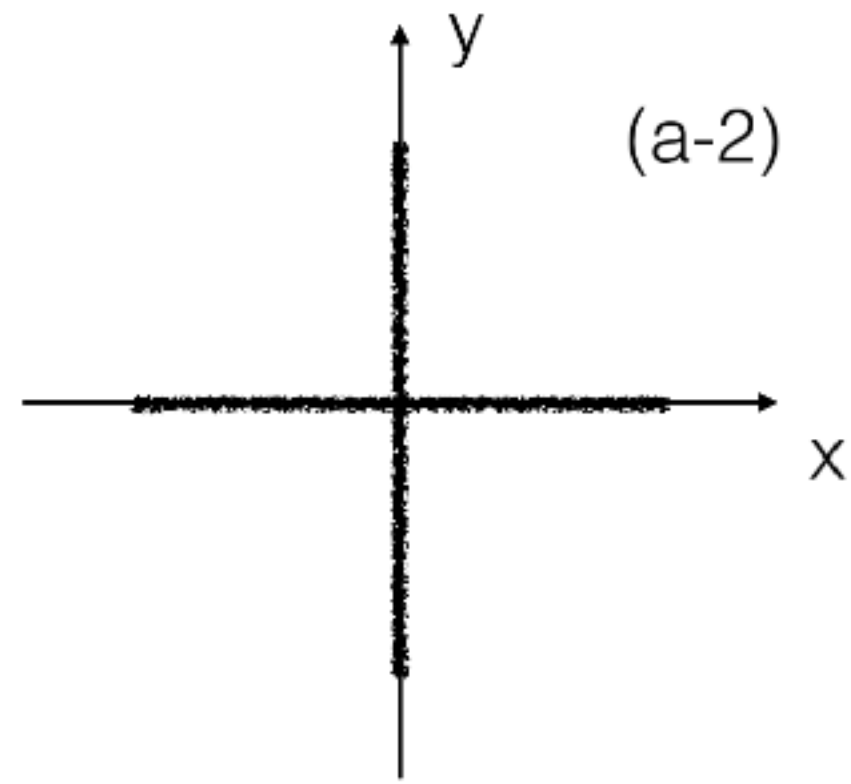


- CMB is weakly polarised!

Polarisation

No polarisation





(b-1)

Polarised in x-direction

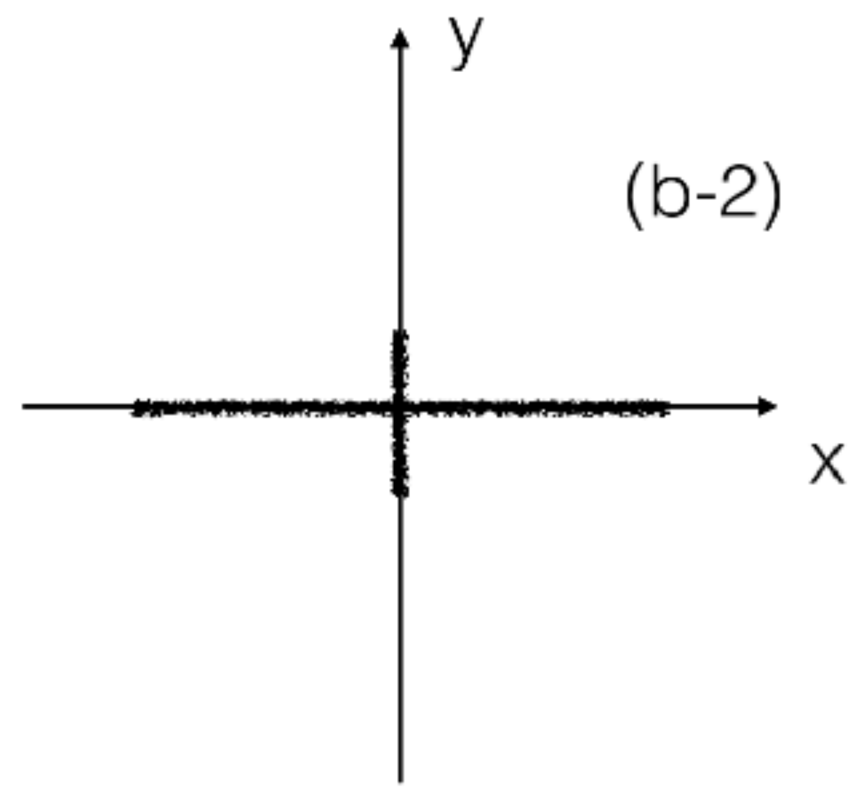



Photo Credit: TALEX


Photo Credit: TALEX
horizontally polarised

Photo Credit: TALEX

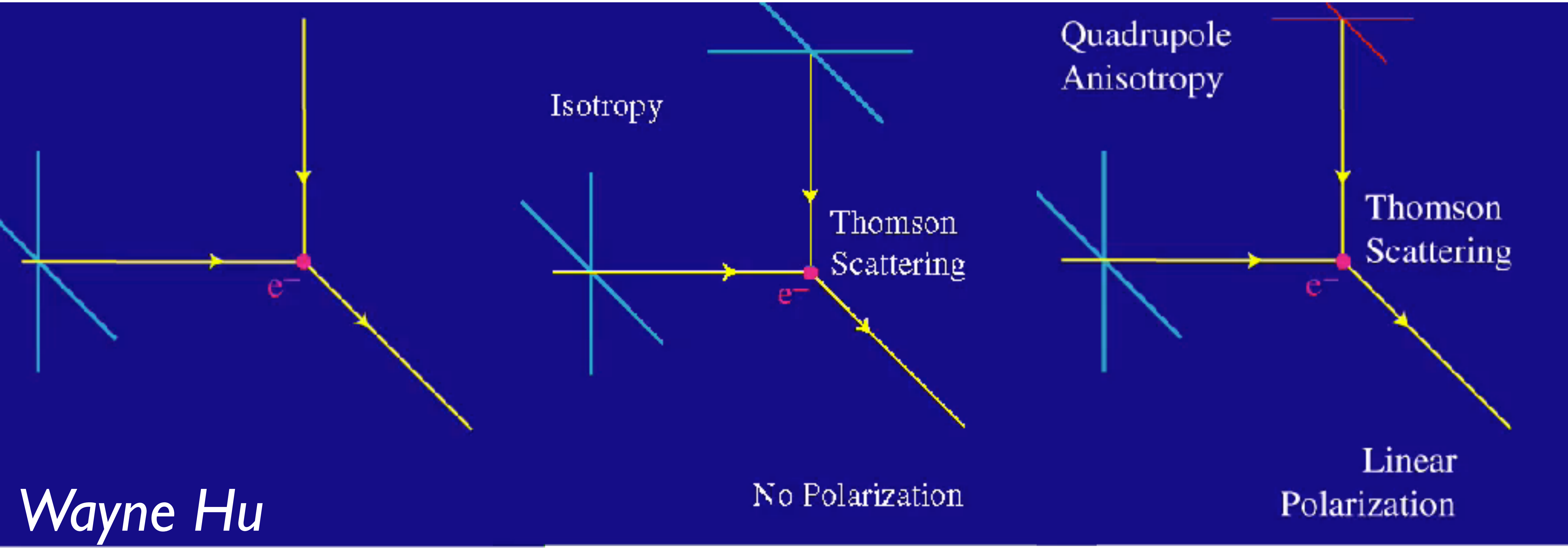
Necessary and sufficient conditions for generating polarisation

- You need to have two things to produce linear polarisation

  1. Scattering
  2. Anisotropic incident light

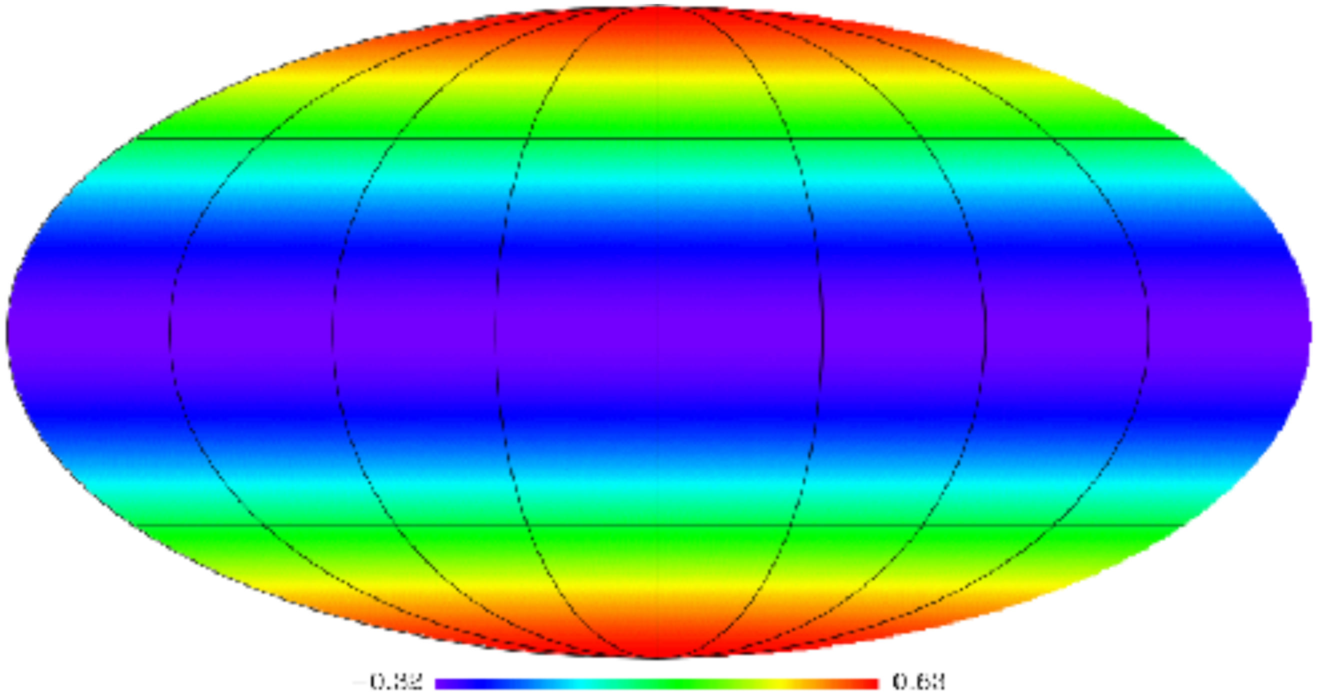
- However, the Universe does not have a preferred direction. How do we generate anisotropic incident light?

Need for a local quadrupole temperature anisotropy

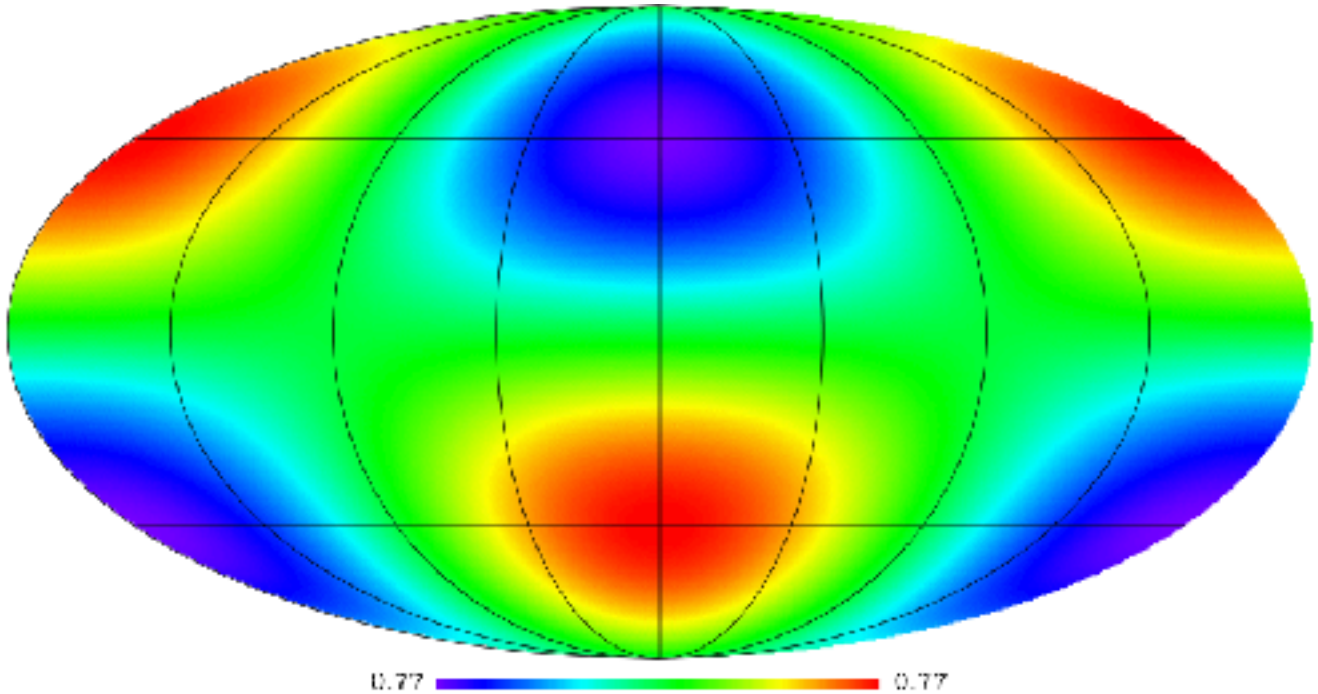


- How do we create a local temperature quadrupole?

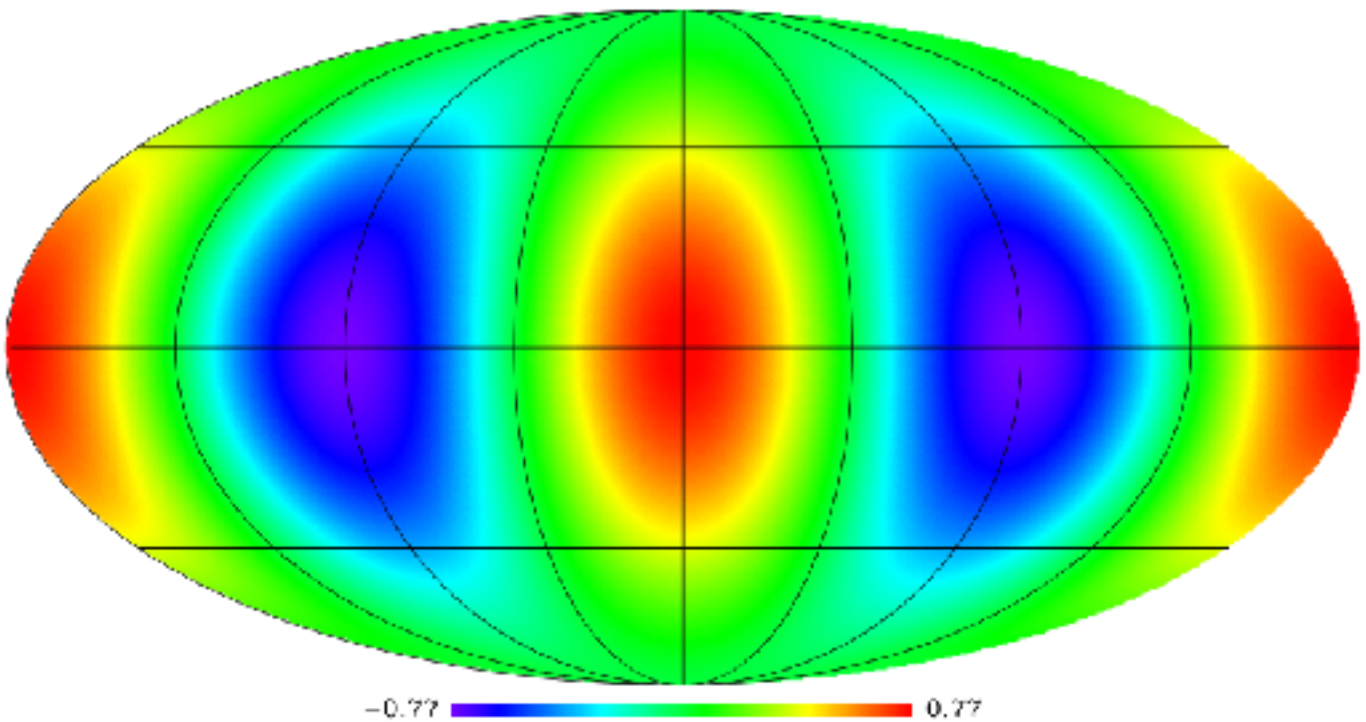
(l,m)=(2,0)



(l,m)=(2,1)



(l,m)=(2,2)



Quadrupole temperature anisotropy seen from an electron

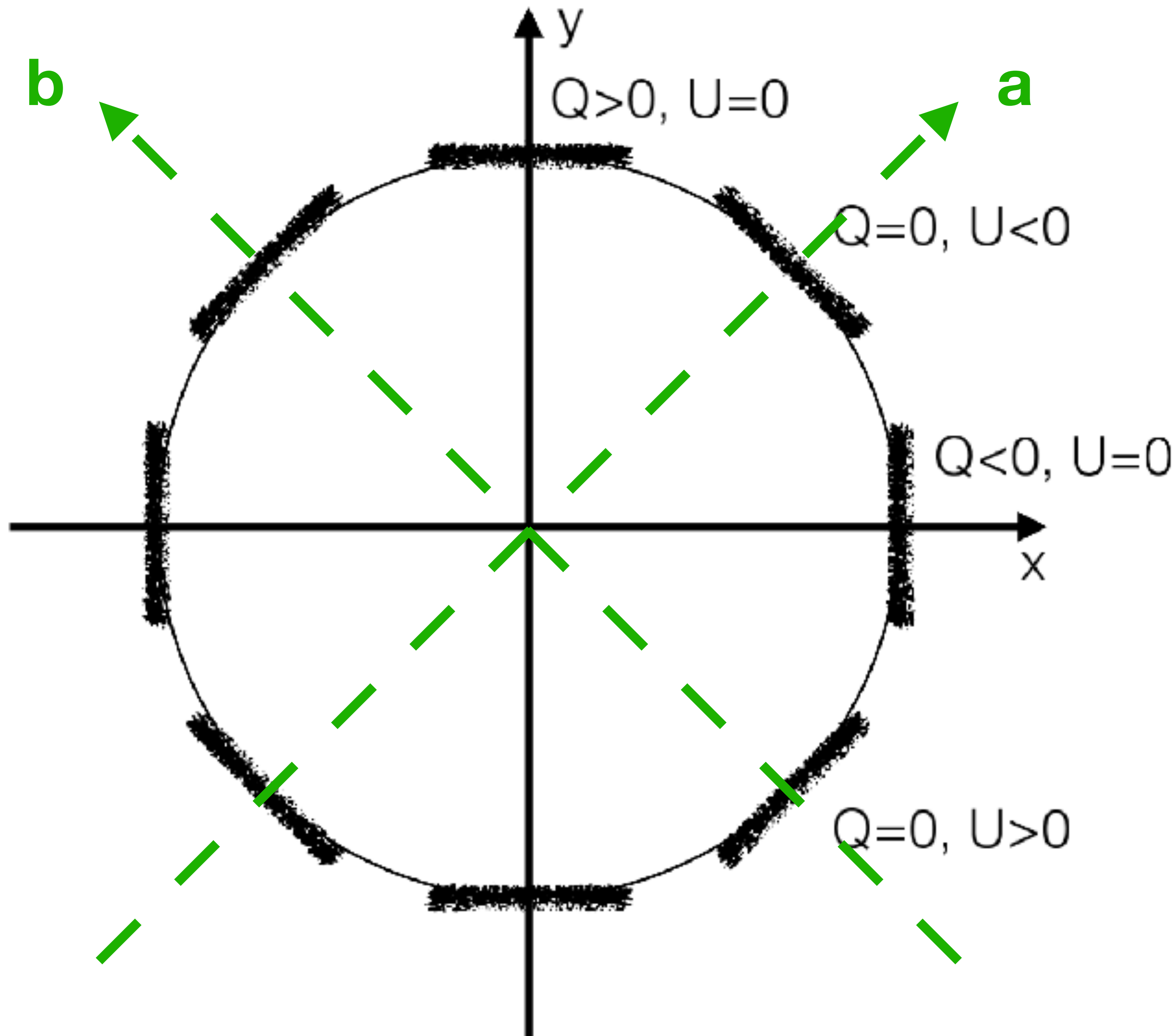
Quadrupole Generation: A Punch Line

- When Thomson scattering is efficient (i.e., tight coupling between photons and baryons via electrons), the distribution of photons from the rest frame of baryons is isotropic
- **Only when tight coupling relaxes**, a local quadrupole temperature anisotropy in the rest frame of a photon-baryon fluid can be generated
- In fact, "a local *temperature anisotropy in the rest frame of a photon-baryon fluid*" is equal to **viscosity**

Stokes Parameters
[Flat Sky, Cartesian coordinates]

$$Q \propto E_x^2 - E_y^2$$

$$U \propto E_a^2 - E_b^2$$

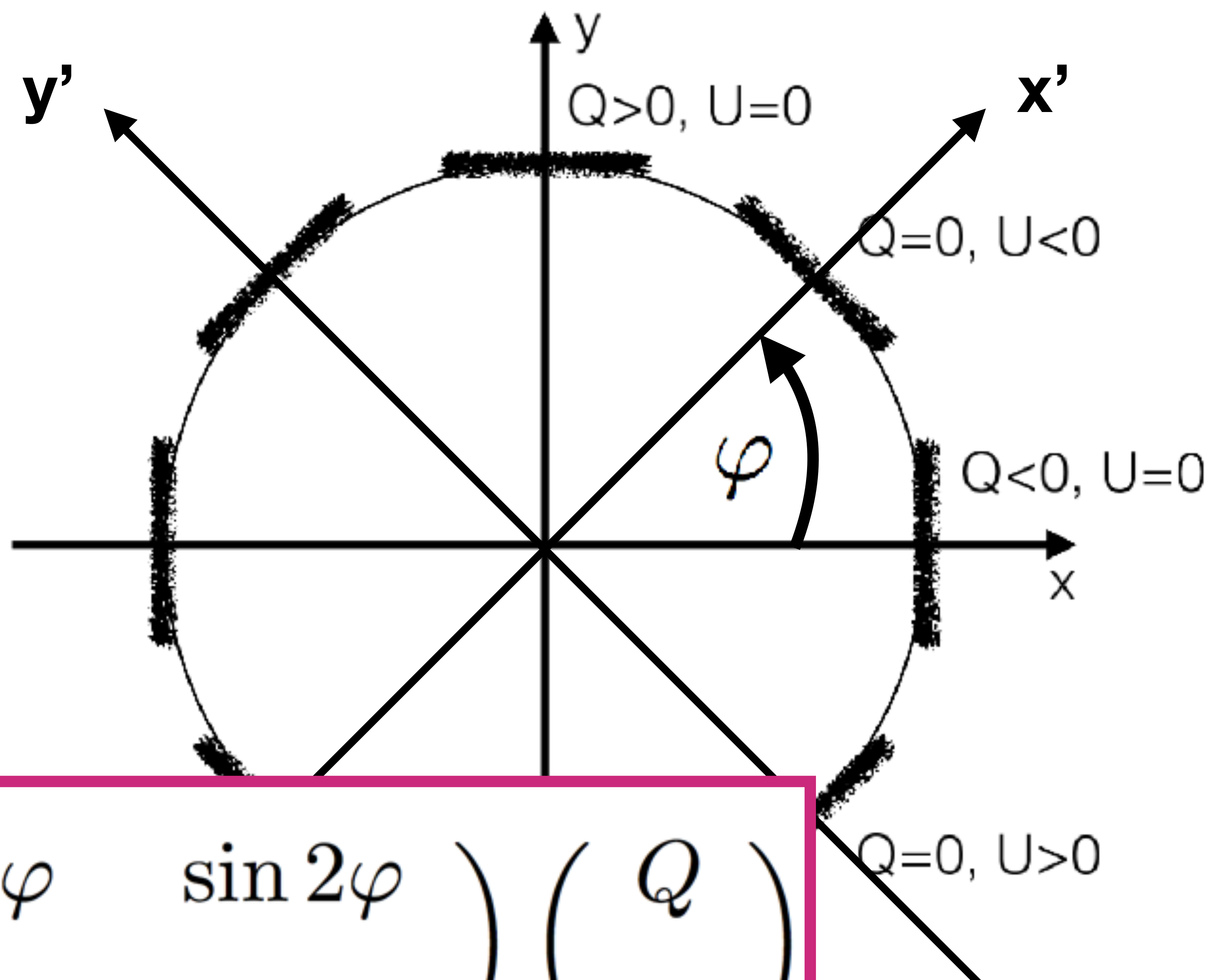


Stokes Parameters change under coordinate rotation

Under (x,y) -> (x',y'):

$$Q \longrightarrow \tilde{Q}$$

$$U \longrightarrow \tilde{U}$$



$$\begin{pmatrix} \tilde{Q} \\ \tilde{U} \end{pmatrix} = \begin{pmatrix} \cos 2\varphi & \sin 2\varphi \\ -\sin 2\varphi & \cos 2\varphi \end{pmatrix} \begin{pmatrix} Q \\ U \end{pmatrix}$$

Compact Expression

- Using an imaginary number, write $Q + iU$

Then, under coordinate rotation we have

$$\tilde{Q} + i\tilde{U} = \exp(-2i\varphi)(Q + iU)$$

$$\tilde{Q} - i\tilde{U} = \exp(2i\varphi)(Q - iU)$$

Alternative Expression

- With the polarisation amplitude, P, and angle, α , defined by

$$P \equiv \sqrt{Q^2 + U^2}, \;\; U/Q \equiv \tan 2\alpha$$

We write

$$Q + iU \; = \; P \exp(2i\alpha)$$

Then, under coordinate rotation we have

$$\tilde{\alpha} = \alpha - \varphi$$

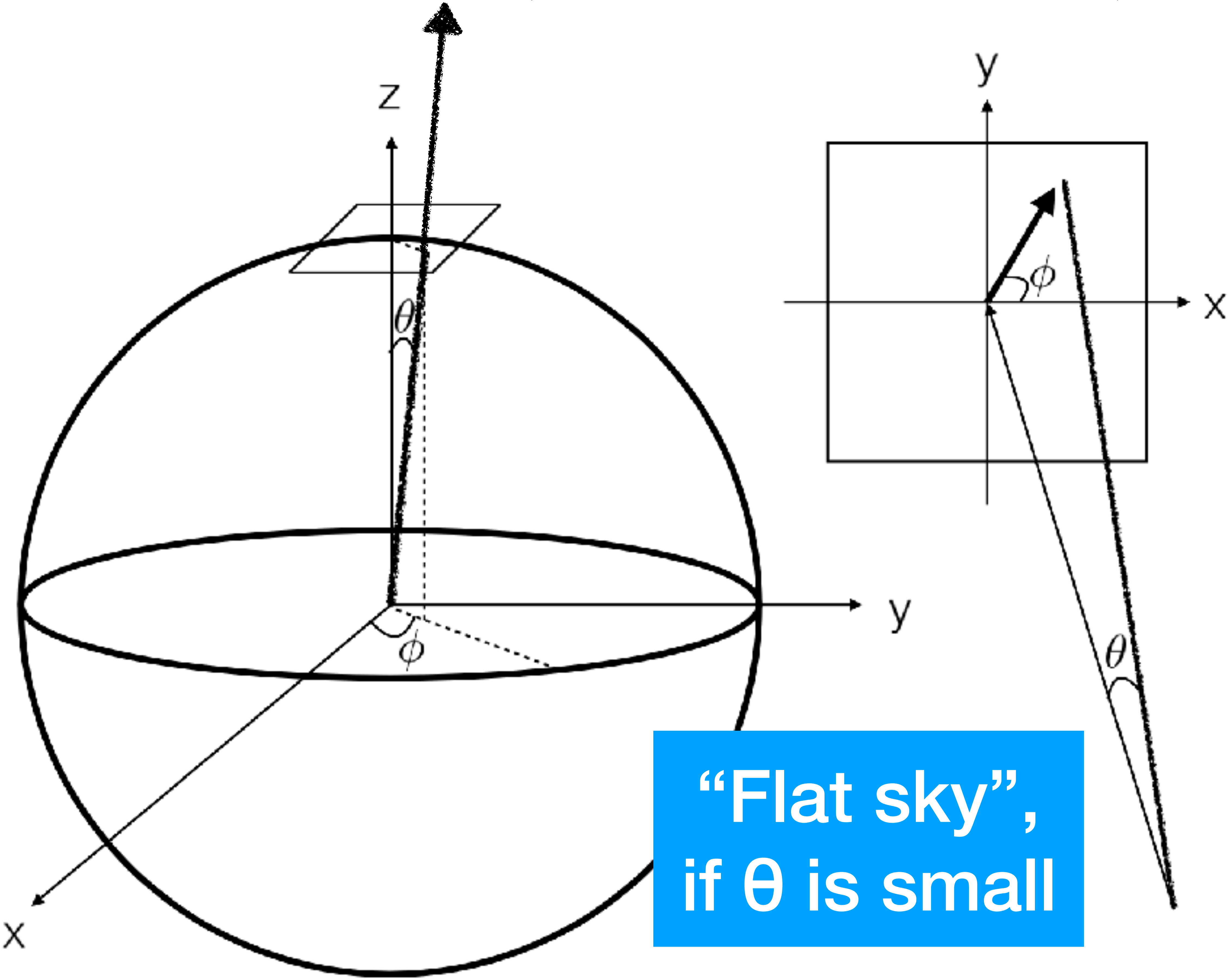
and P is invariant under rotation

E and B decomposition

- That Q and U depend on coordinates is not very convenient…
  - Someone said, "I measured Q!" but then someone else may say, "No, it's U!". They flight to death, only to realise that their coordinates are 45 degrees rotated from one another…
- The best way to avoid this unfortunate fight is to define a coordinate-independent quantity for the distribution of polarisation **patterns** in the sky

To achieve this, we need to go to Fourier space

$$\hat{n} = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$$



Fourier-transforming Stokes Parameters?

$$Q(\boldsymbol{\theta}) + iU(\boldsymbol{\theta}) = \int \frac{d^2\ell}{(2\pi)^2}\ a_{\boldsymbol{\ell}} \exp(i\boldsymbol{\ell}\cdot\boldsymbol{\theta})$$

where

$$\boldsymbol{\ell} = (\ell\cos\phi_\ell, \ell\sin\phi_\ell)$$

- As Q+iU changes under rotation, the Fourier coefficients $a_{\boldsymbol{\ell}}$ change as well
- So…

(*) Nevermind the overall minus sign. This is just for convention

Tweaking Fourier Transform

$$Q(\boldsymbol{\theta}) + iU(\boldsymbol{\theta}) = \int \frac{d^2\ell}{(2\pi)^2}\, a_{\boldsymbol{\ell}} \exp(i\boldsymbol{\ell}\cdot\boldsymbol{\theta})$$

where we write the coefficients as(*)

$$a_{\boldsymbol{\ell}} = -{}_2a_{\boldsymbol{\ell}} \exp(2i\phi_\ell)$$

- Under rotation, the azimuthal angle of a Fourier wavevector, ϕ_l, changes as $\phi_\ell \to \tilde{\phi}_\ell = \phi_\ell - \varphi$
- This cancels the factor in the left hand side: $\tilde{Q} + i\tilde{U} = \exp(-2i\varphi)(Q + iU)$

Seljak (1997); Zaldarriaga & Seljak (1997); Kamionkowski, Kosowky, Stebbins (1997)

Tweaking Fourier Transform

- We thus write

$$Q(\boldsymbol{\theta}) \pm iU(\boldsymbol{\theta}) = -\int \frac{d^2\ell}{(2\pi)^2}\, {}_{\pm 2}a_{\boldsymbol{\ell}} \exp(\pm 2i\phi_\ell + i\boldsymbol{\ell}\cdot\boldsymbol{\theta})$$

- And, defining ${}_{\pm 2}a_{\boldsymbol{\ell}} \equiv -(E_{\boldsymbol{\ell}} \pm iB_{\boldsymbol{\ell}})$

$$Q(\boldsymbol{\theta}) \pm iU(\boldsymbol{\theta}) = \int \frac{d^2\ell}{(2\pi)^2}\, (E_{\boldsymbol{\ell}} \pm iB_{\boldsymbol{\ell}}) \exp(\pm 2i\phi_\ell + i\boldsymbol{\ell}\cdot\boldsymbol{\theta})$$

By construction E_l and B_l do not pick up a factor of exp(2iϕ) under coordinate rotation. **That's great!** What kind of polarisation patterns do these quantities represent?

Pure E, B Modes

- Q and U produced by E and B modes are given by

$$Q(\boldsymbol{\theta}) = \int \frac{d^2\ell}{(2\pi)^2}(E_{\boldsymbol{\ell}}\cos 2\phi_\ell - B_{\boldsymbol{\ell}}\sin 2\phi_\ell)\exp(i\boldsymbol{\ell}\cdot\boldsymbol{\theta})$$

$$U(\boldsymbol{\theta}) = \int \frac{d^2\ell}{(2\pi)^2}(E_{\boldsymbol{\ell}}\sin 2\phi_\ell + B_{\boldsymbol{\ell}}\cos 2\phi_\ell)\exp(i\boldsymbol{\ell}\cdot\boldsymbol{\theta})$$

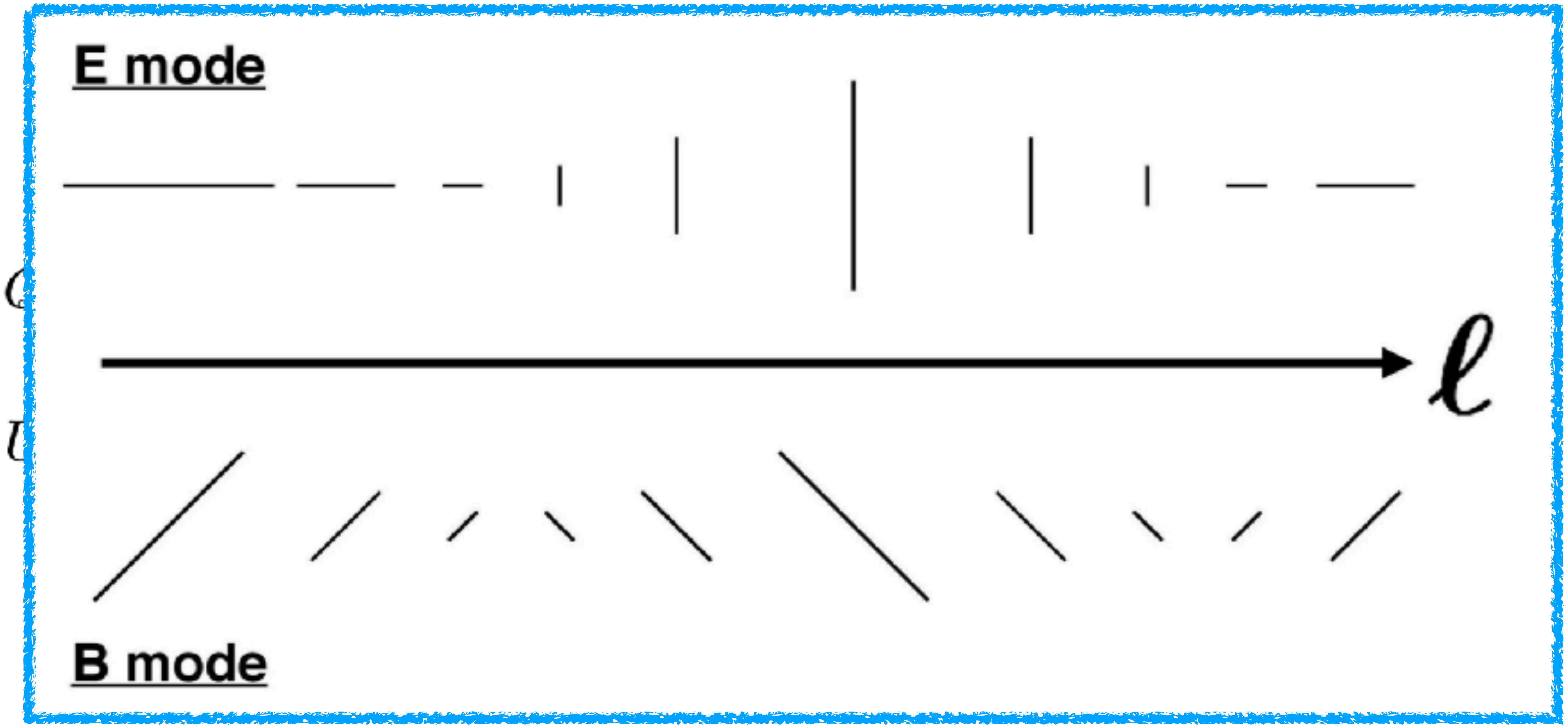
- Let's consider Q and U that are produced by a single Fourier mode

- Taking the x-axis to be the direction of a wavevector, we obtain

$$Q(\theta) = E_\ell \exp(i\ell\theta)$$

$$U(\theta) = B_\ell \exp(i\ell\theta)$$

Pure E, B Modes

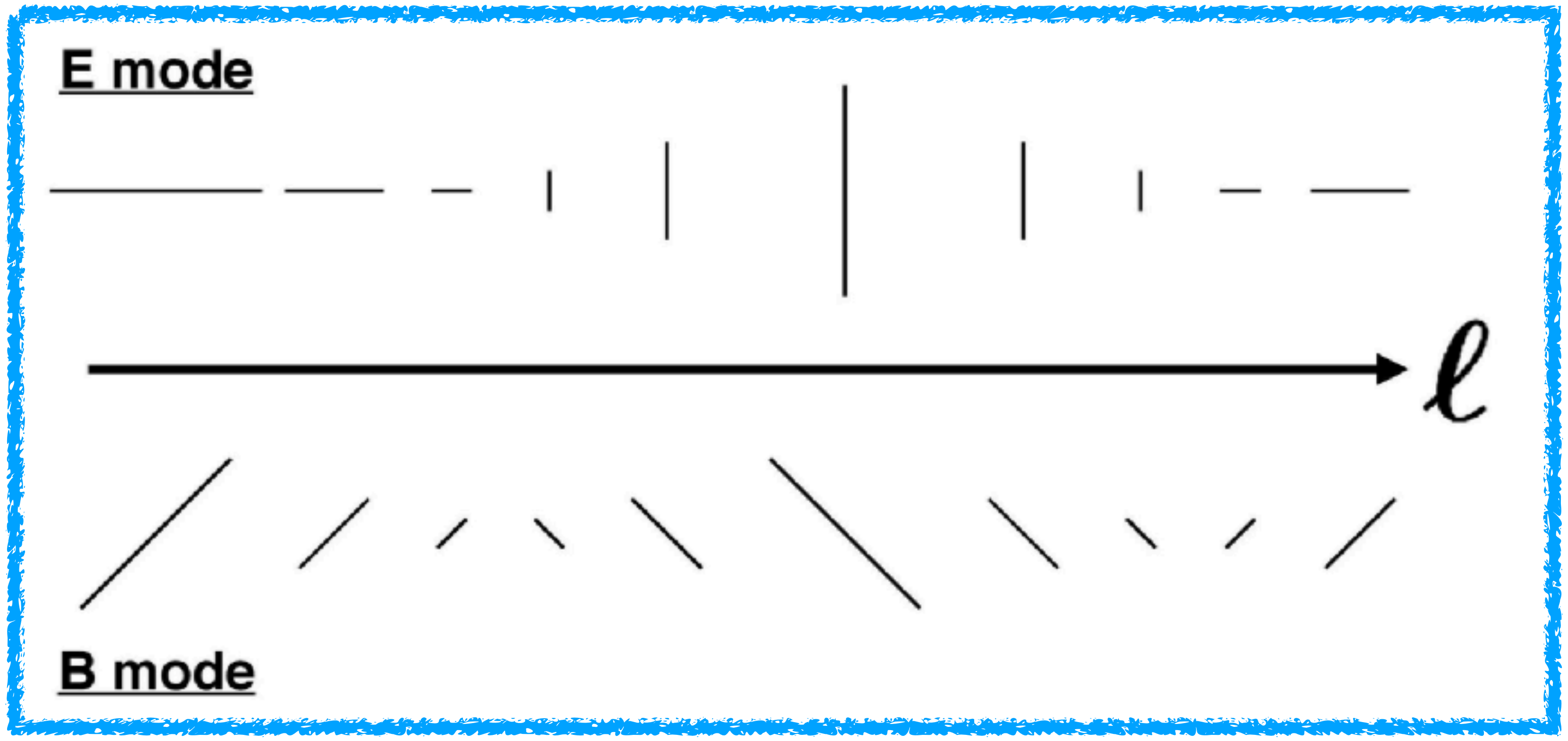


- Taking the x-axis to be the direction of a wavevector, we obtain

$$Q(\theta) = E_\ell \exp(i\ell\theta)$$

$$U(\theta) = B_\ell \exp(i\ell\theta)$$

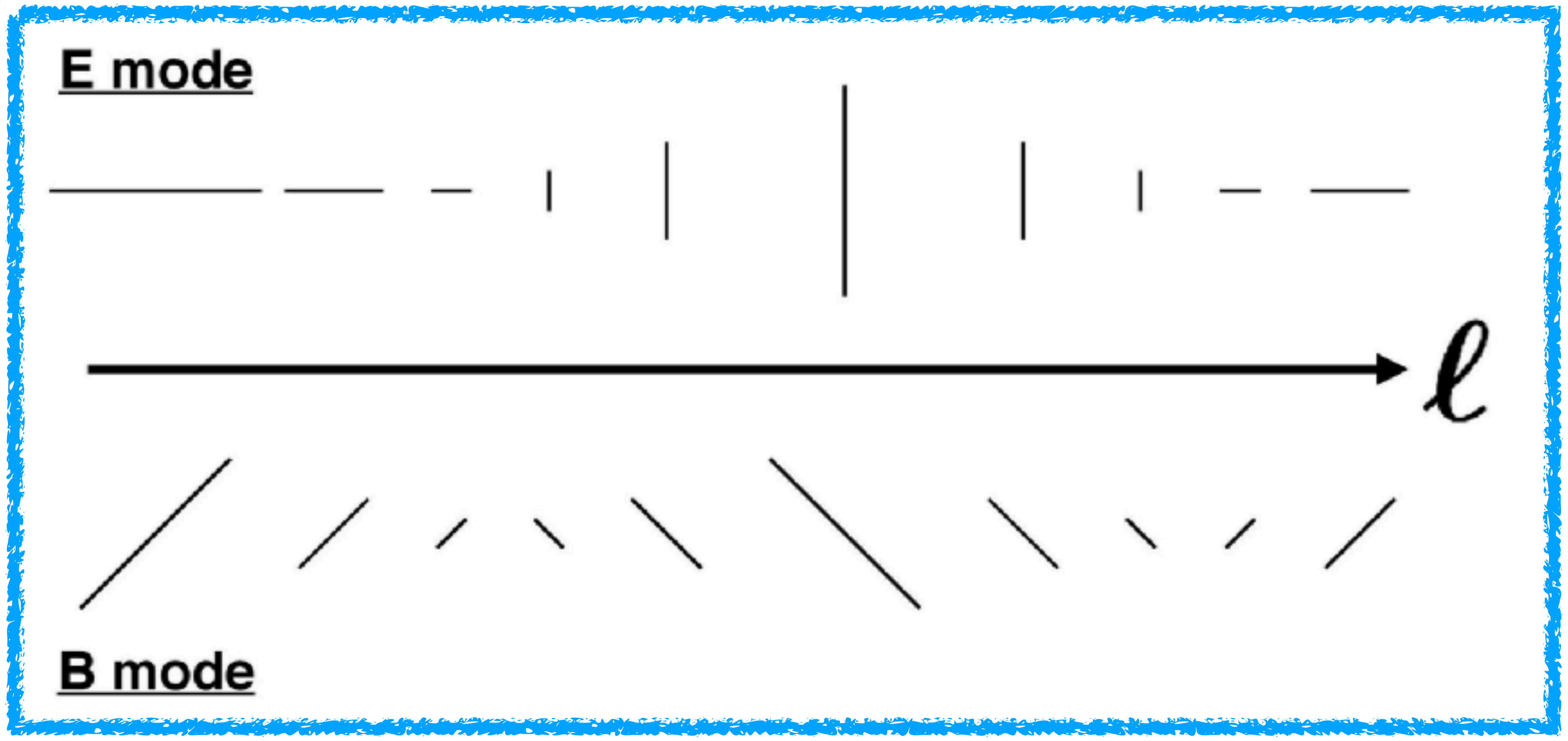
Geometric Meaning (1)

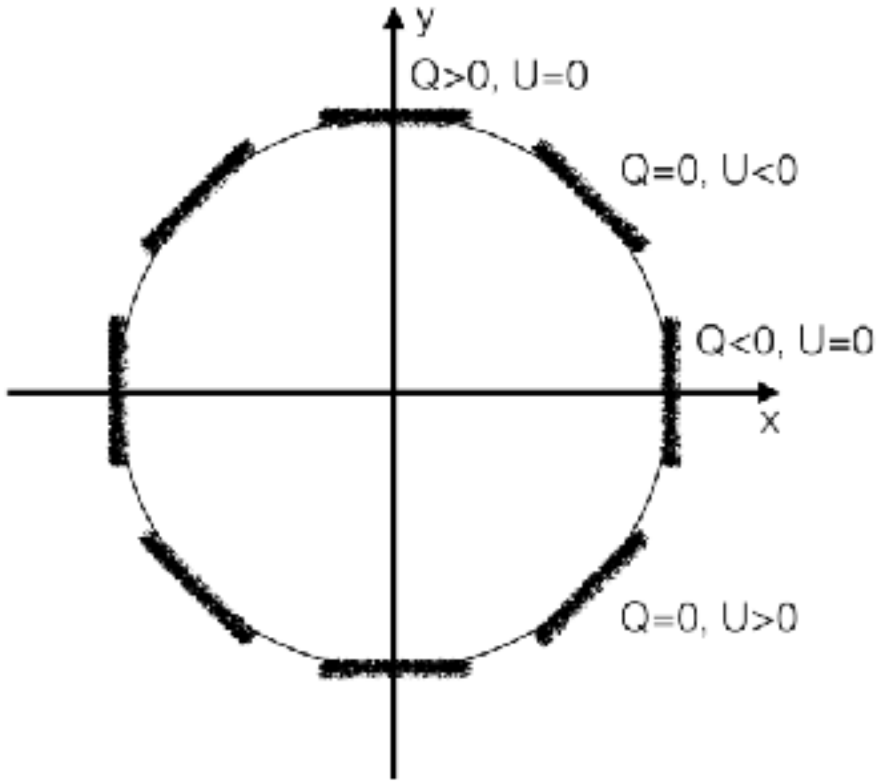


- **E mode**: Polarisation directions parallel or perpendicular to the wavevector

- **B mode**: Polarisation directions 45 degree tilted with respect to the wavevector

Geometric Meaning (2)

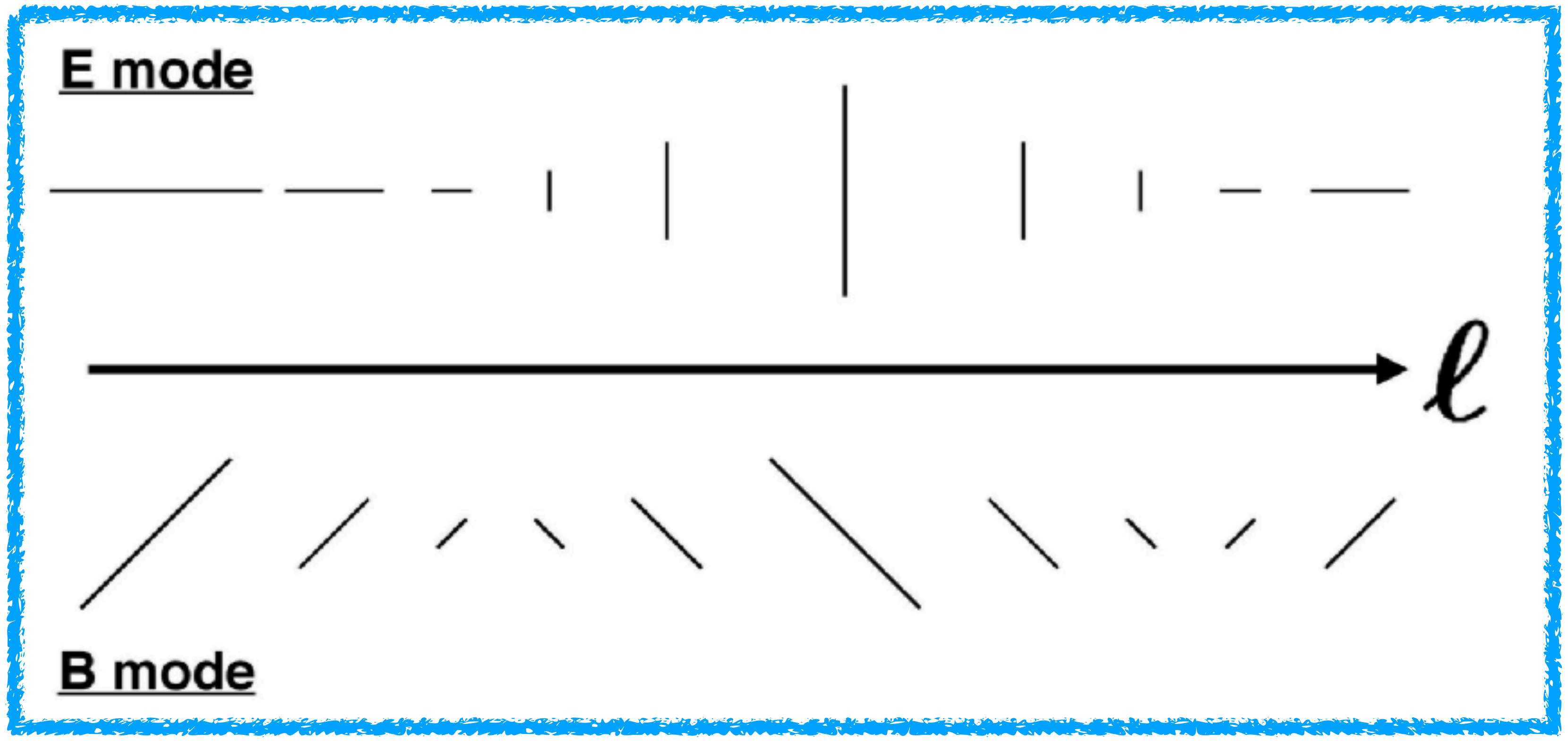




- **<u>E mode</u>**: Stokes Q, defined with respect to ℓ as the x-axis
- **<u>B mode</u>**: Stokes U, defined with respect to ℓ as the y-axis

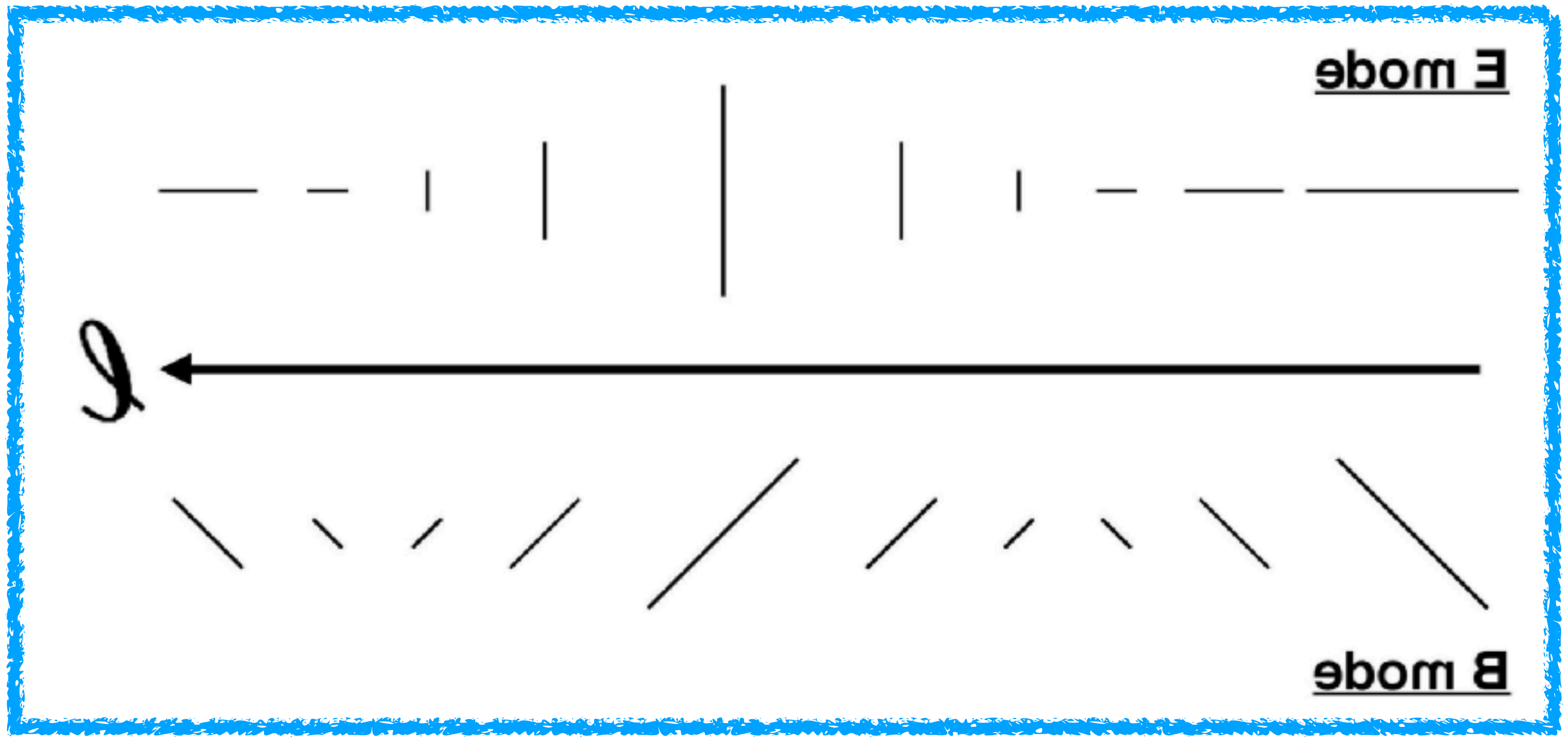
<u>IMPORTANT</u>: These are all coordinate-independent statements

Parity



- **<u>E mode</u>**: Parity even
- **<u>B mode</u>**: Parity odd

Parity



- **E mode**: Parity even
- **B mode**: Parity odd

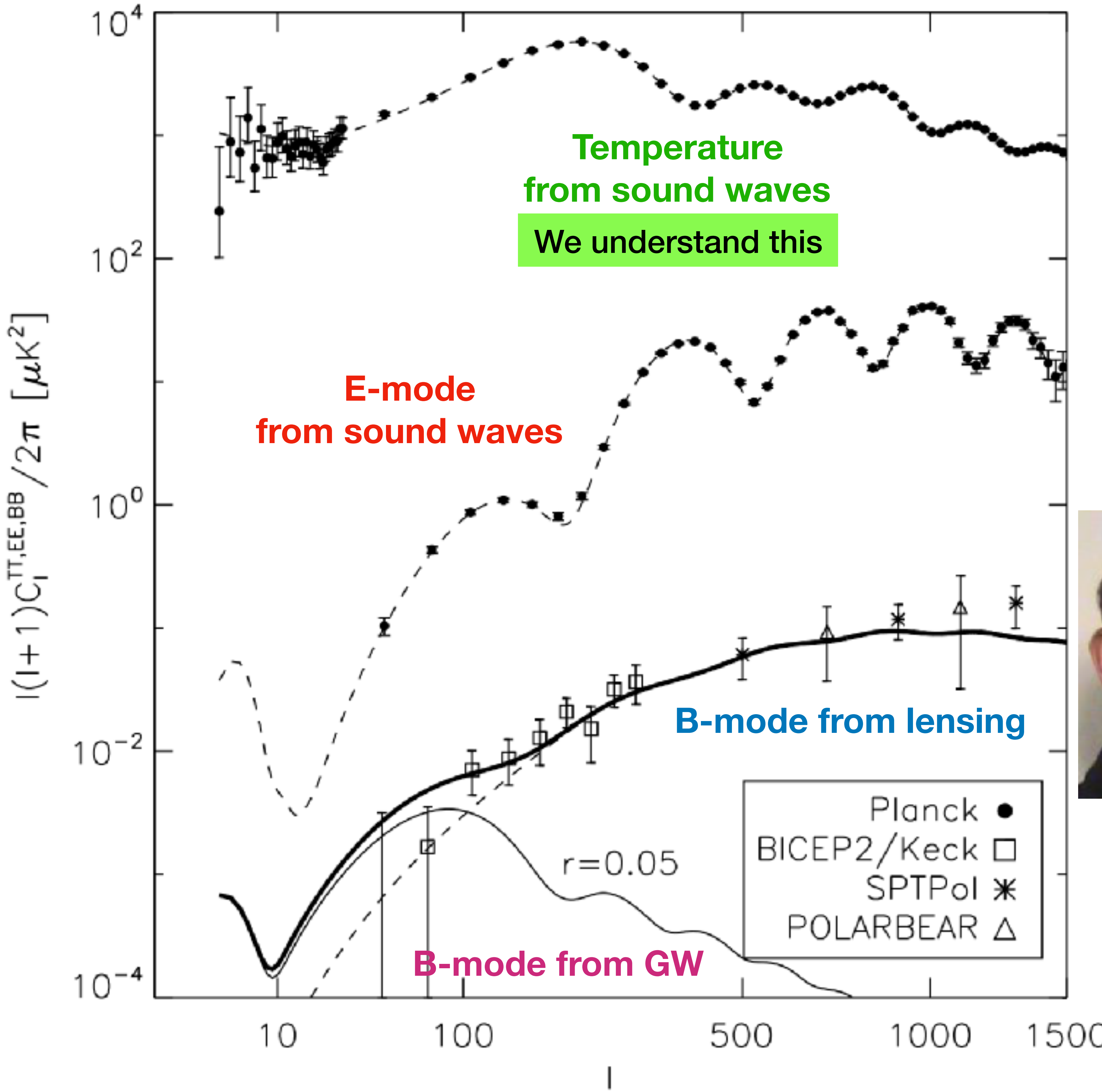
Power Spectra

$$\langle E_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{EE}$$

$$\langle B_{\boldsymbol{\ell}} B^*_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{BB}$$

$$\langle T_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = \langle T^*_{\boldsymbol{\ell}} E_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{TE}$$

- However, <EB> and <TB> vanish for parity-preserving fluctuations because <EB> and <TB> change sign under parity flip



Antony Lewis