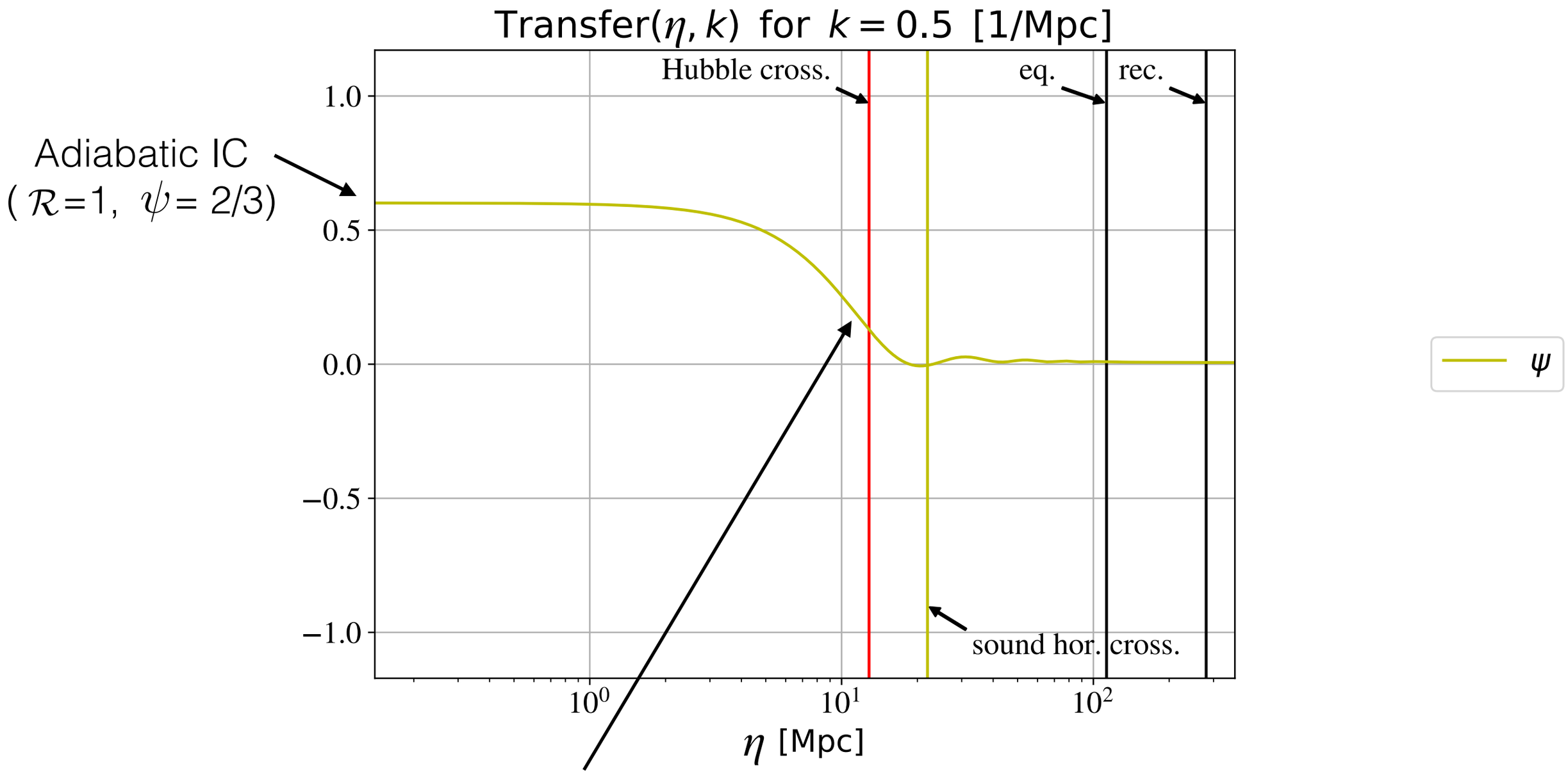
Evolution for one mode with given k

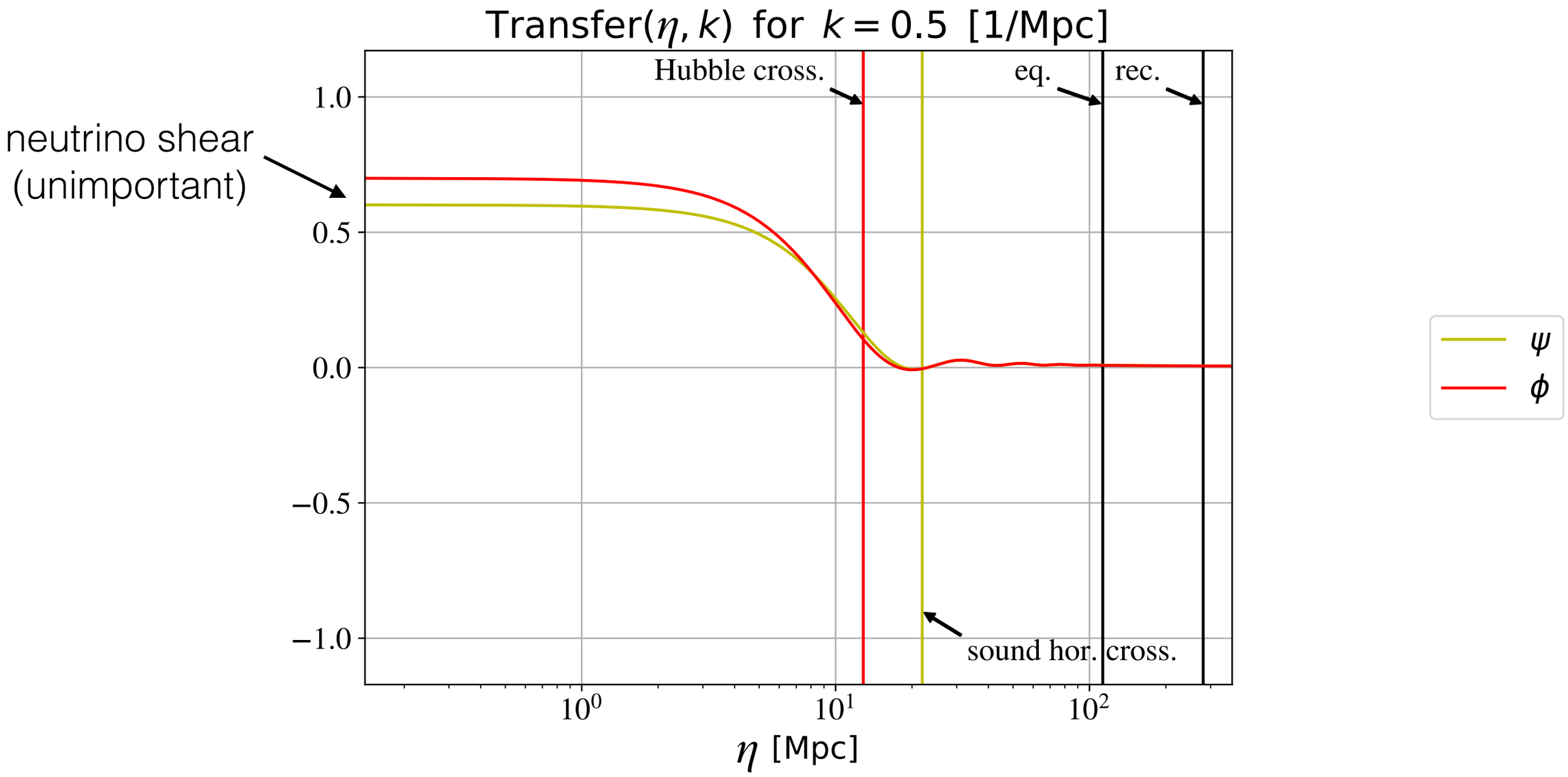


Metric damped near Hubble crossing during RD

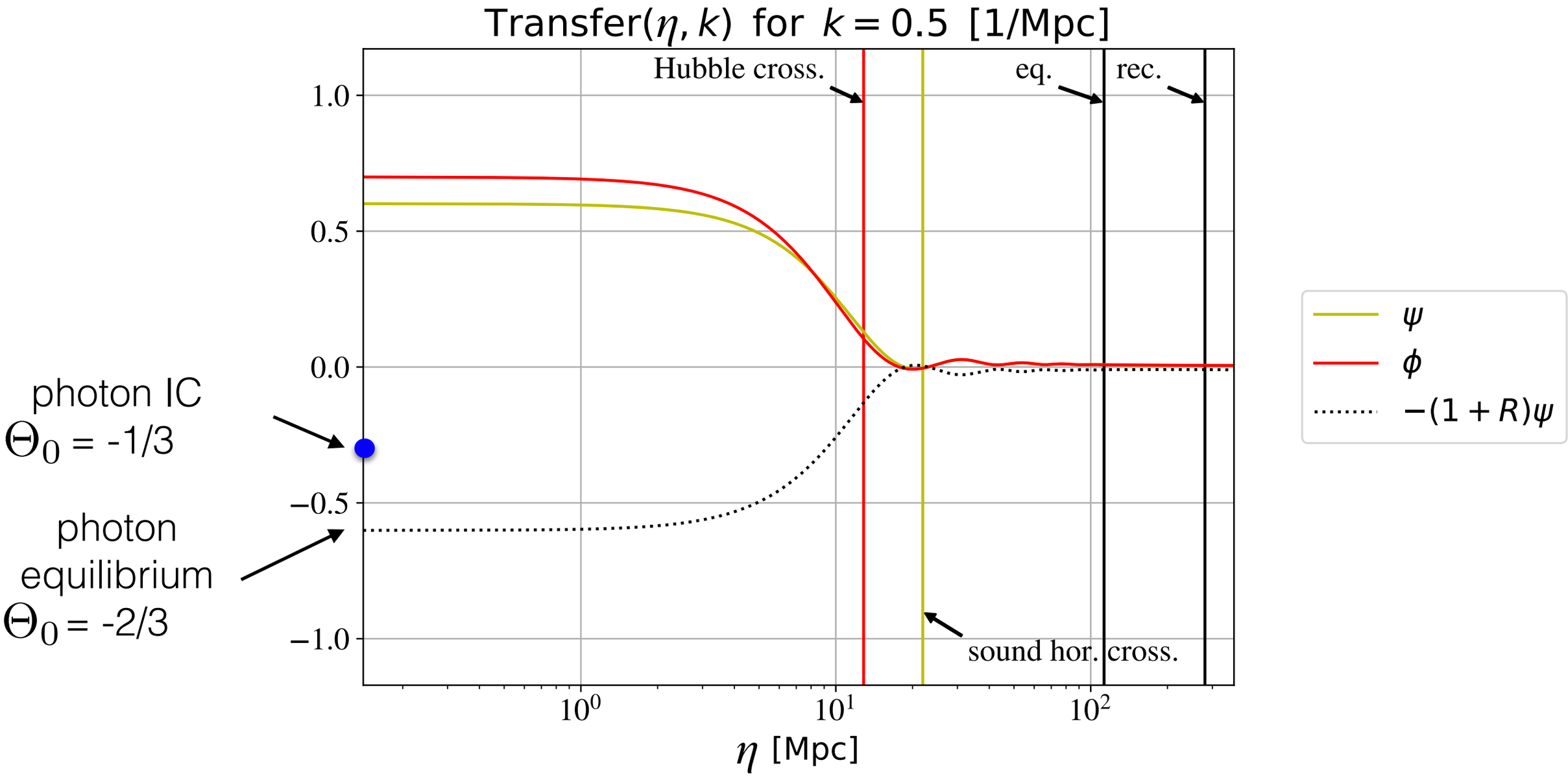
—> photon pressure, Poisson: $-k^2\phi = 4\pi G\, a^2\, \delta\rho_r \propto a^2 \rho_r\, \delta_r \sim a^{2-4+0} \sim a^{-2}$

—> very different from MD: $-k^2\phi = 4\pi G\, a^2\, \delta\rho_m \propto a^2 \rho_m\, \delta_m \sim a^{2-3+1} \sim \text{constant}$

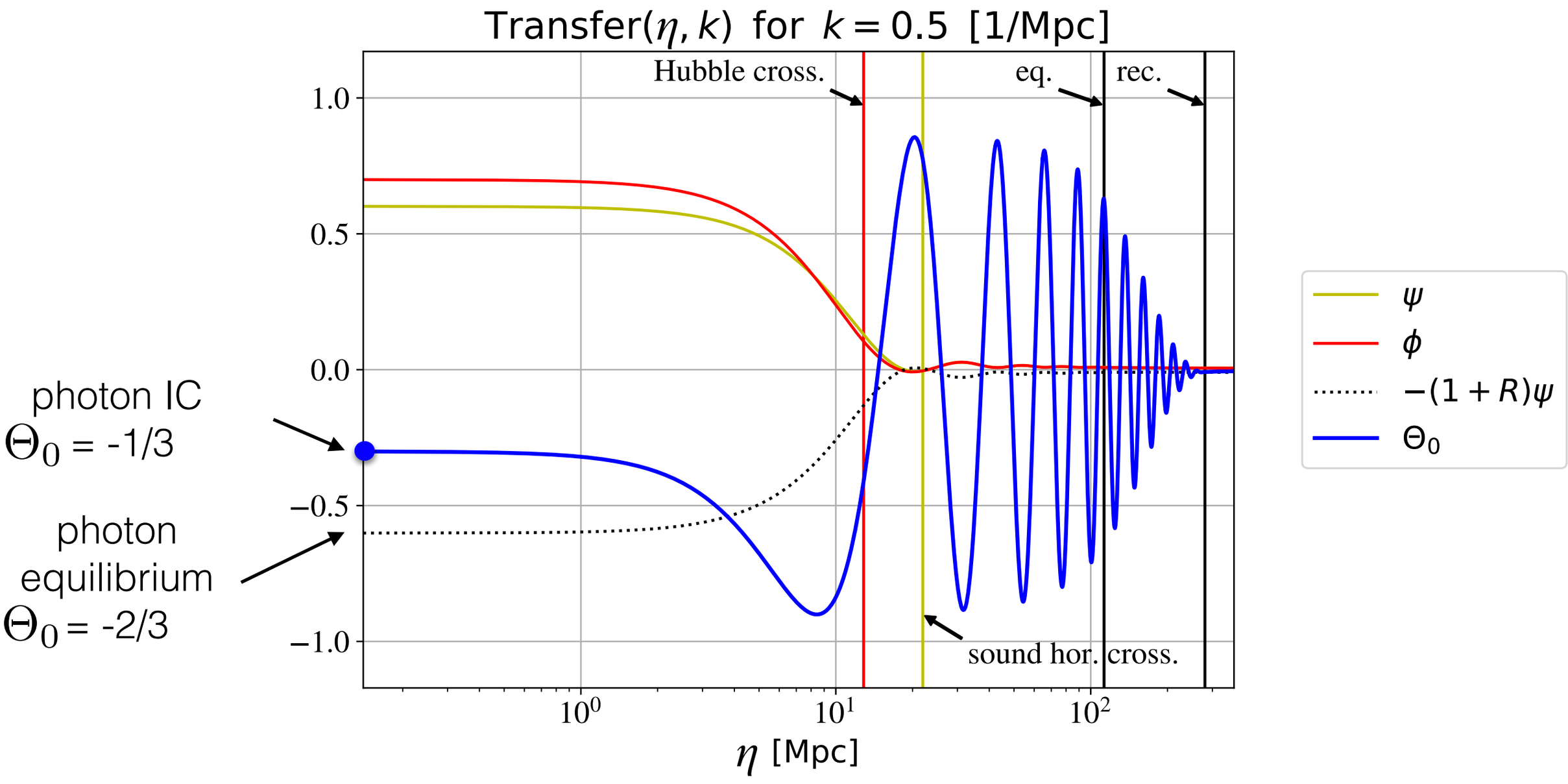
Evolution for one mode



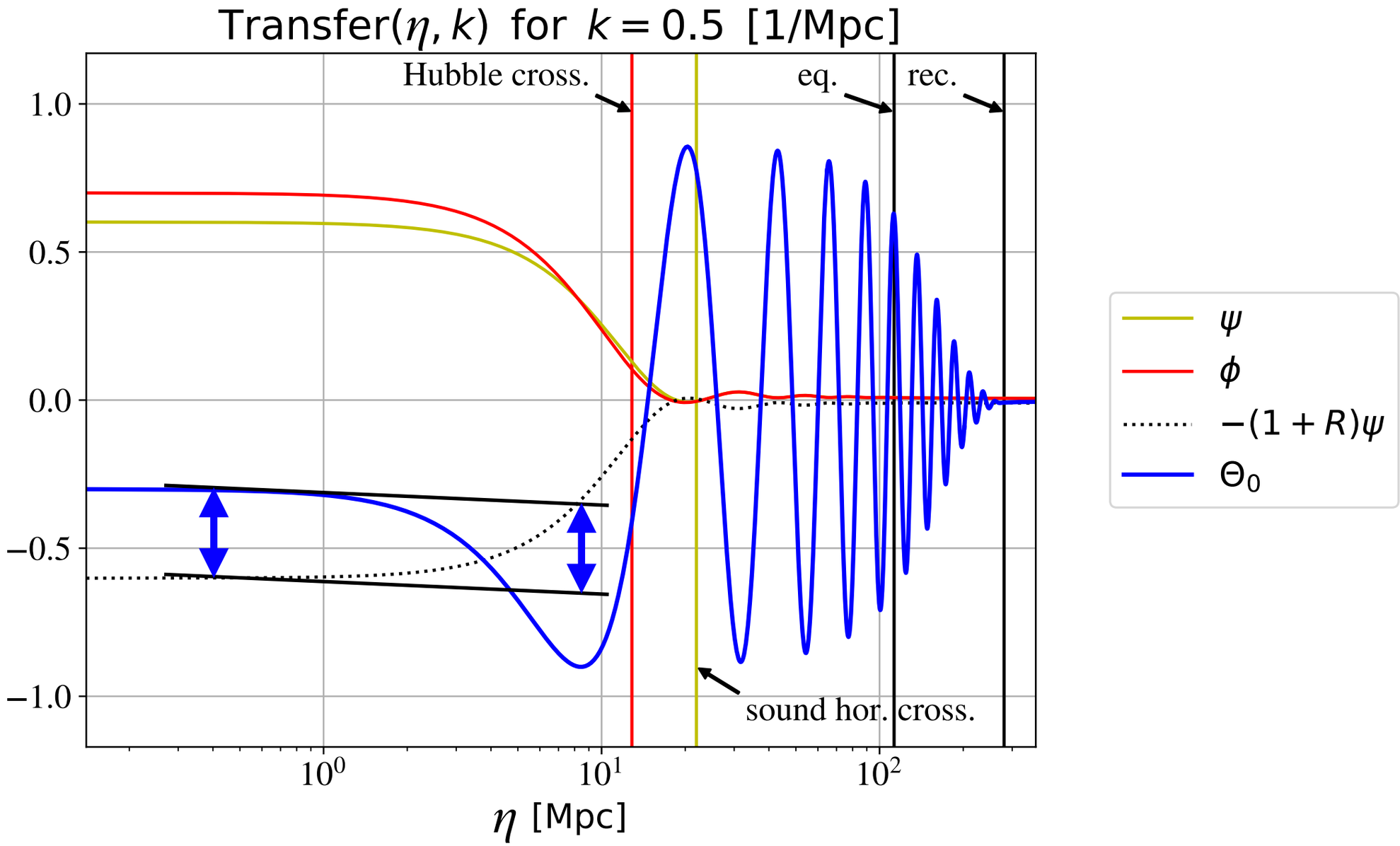
Evolution for one mode



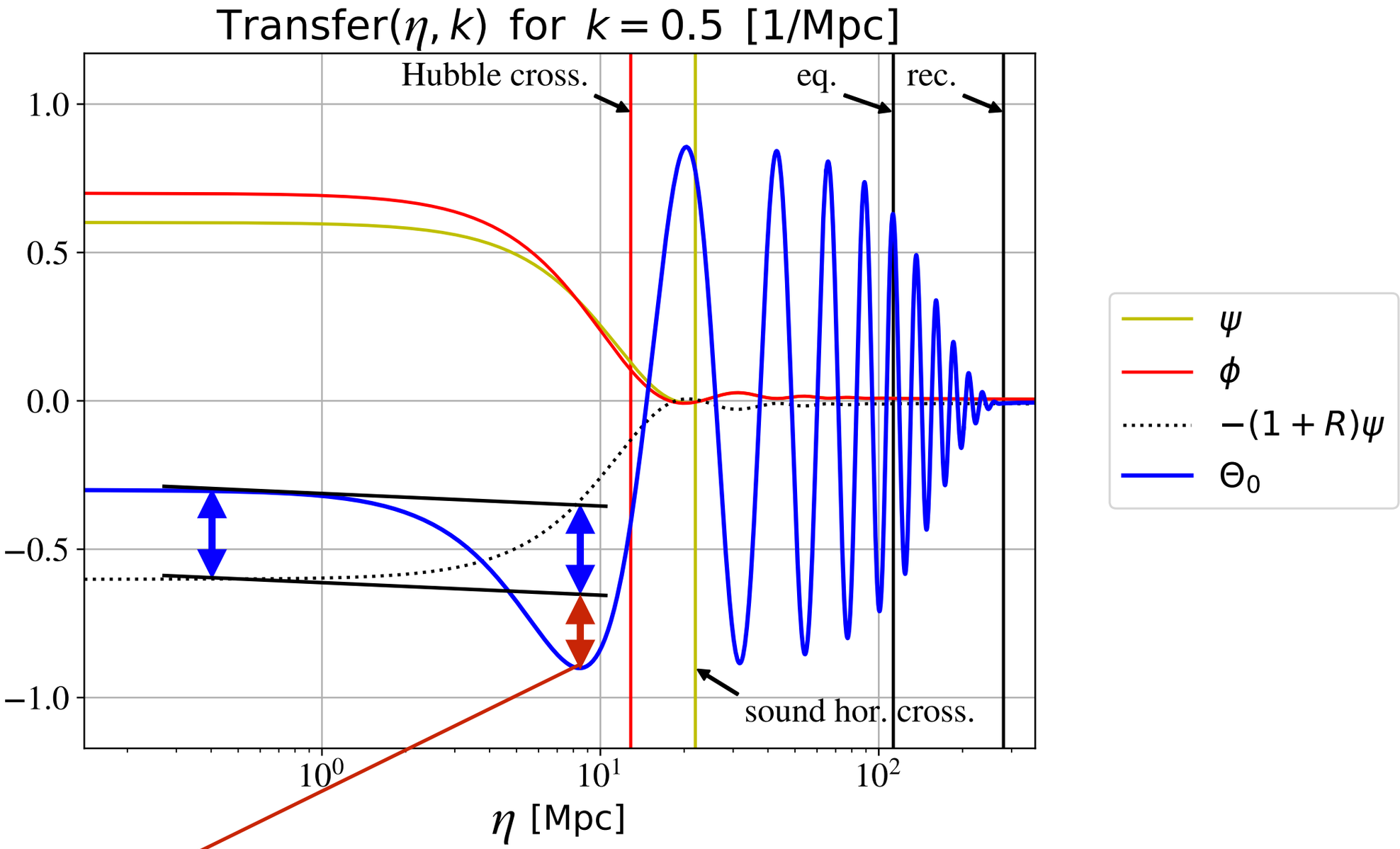
Evolution for one mode



Evolution for one mode



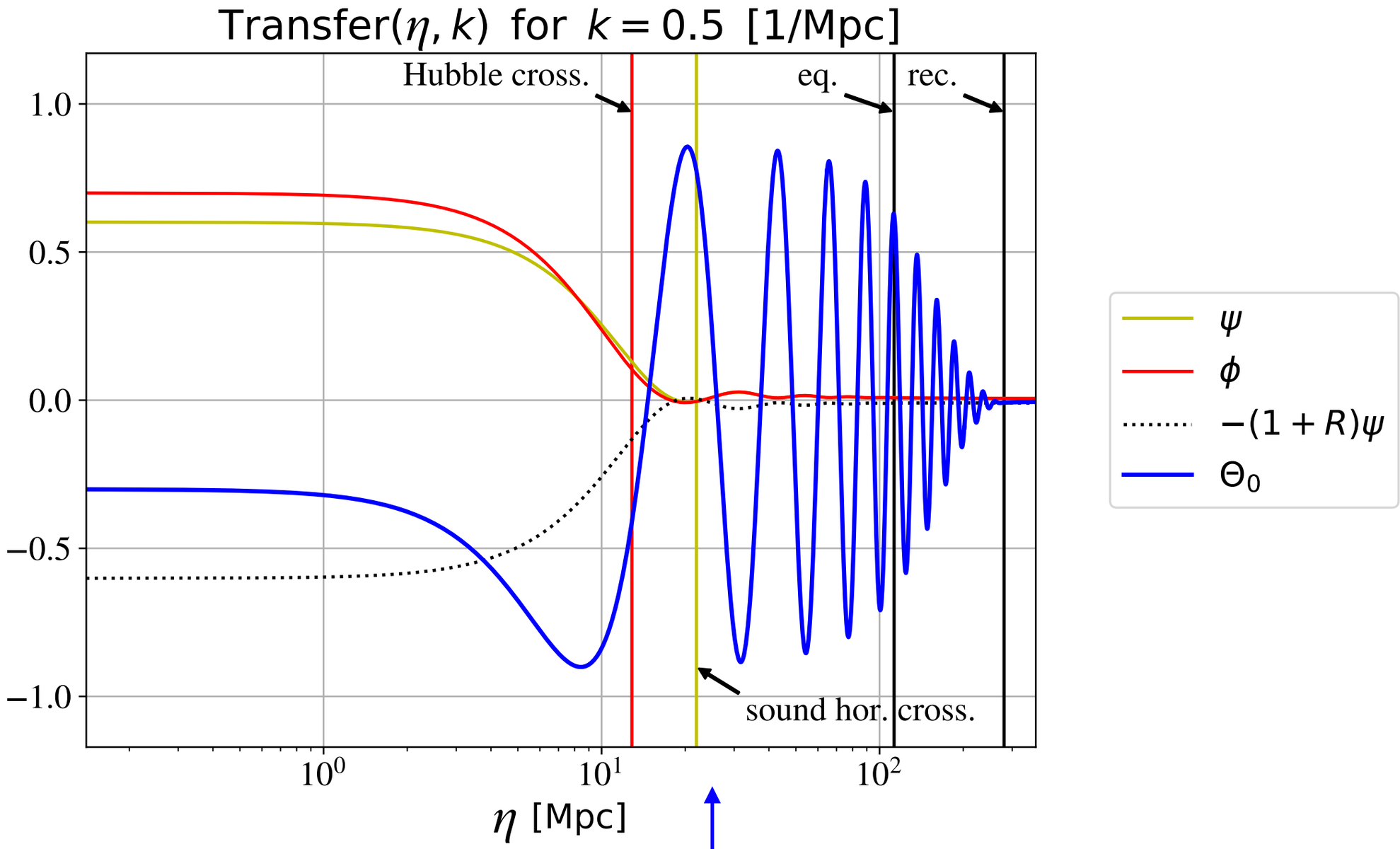
Evolution for one mode



Gravity boost effect from $\frac{R'}{1+R}\phi' + \phi''$

Will be important for effect of neutrinos, DR…

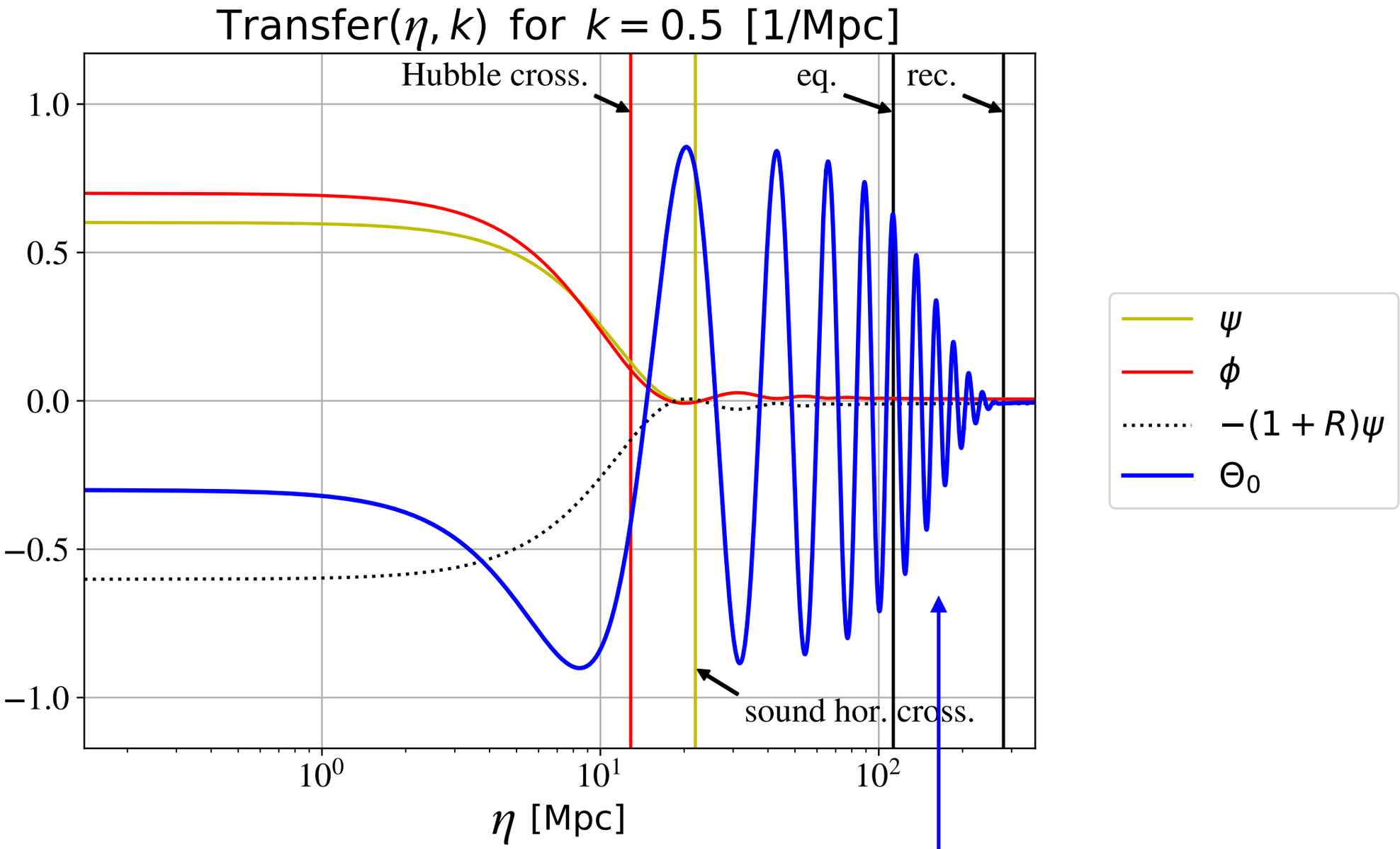
Evolution for one mode



symmetric and stationary oscillation

(deep sub-Hubble, deep DR)

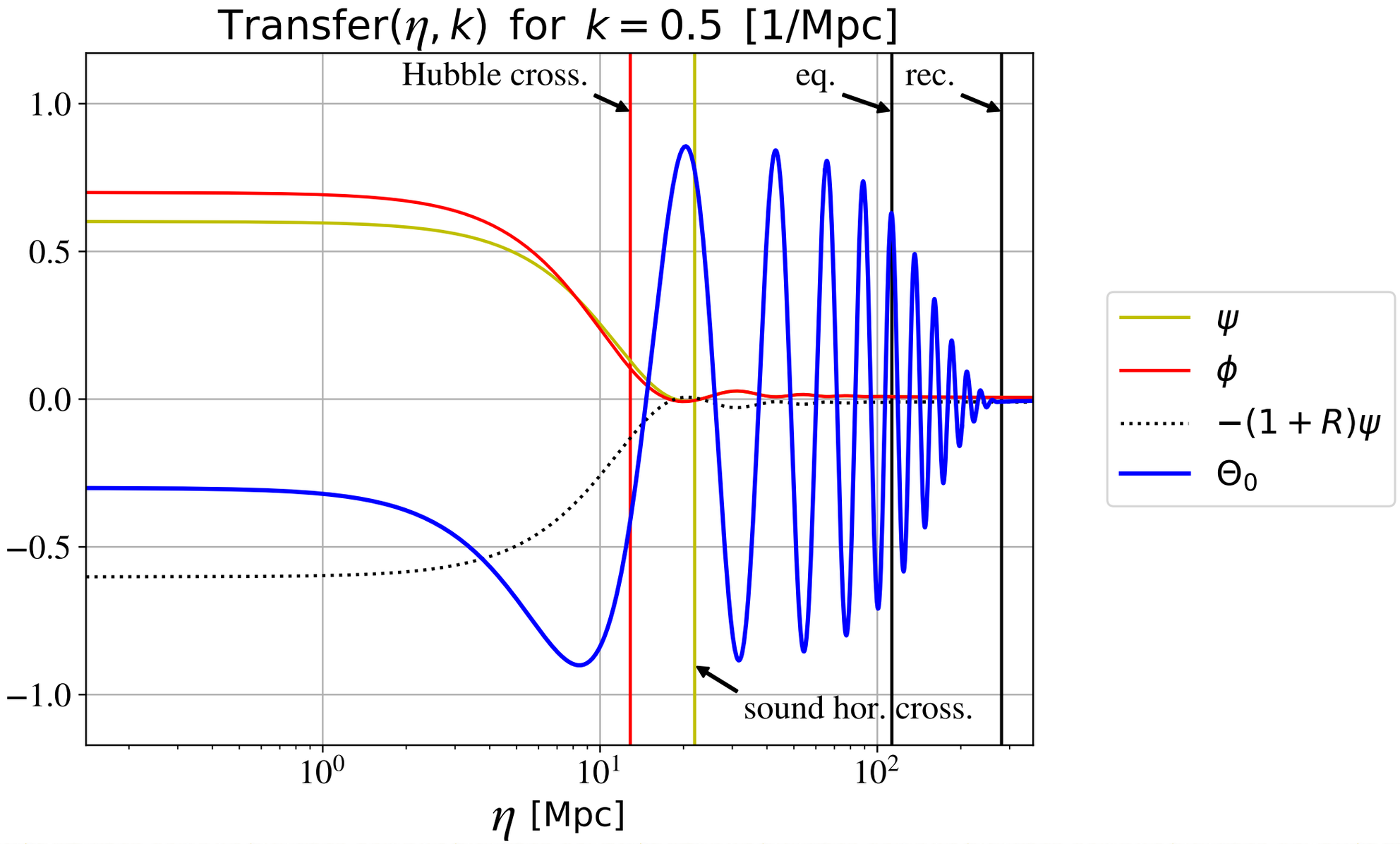
Evolution for one mode



exponentially damped oscillations

(approaching recombination)

Evolution for one mode



Final goal:

(MZ's line-of-sight integral)

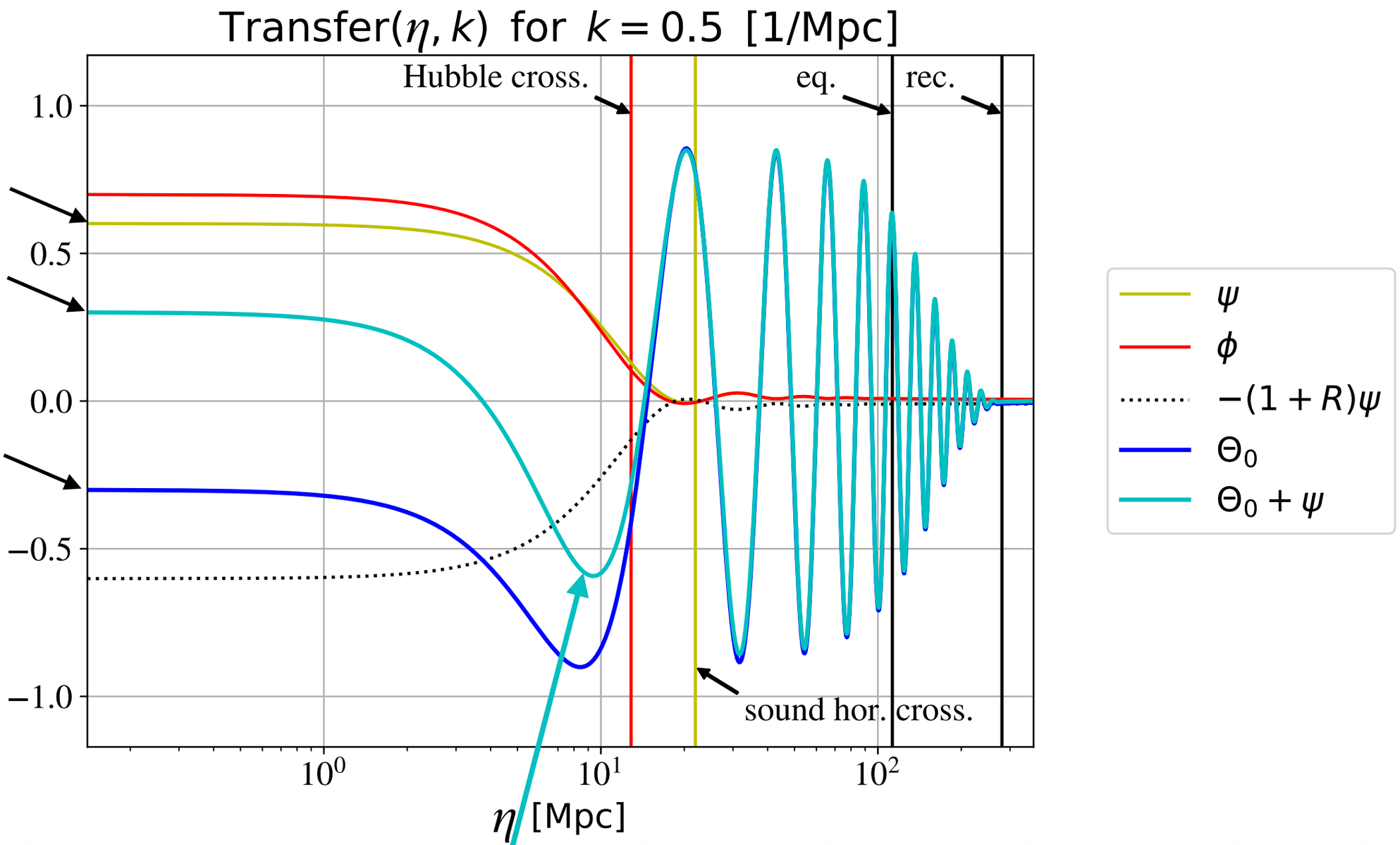
$$\Theta_l(\eta_0,k) = \int_{\eta_{\rm ini}}^{\eta_0} d\eta \left(\underbrace{g\,(\Theta_0+\psi)}_{\rm SW} + \underbrace{\left(g\,k^{-2}\theta_{\rm b}\right)'}_{\rm Doppler} + \underbrace{e^{-\tau}(\phi'+\psi')}_{\rm ISW} \right) j_l(k(\eta_0-\eta))$$

Evolution for one mode

Adiabatic IC
($\mathcal{R}$=1, ψ= 2/3)

$\Theta_0 + \psi = 1/3$

photon IC
Θ_0 = -1/3



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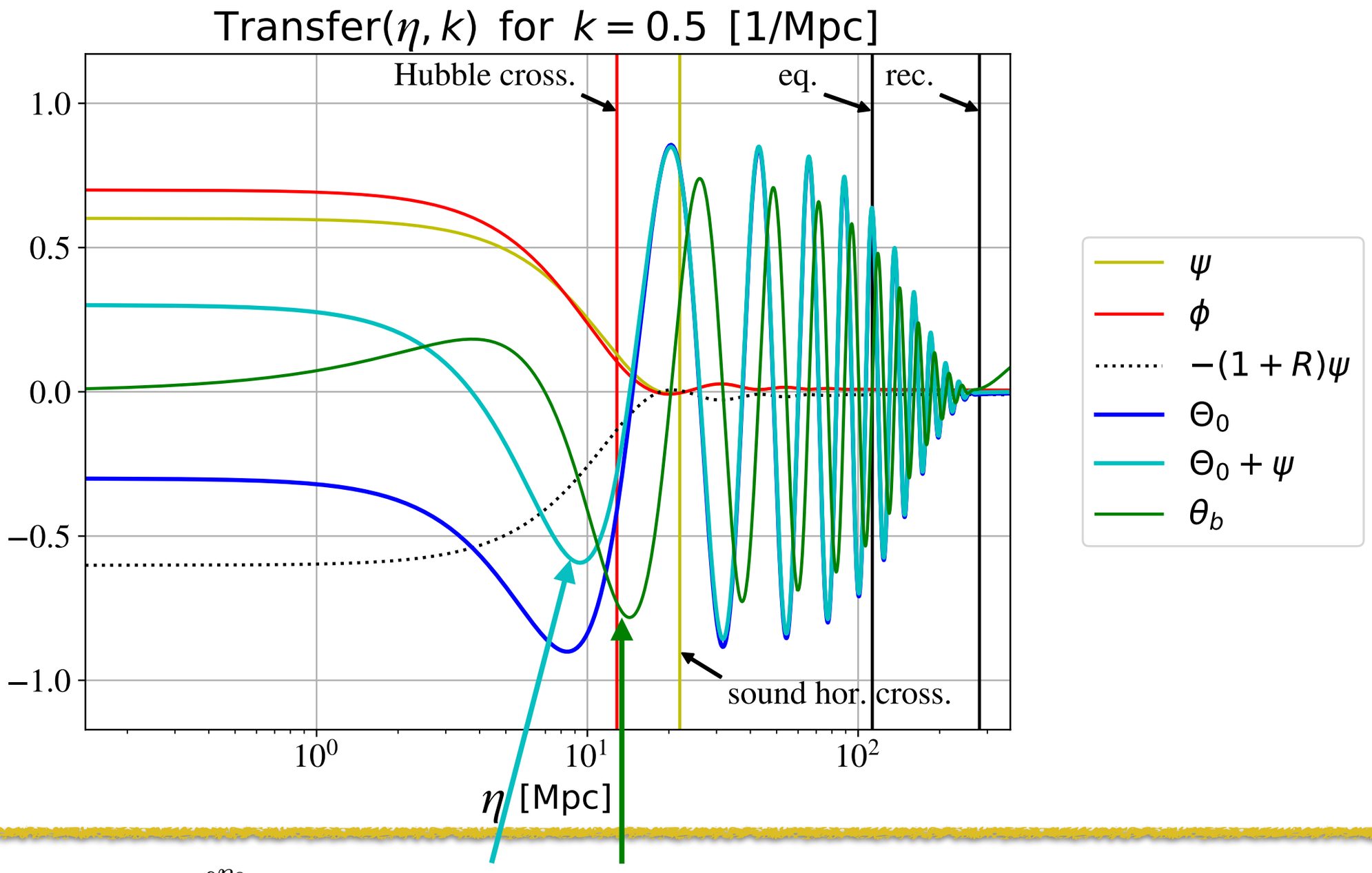

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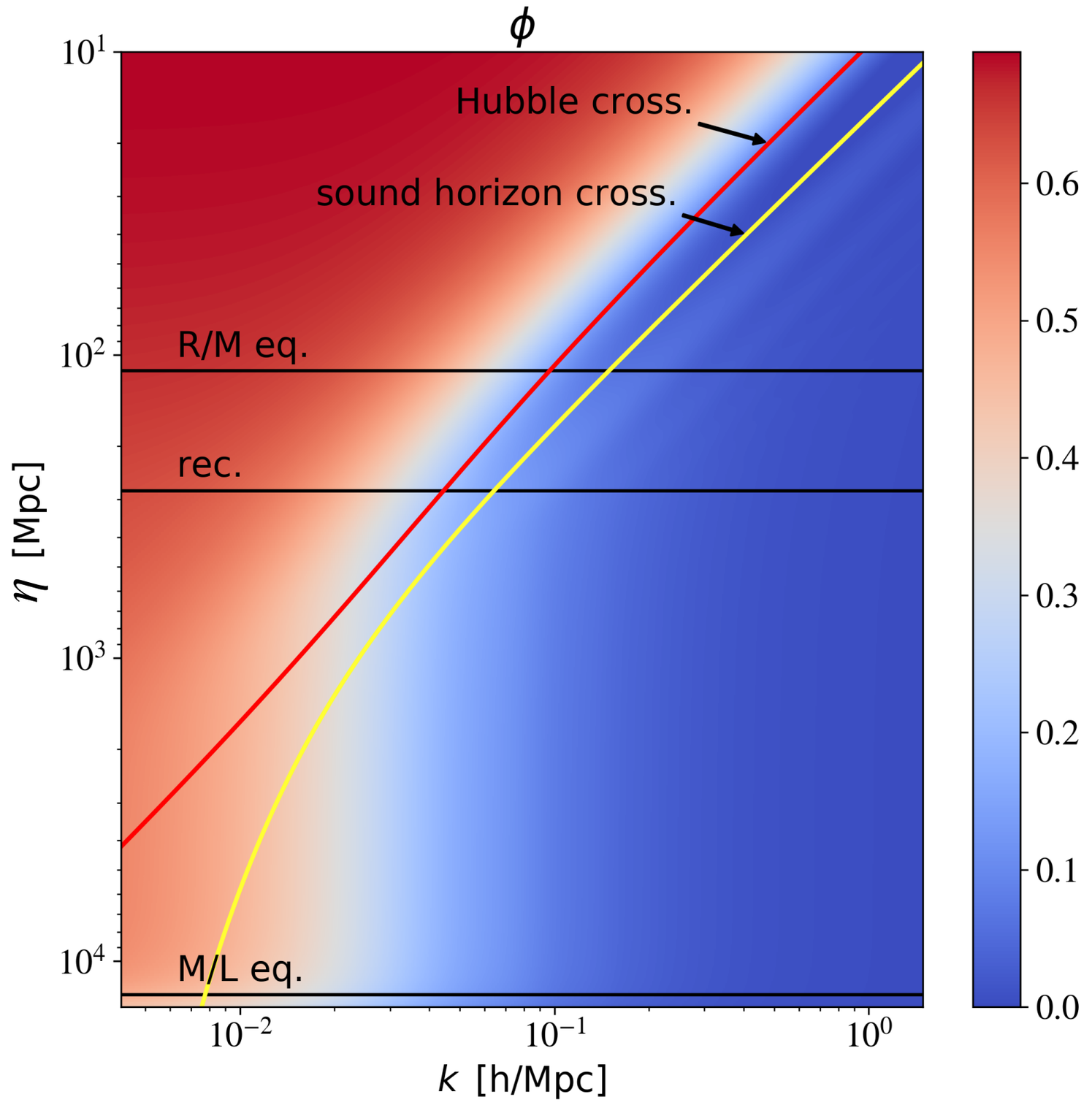
Evolution for all wavenumbers

Metric $\phi(\eta, k)$:



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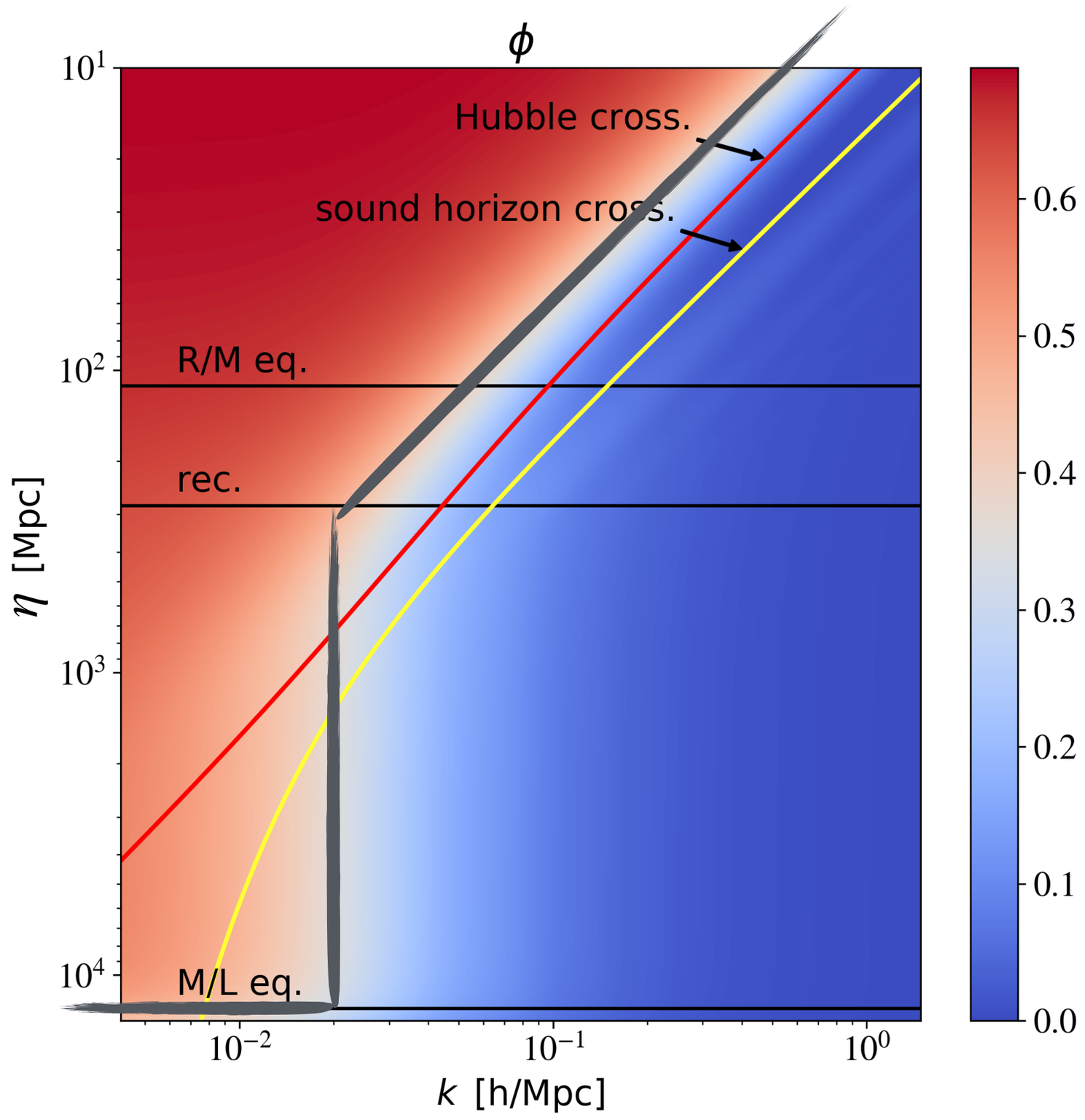
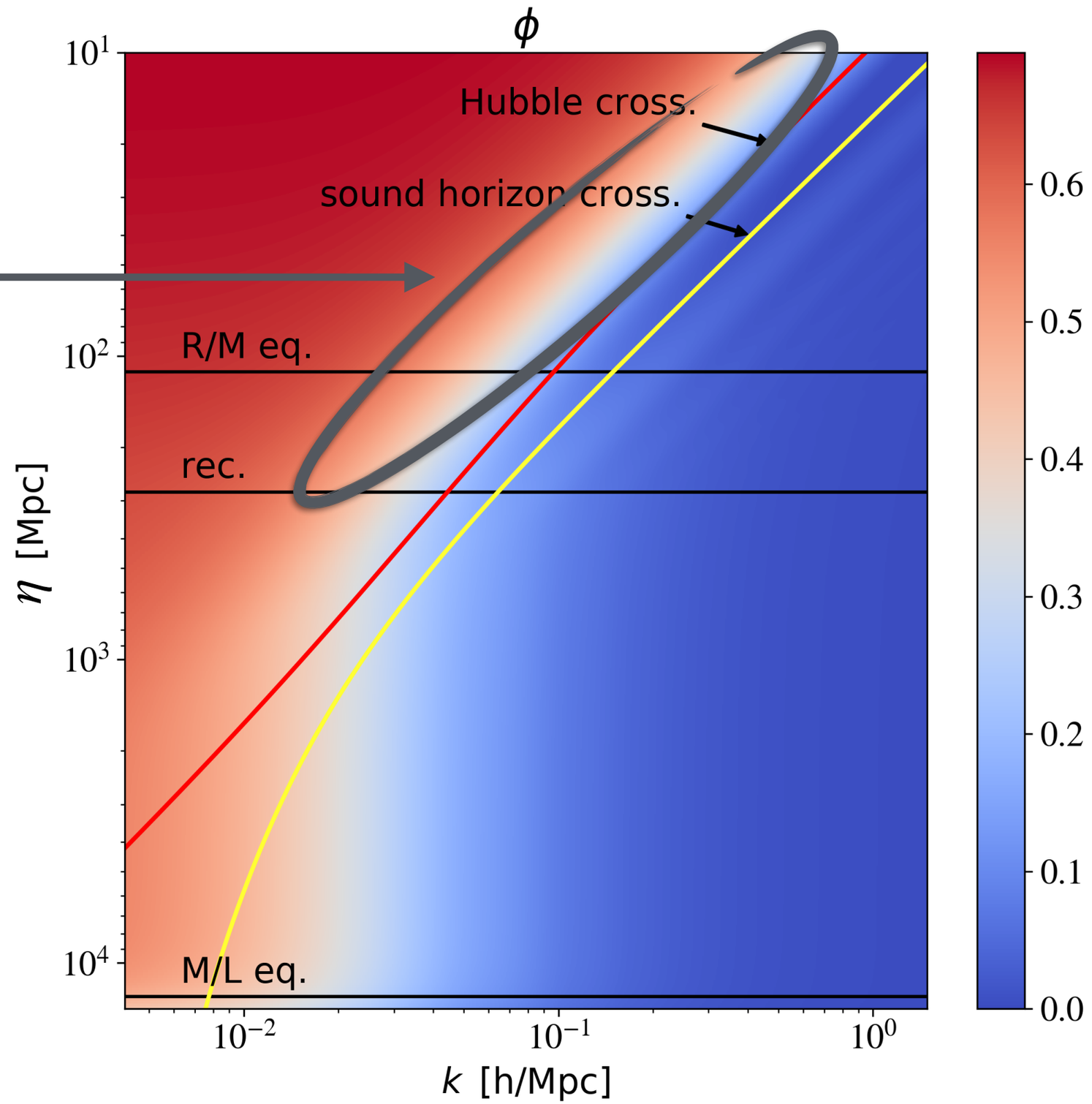


Evolution for all wavenumbers

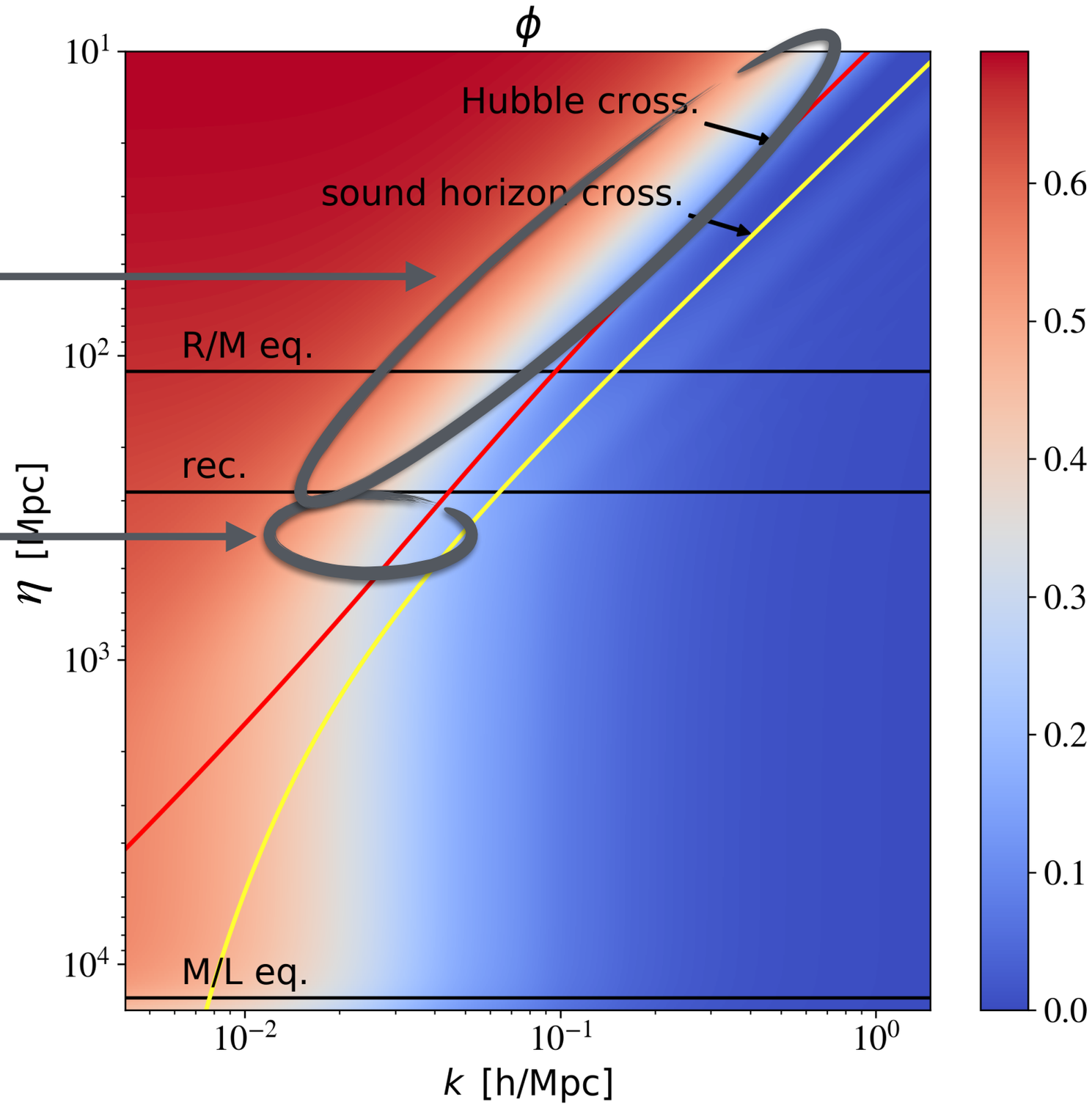
$$\frac{R'}{1+R}\phi' + \phi'' \Rightarrow \text{gravity boost}$$



Evolution for all wavenumbers

$$\frac{R'}{1+R}\phi' + \phi''$$ gravity boost

$$\underbrace{e^{-\tau}(\phi' + \psi')}_{\text{ISW}}$$ early ISW

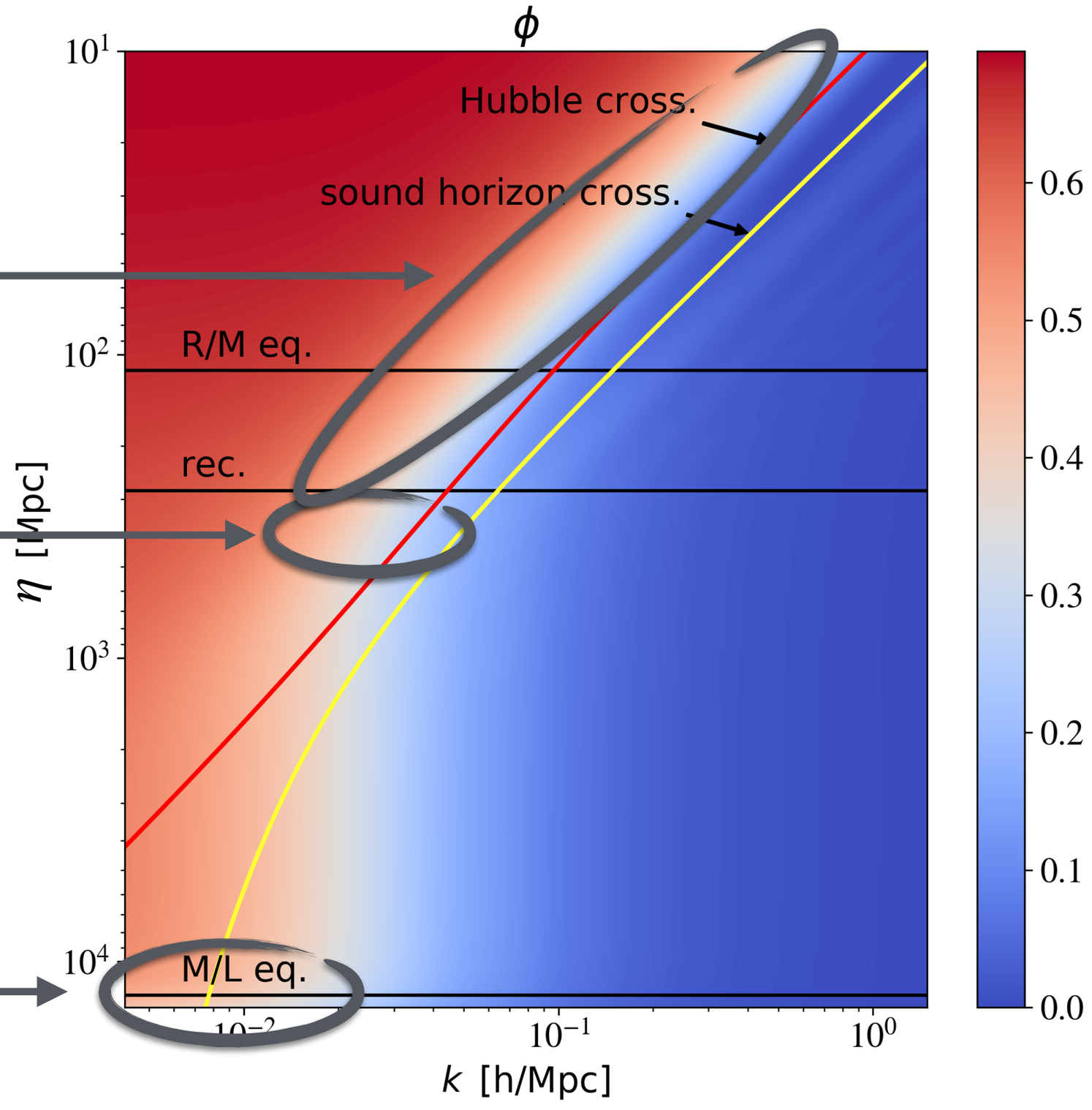


Evolution for all wavenumbers

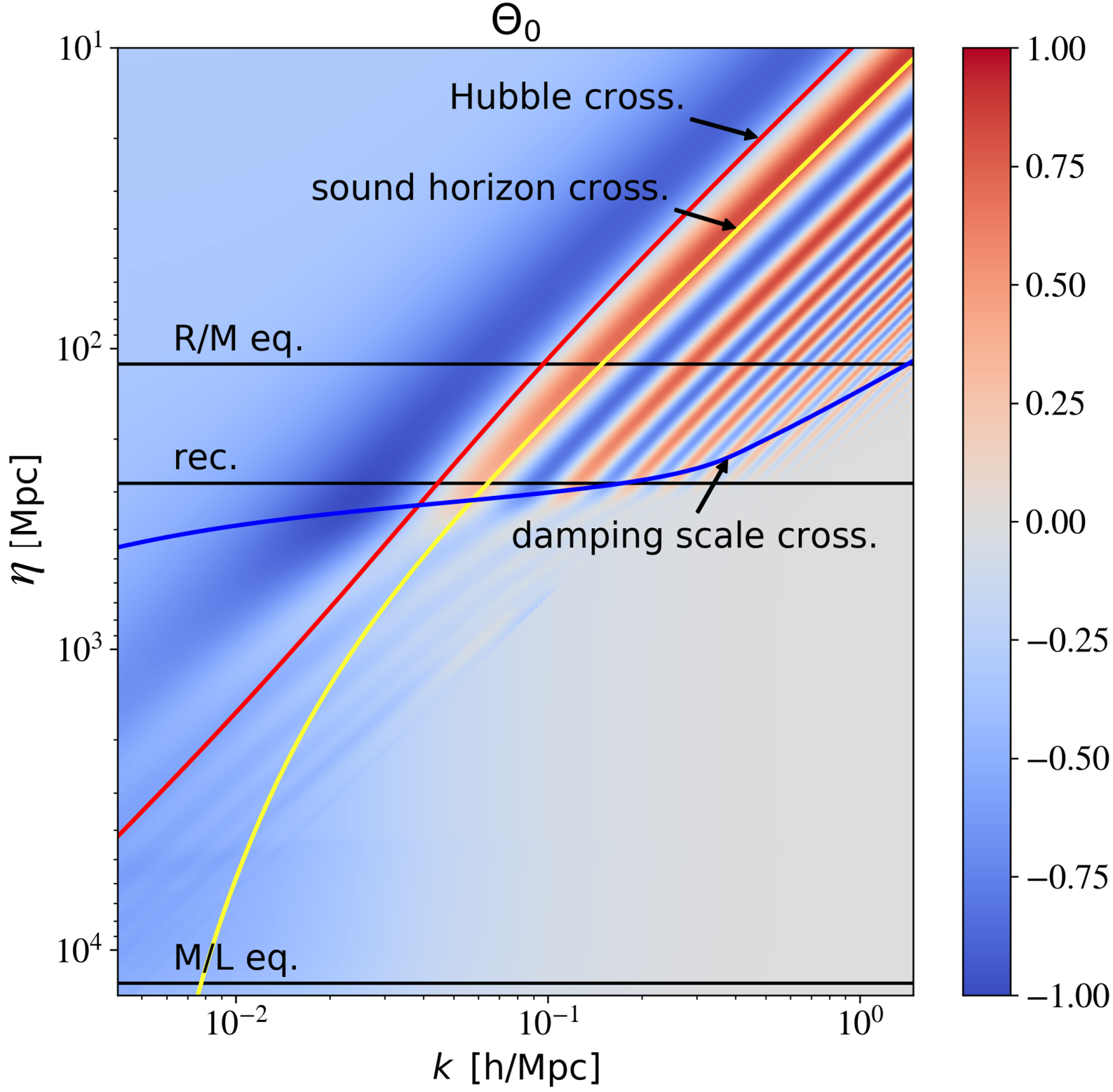
$$\frac{R'}{1+R}\phi' + \phi''$$ gravity boost

$$\underbrace{e^{-\tau}(\phi' + \psi')}_{\text{ISW}}$$ early ISW

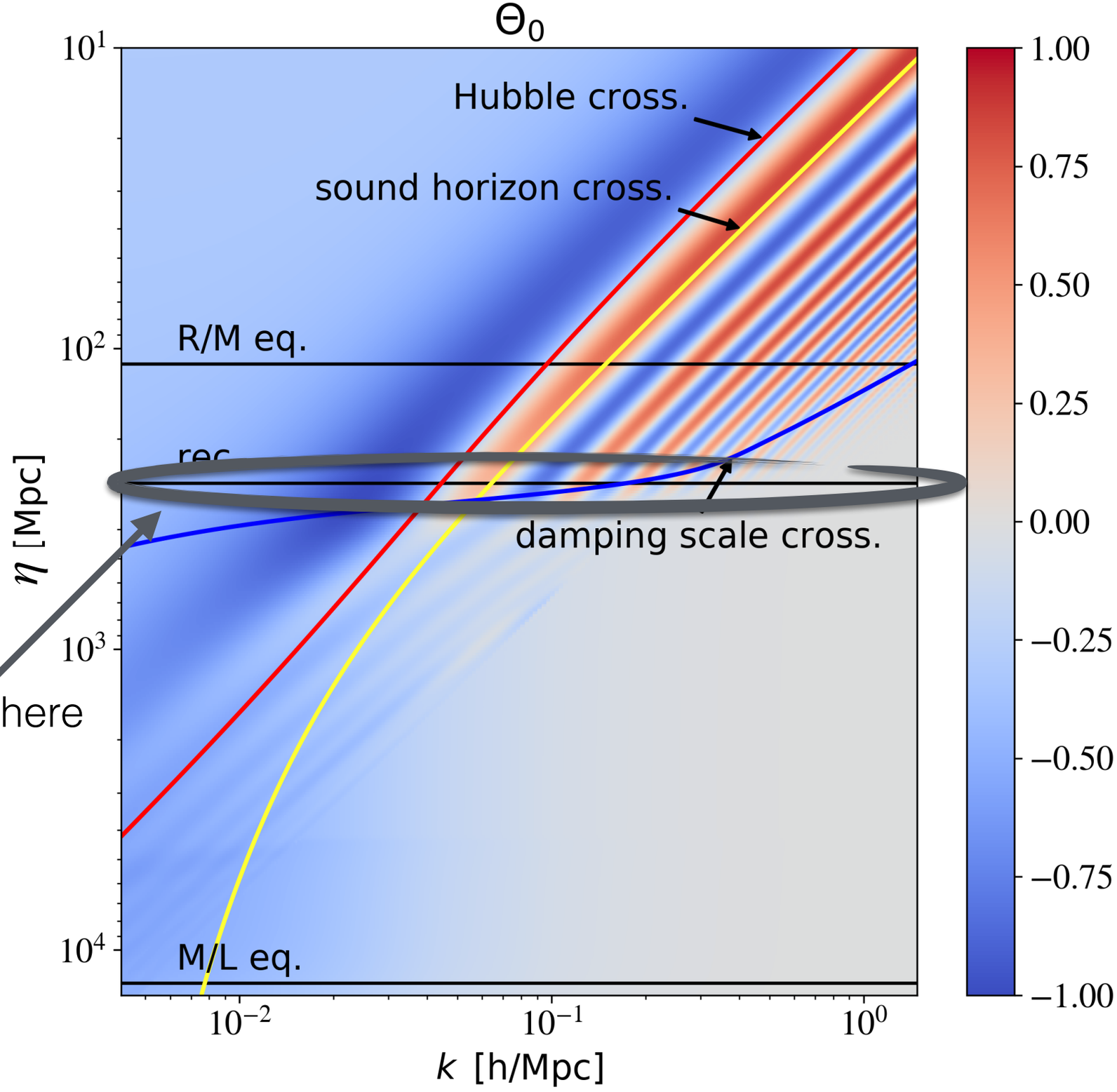
$$\underbrace{e^{-\tau}(\phi' + \psi')}_{\text{ISW}}$$ late ISW



Evolution for all wavenumbers



Evolution for all wavenumbers



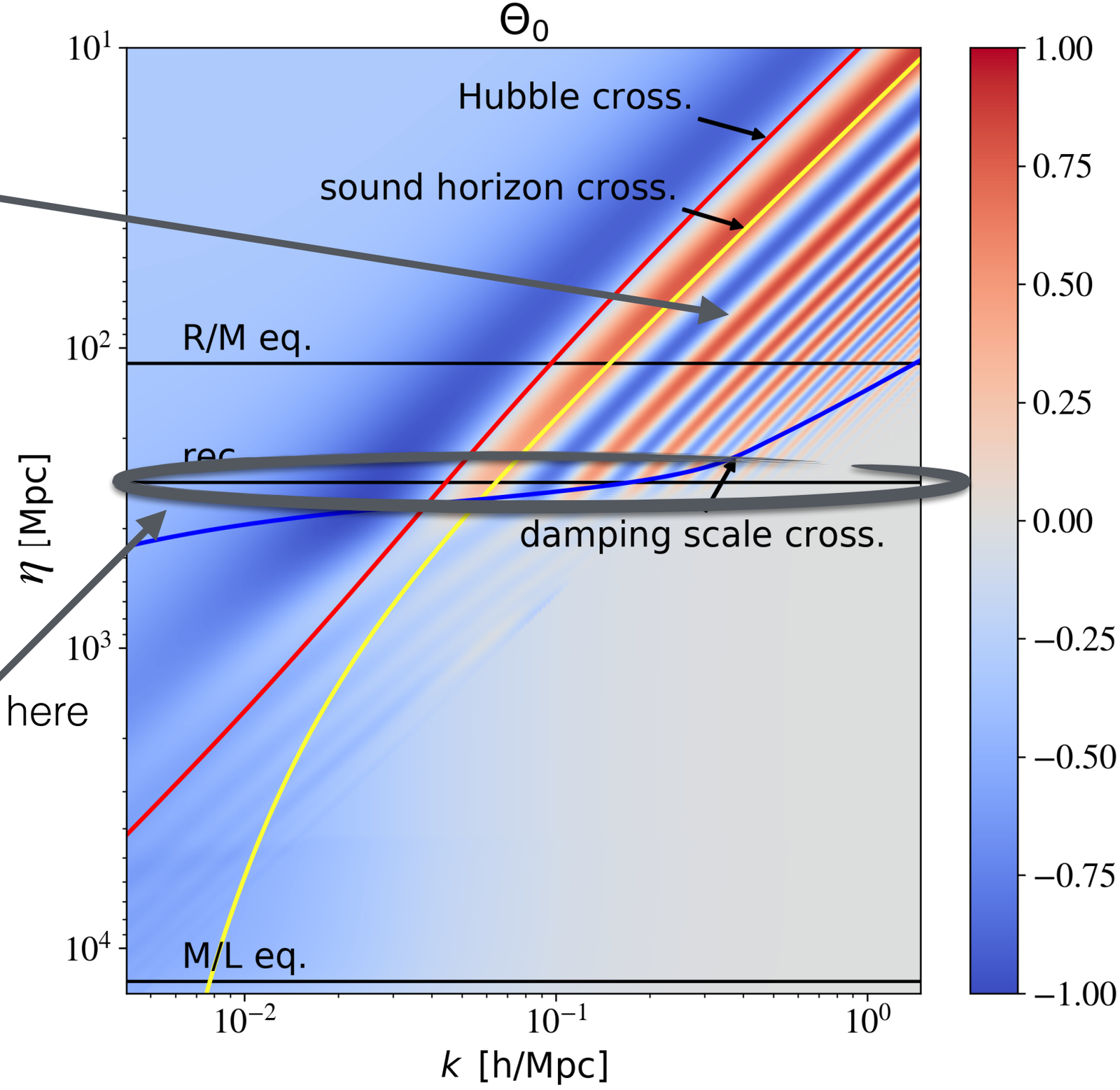
CMB patterns mainly come from here

Evolution for all wavenumbers

45° symmetry comes from

$$\cos(kc_s\eta)$$

CMB patterns mainly come from here



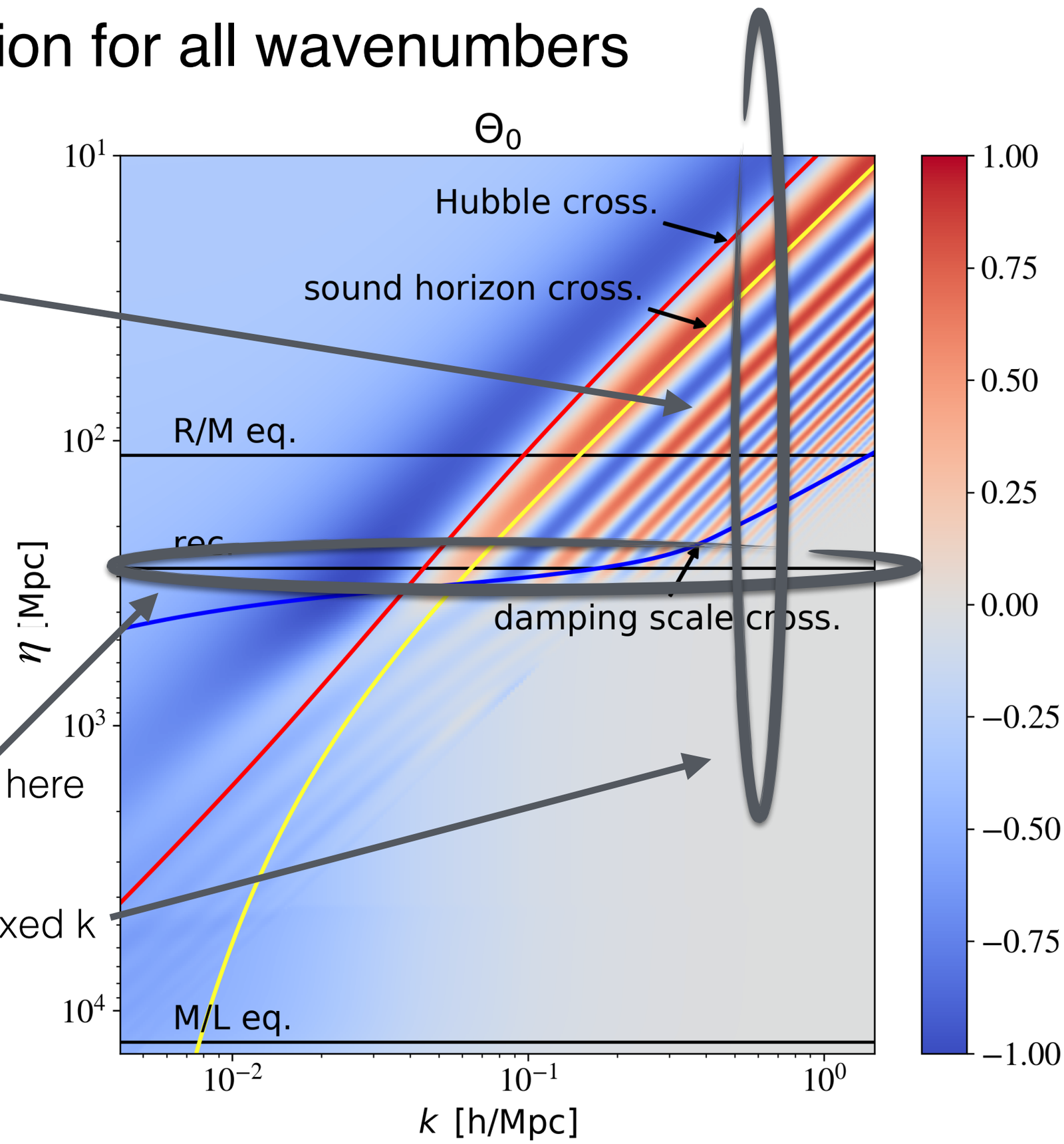
Evolution for all wavenumbers

45° symmetry comes from

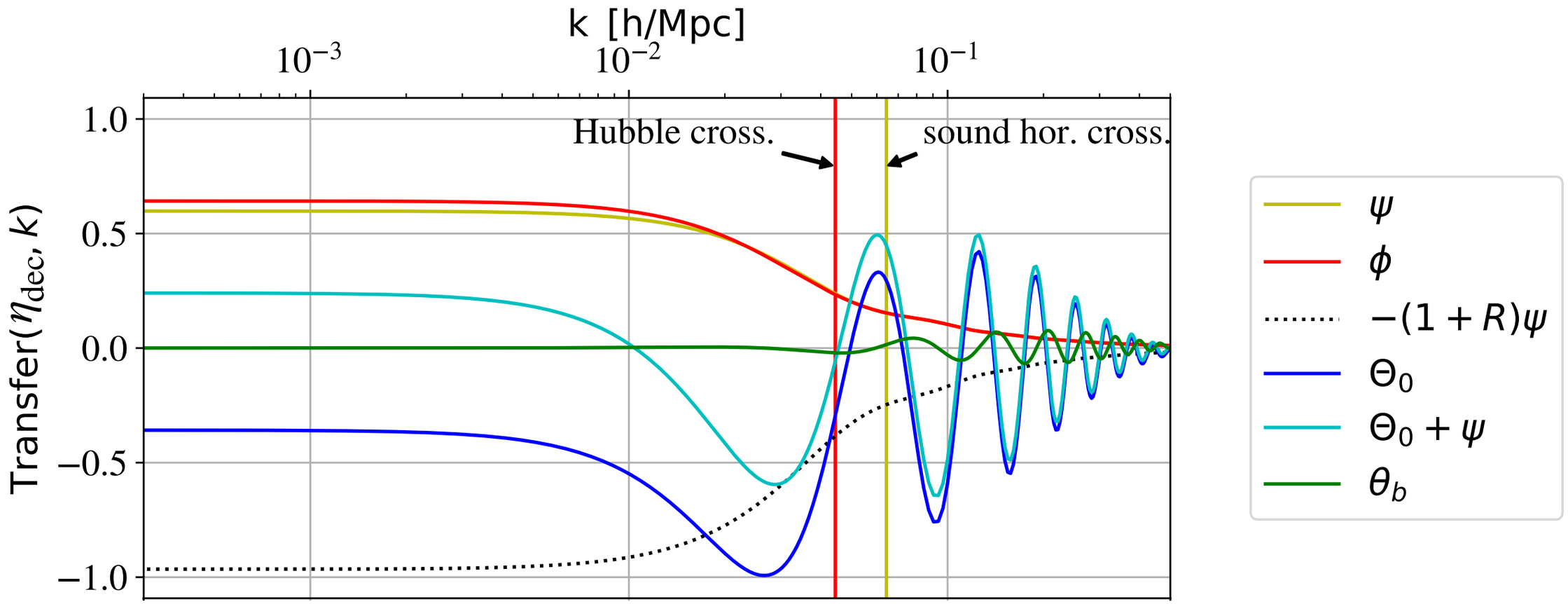
$$\cos(kc_s\eta)$$

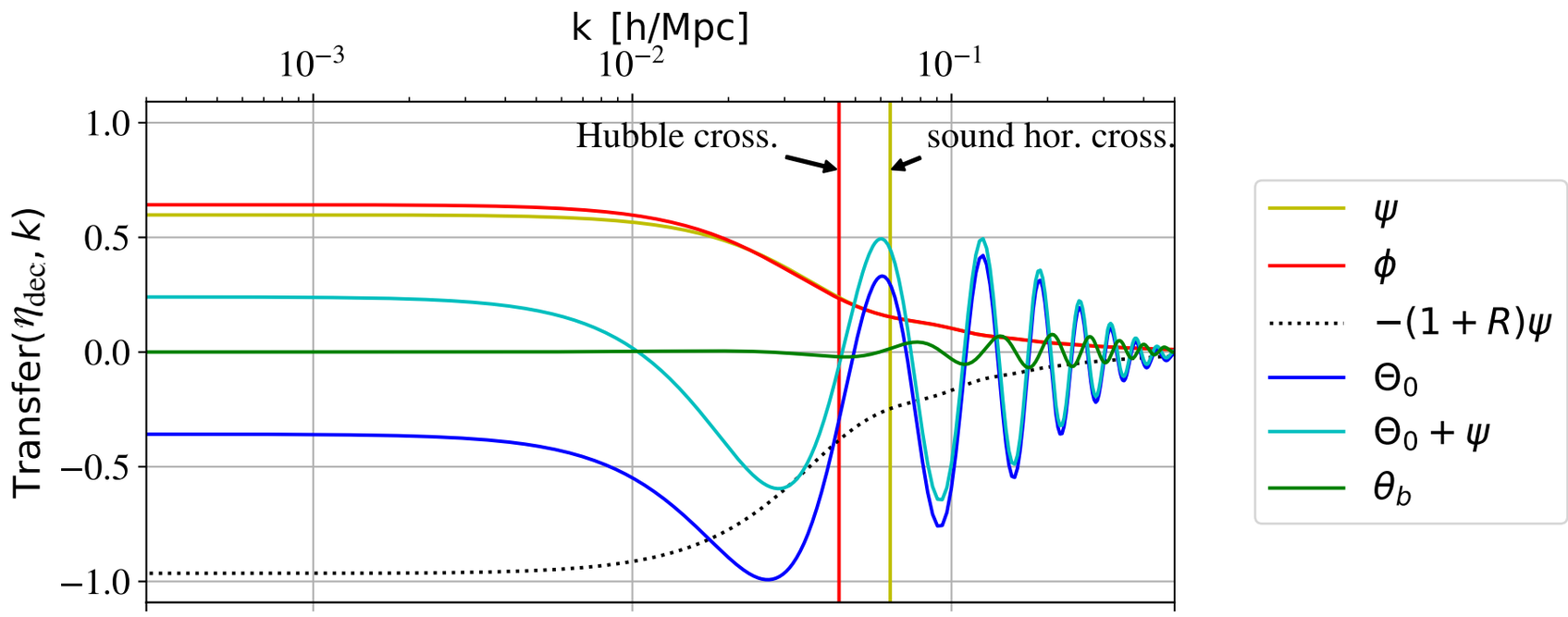
CMB patterns mainly come from here

fixed time will look like previous fixed k



Transfer functions at recombination/decoupling





from transfer to C_ℓ :

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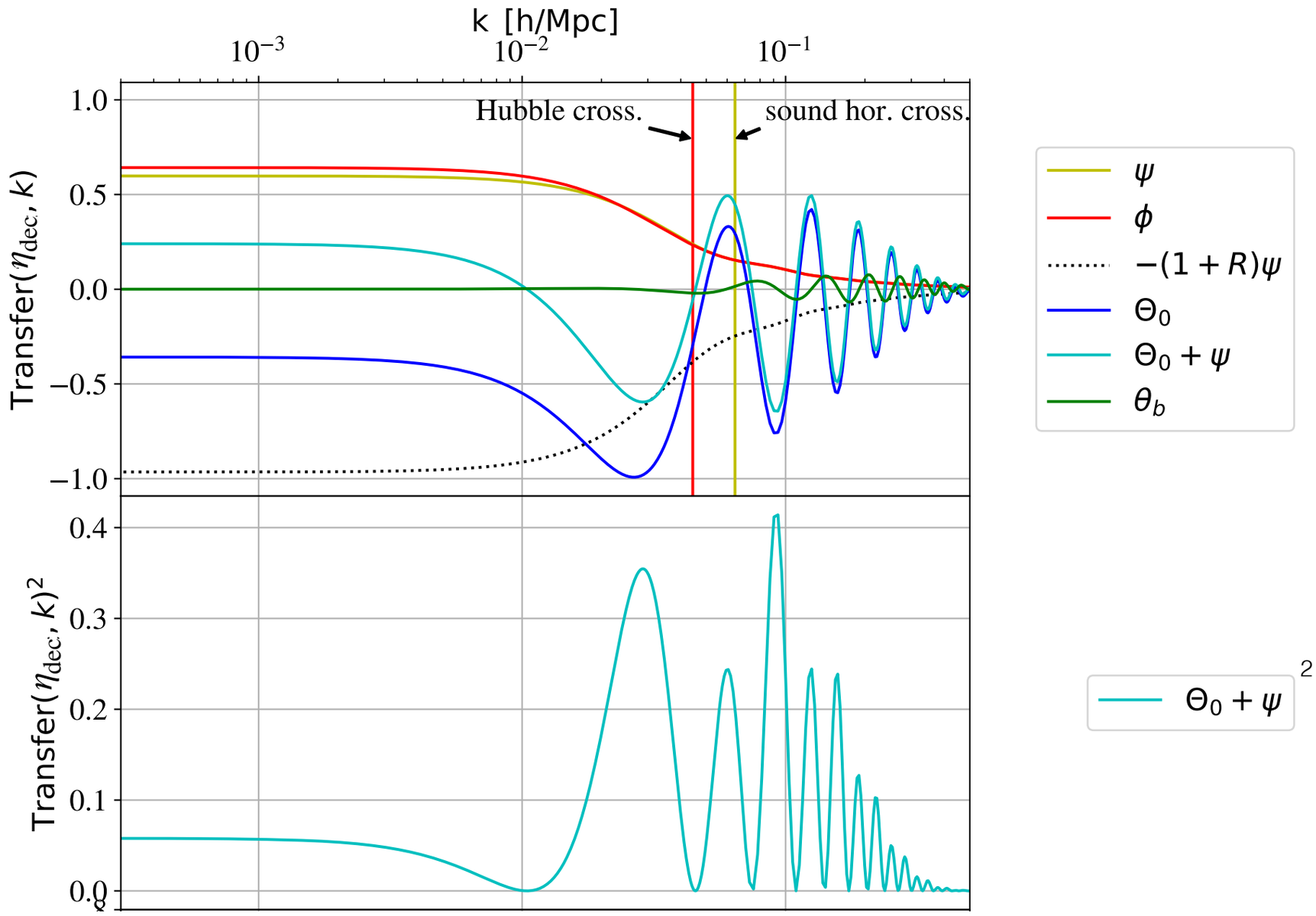
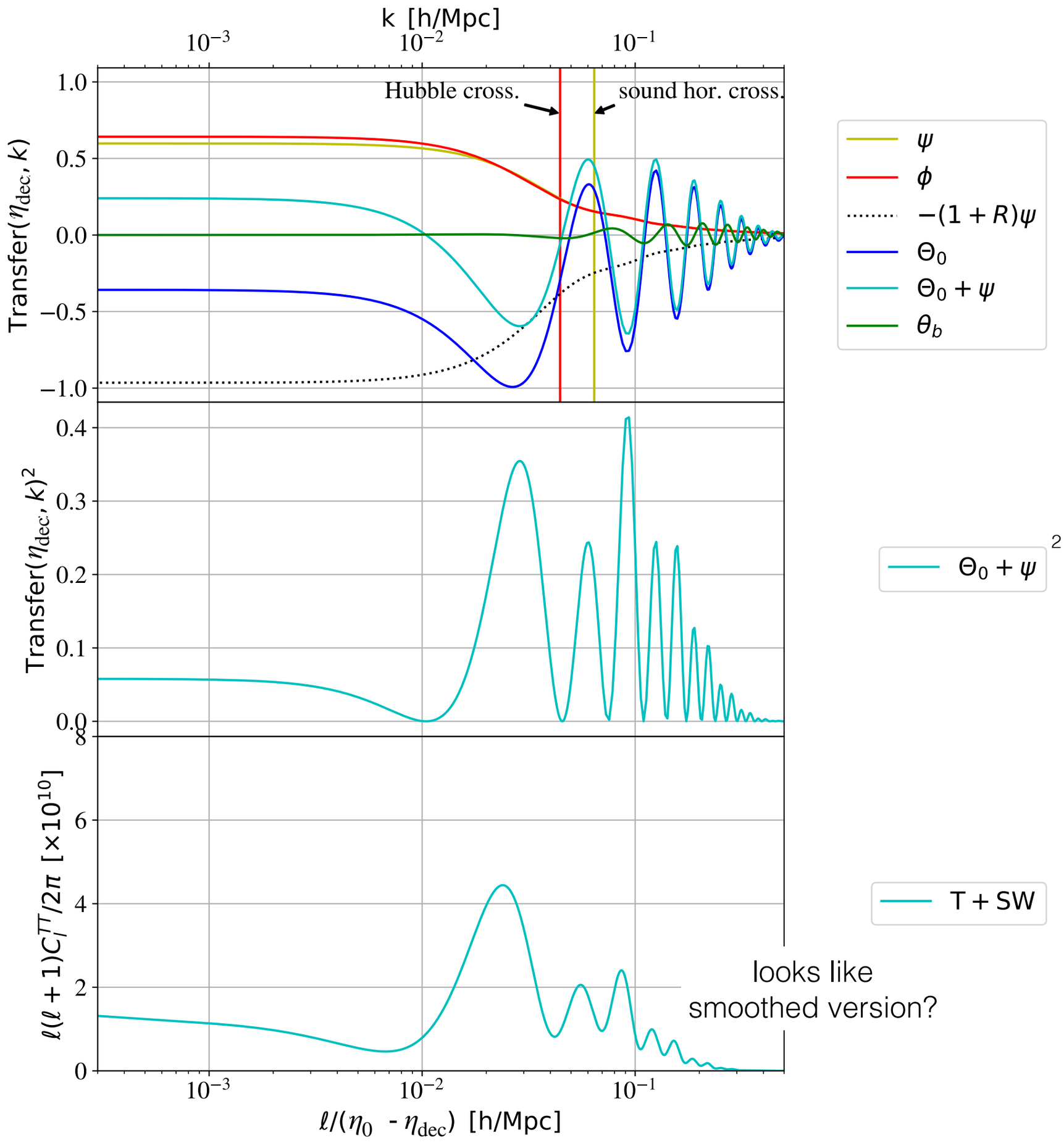


from transfer to C_ℓ :

$$\Theta_0(\eta_{\rm dec}, k) + \psi(\eta_{\rm dec}, k)$$

independent of k would give $l(l+1)C_l =$ constant



looks like smoothed version?

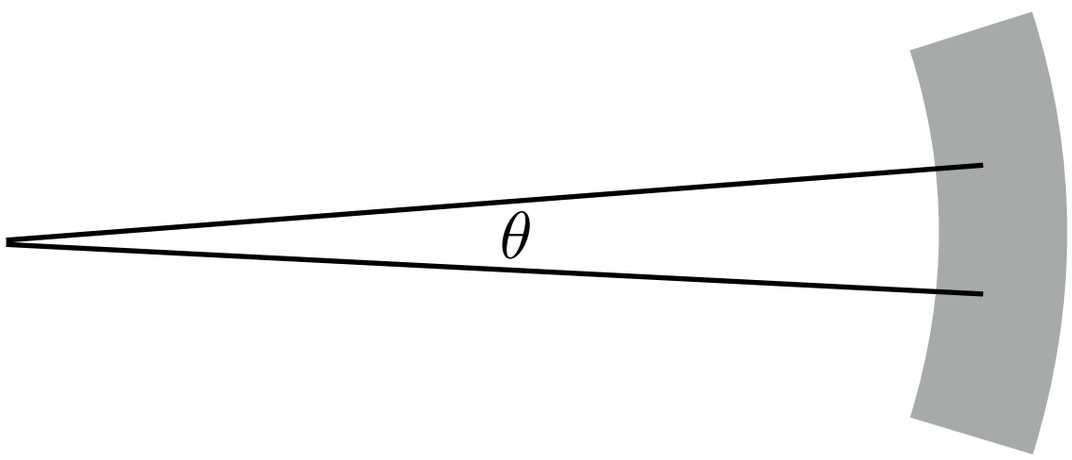
Projection effects

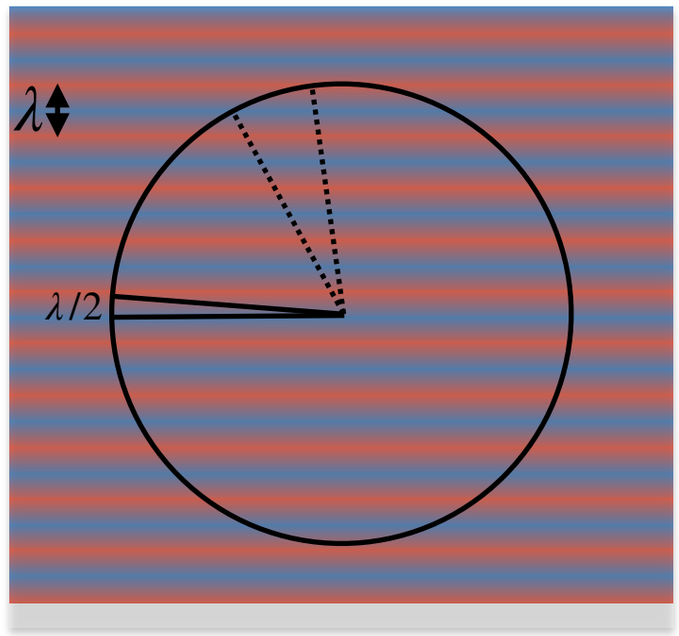
- two reasons for smoothing when going from k-space to l-space:

$$\Theta_l(\eta_0,k) = \int_{\eta_{\rm ini}}^{\eta_0} d\eta \left(g\,(\Theta_0+\psi) + \ldots \right) j_l(k(\eta_0-\eta))$$

$$C_l \equiv \langle |a_{lm}|^2 \rangle = \frac{1}{2\pi^2} \int \frac{dk}{k} \Theta_l^2(\eta_0,k) \mathcal{P}_{\mathcal{R}}(k)$$

—> contribution of wide range of *times* and *wavenumber* to single C_l





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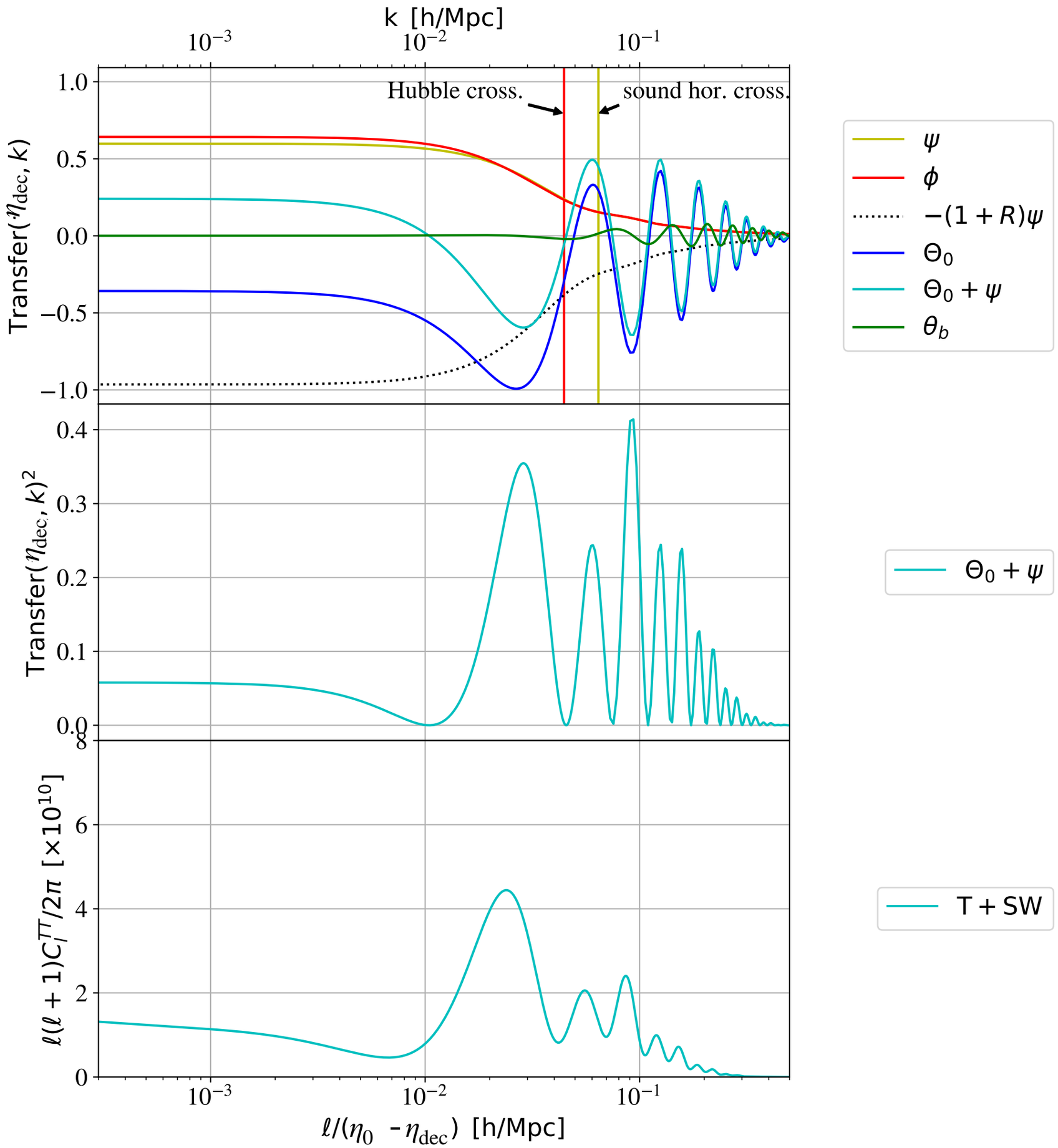


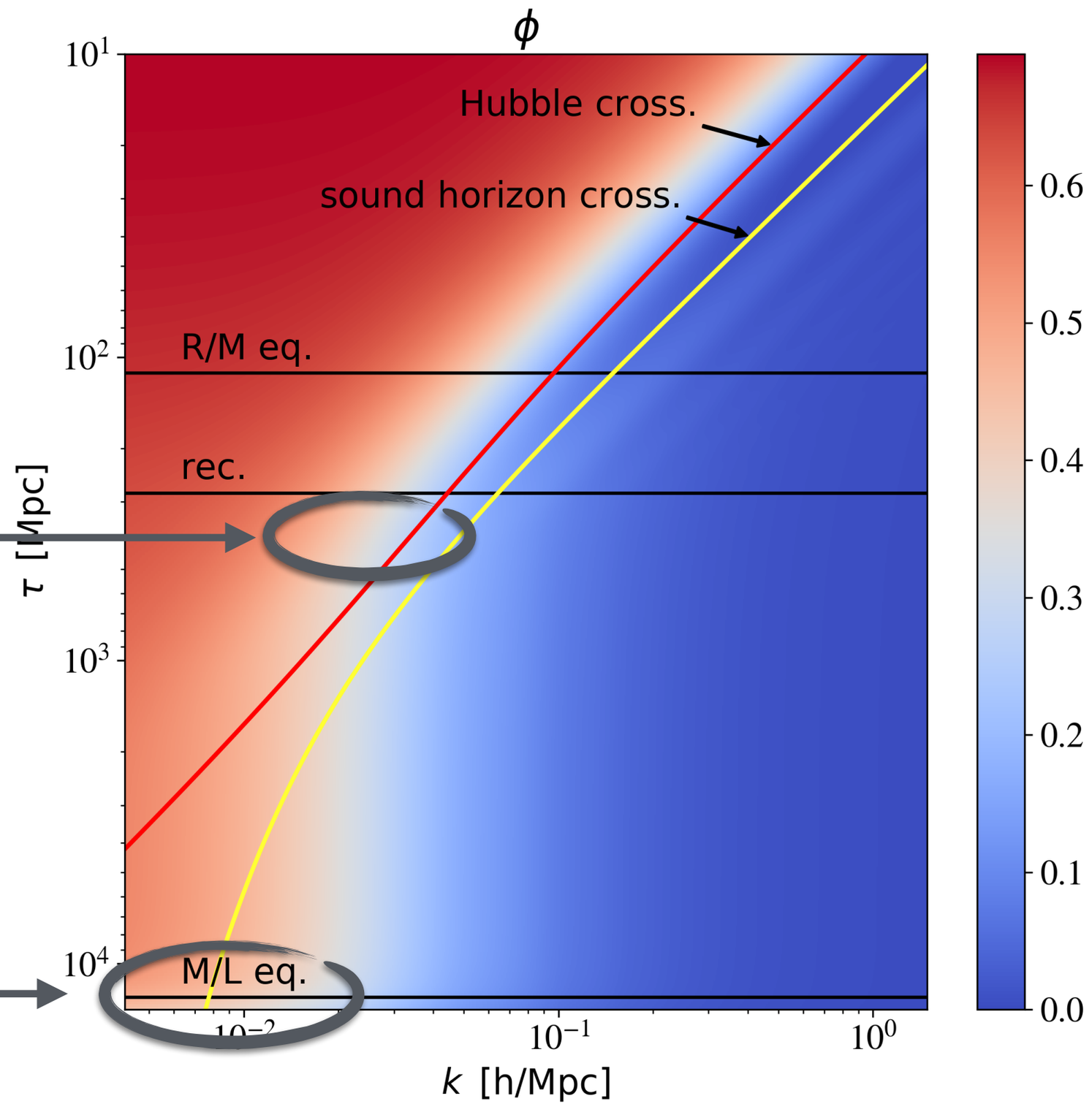
ISW contribution

$$\underbrace{e^{-\kappa}(\phi' + \psi')\}}_{\text{ISW}}$$

early ISW

$$\underbrace{e^{-\kappa}(\phi' + \psi')\}}_{\text{ISW}}$$

late ISW



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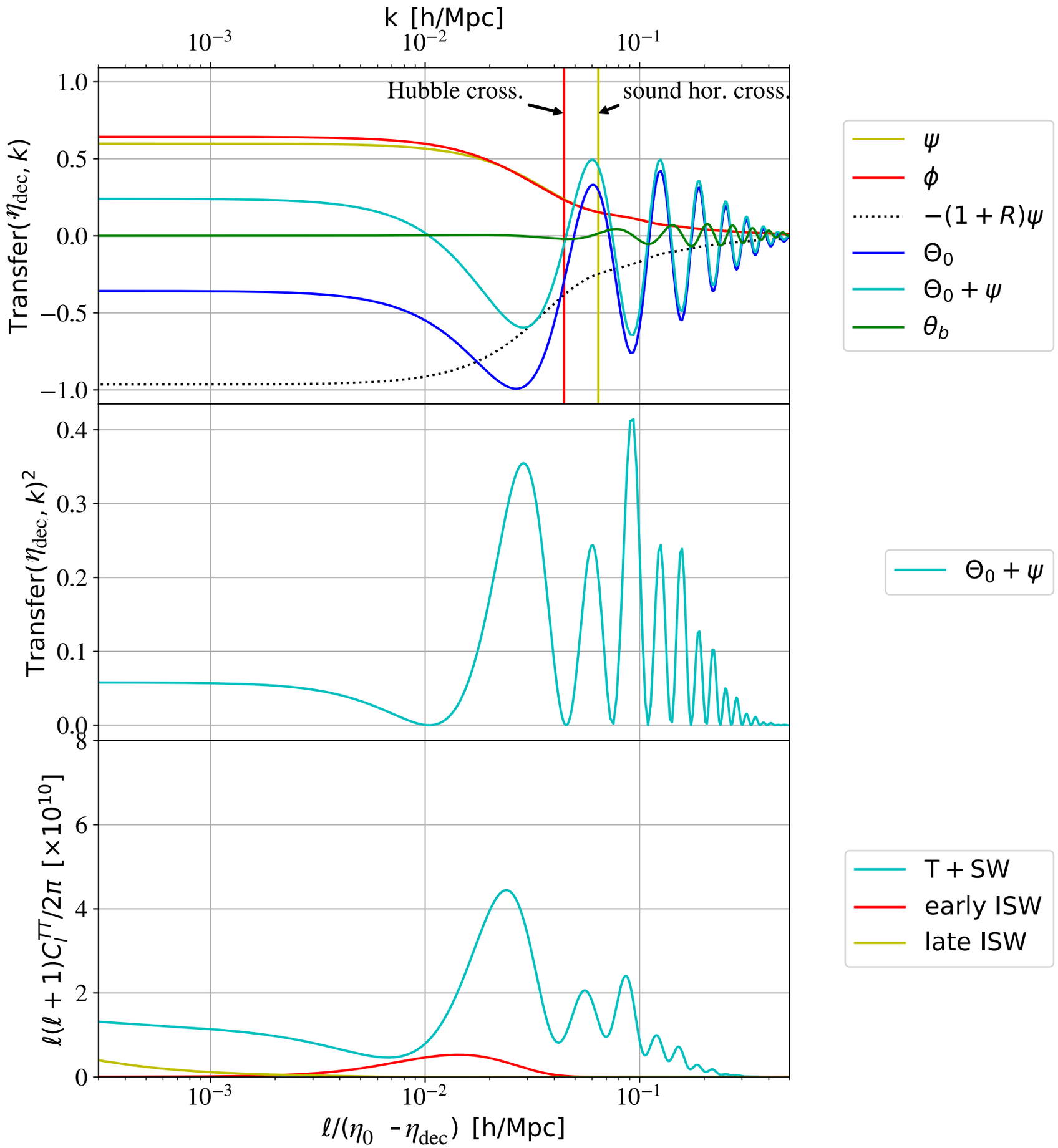

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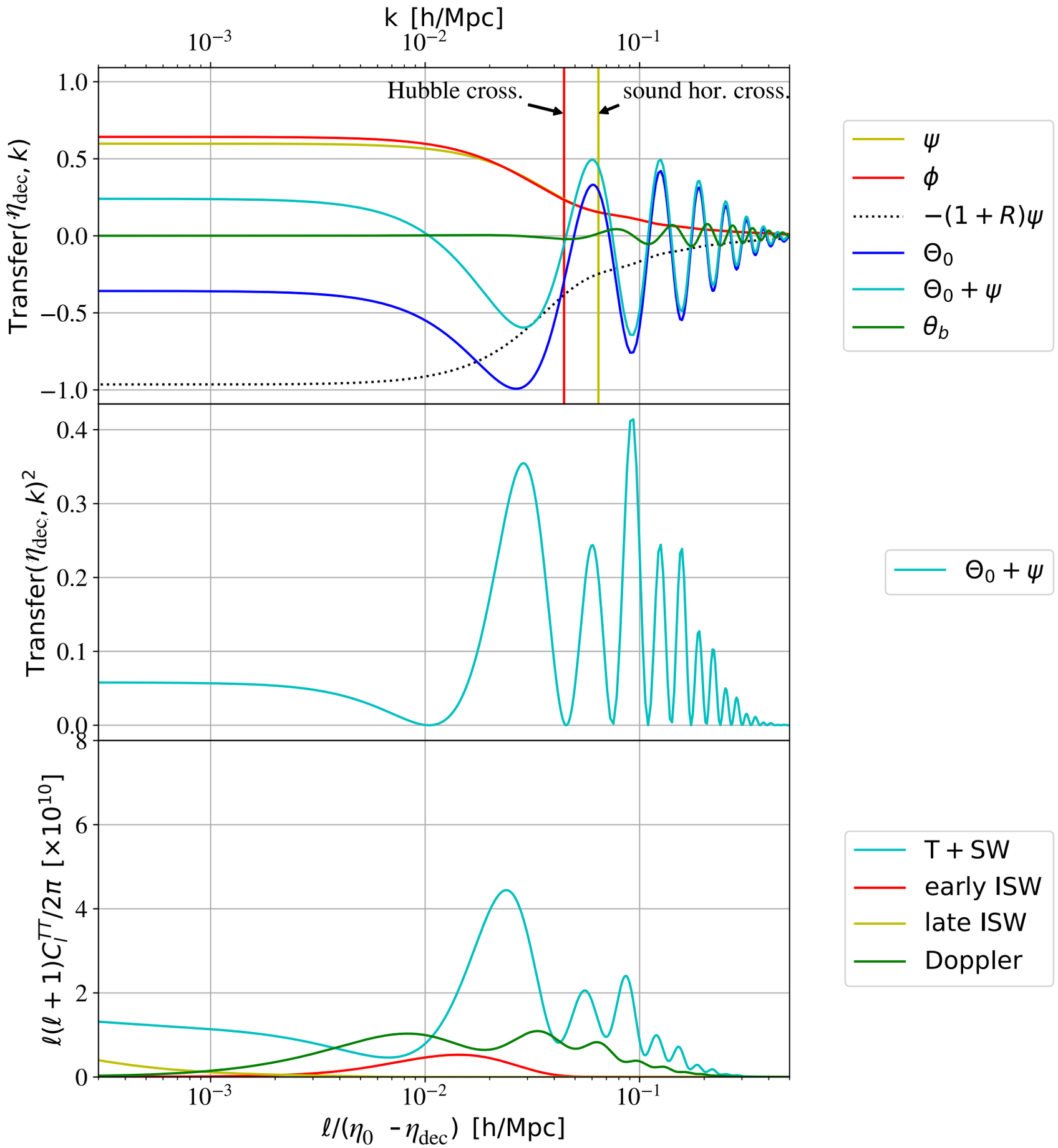

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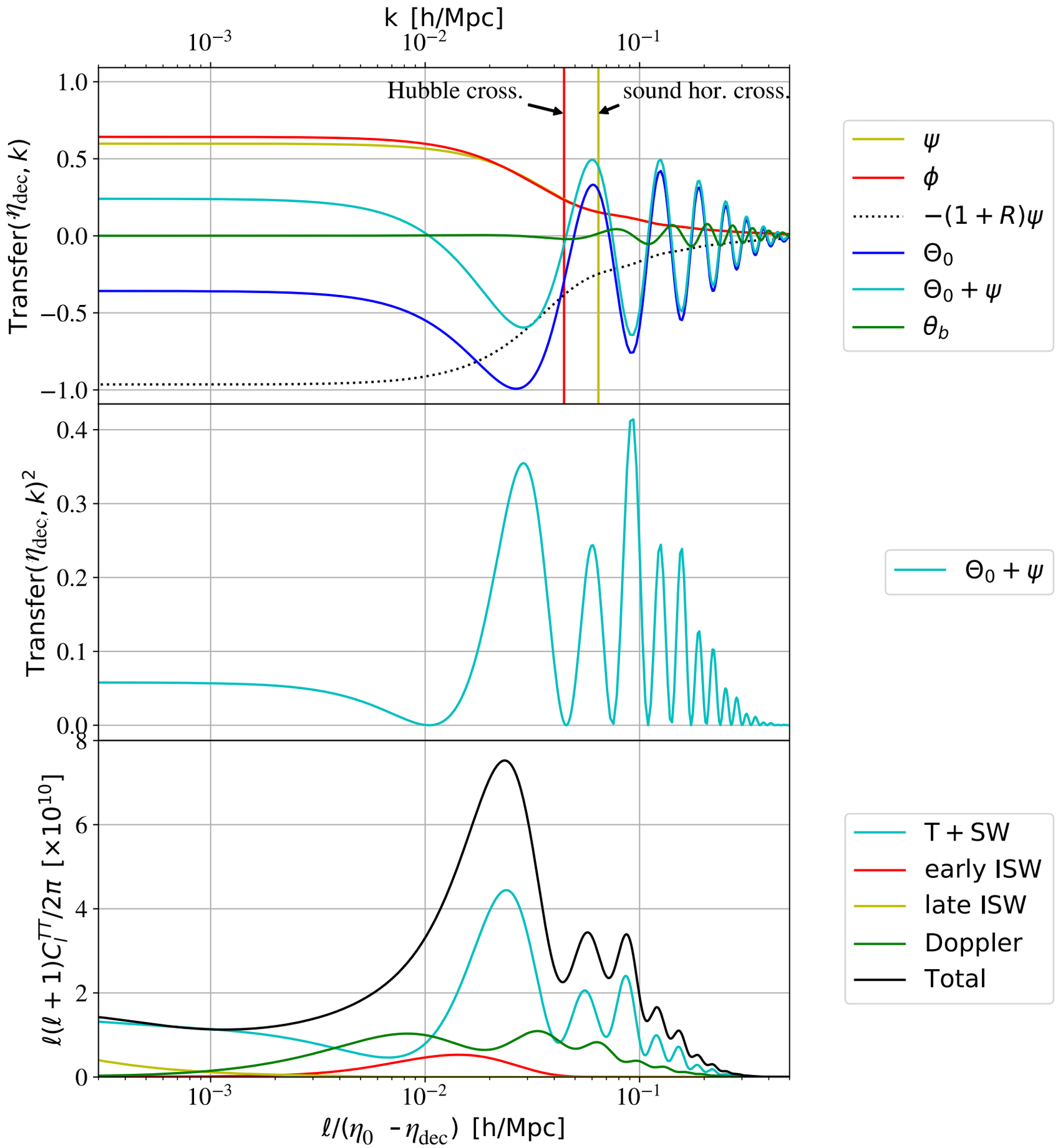


ΛCDM parameter effects on temperature spectrum

Why can we measure 6 ΛCDM parameters independently with CMB?

- Flat FLRW ($\Omega_k = 0$),
- Cosmological constant ($w = -1$),
- Plain decoupled / stable / cold dark matter,
- Neutrino mass neglected or fixed to minimal value,
- $N_{\rm eff} = 3.044$,
- Power-law primordial spectrum…

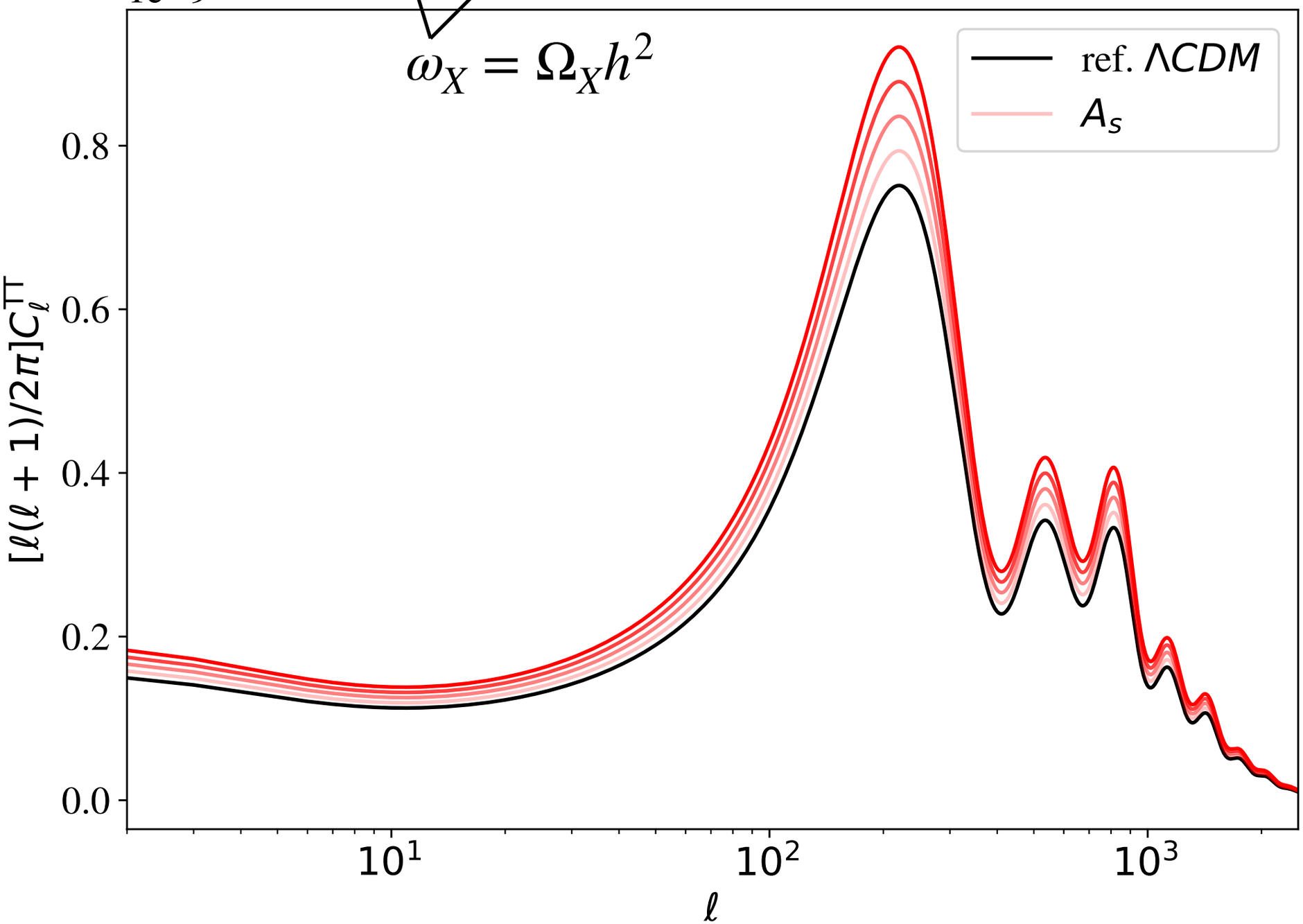
Possible basis: $\{\omega_b, \omega_m, \Omega_\Lambda, \tau_{\rm reio}, A_s, n_s\}$

$\omega_X = \Omega_X h^2$

parameter of CMB, not of LSS

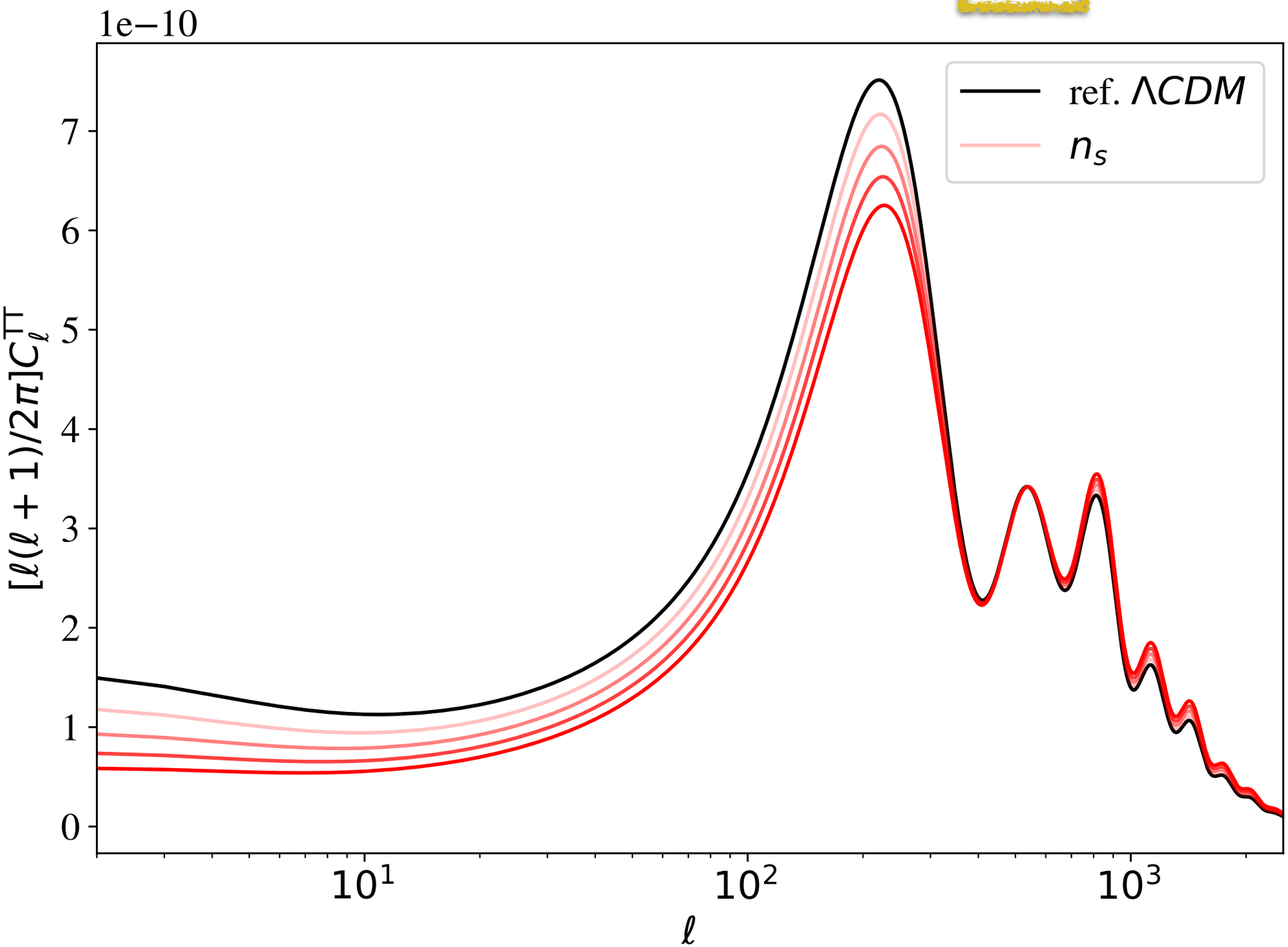
$$\{\omega_b, \omega_m, \Omega_\Lambda, \tau_{\rm reio}, A_s, n_s\}$$

$$\omega_X = \Omega_X h^2$$



$$C_l^{XY} = 4\pi \int dk\ k^2 \Delta_l^X(k) \Delta_l^Y(k) \mathcal{P}_\mathcal{R}(k) \qquad \mathcal{P}_\mathcal{R}(k) = A_s(k_*) \left(\frac{k}{k_*}\right)^{n_s - 1}$$

$$\{\omega_b, \omega_m, \Omega_\Lambda, \tau_{\rm reio}, A_s, n_s\}$$



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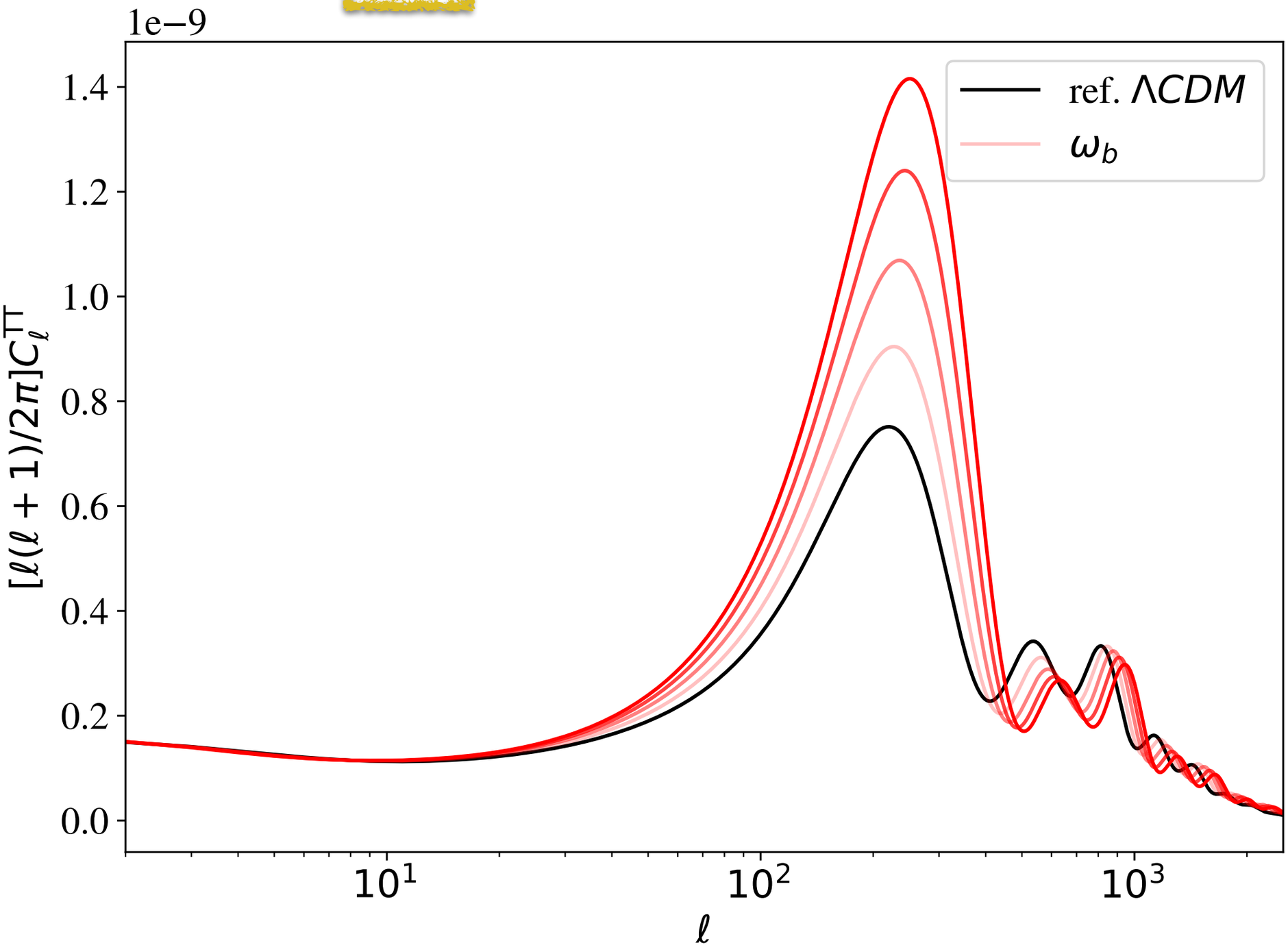

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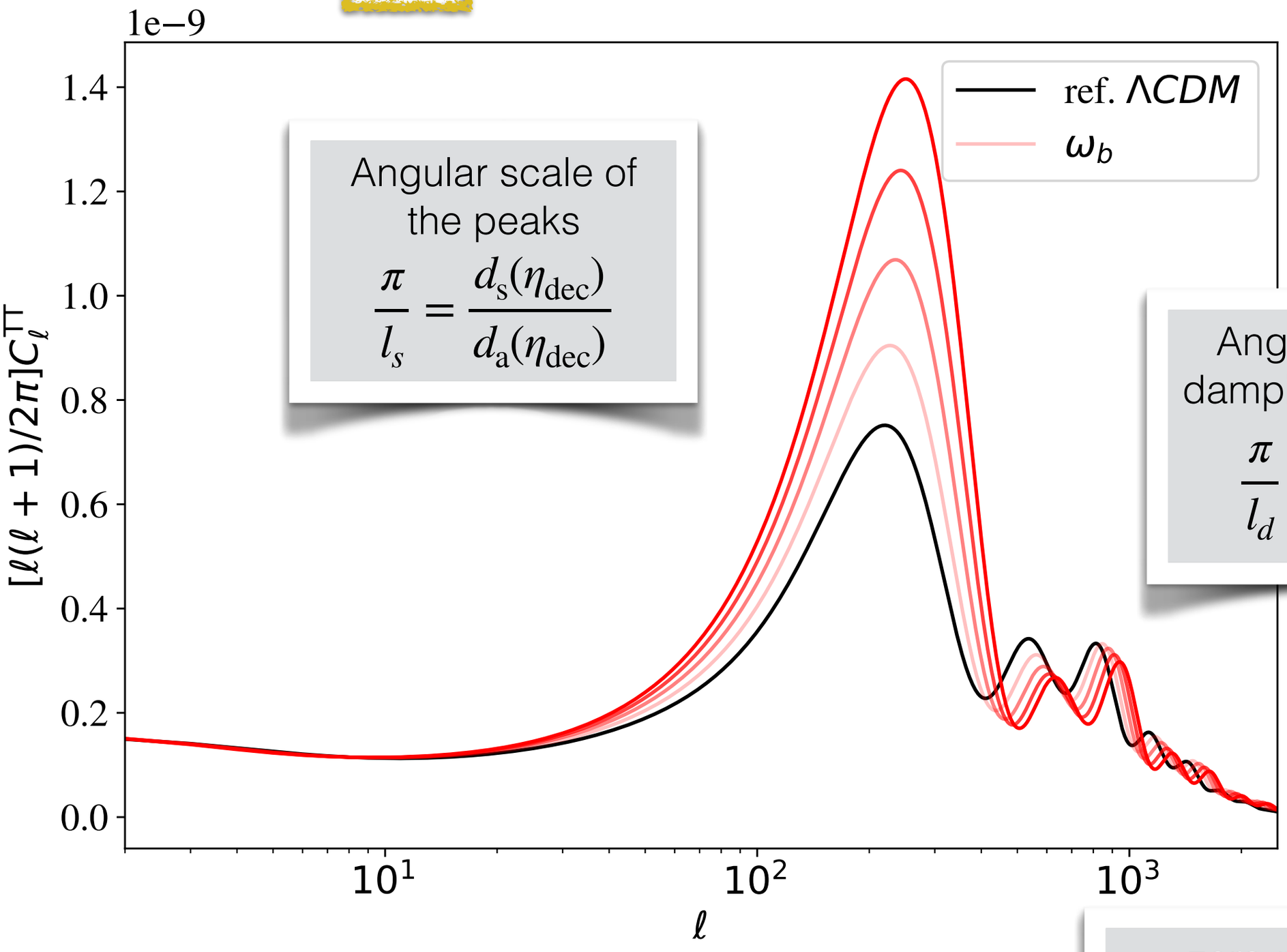


Angular scale of the peaks

$$\frac{\pi}{l_s} = \frac{d_{\rm s}(\eta_{\rm dec})}{d_{\rm a}(\eta_{\rm dec})}$$

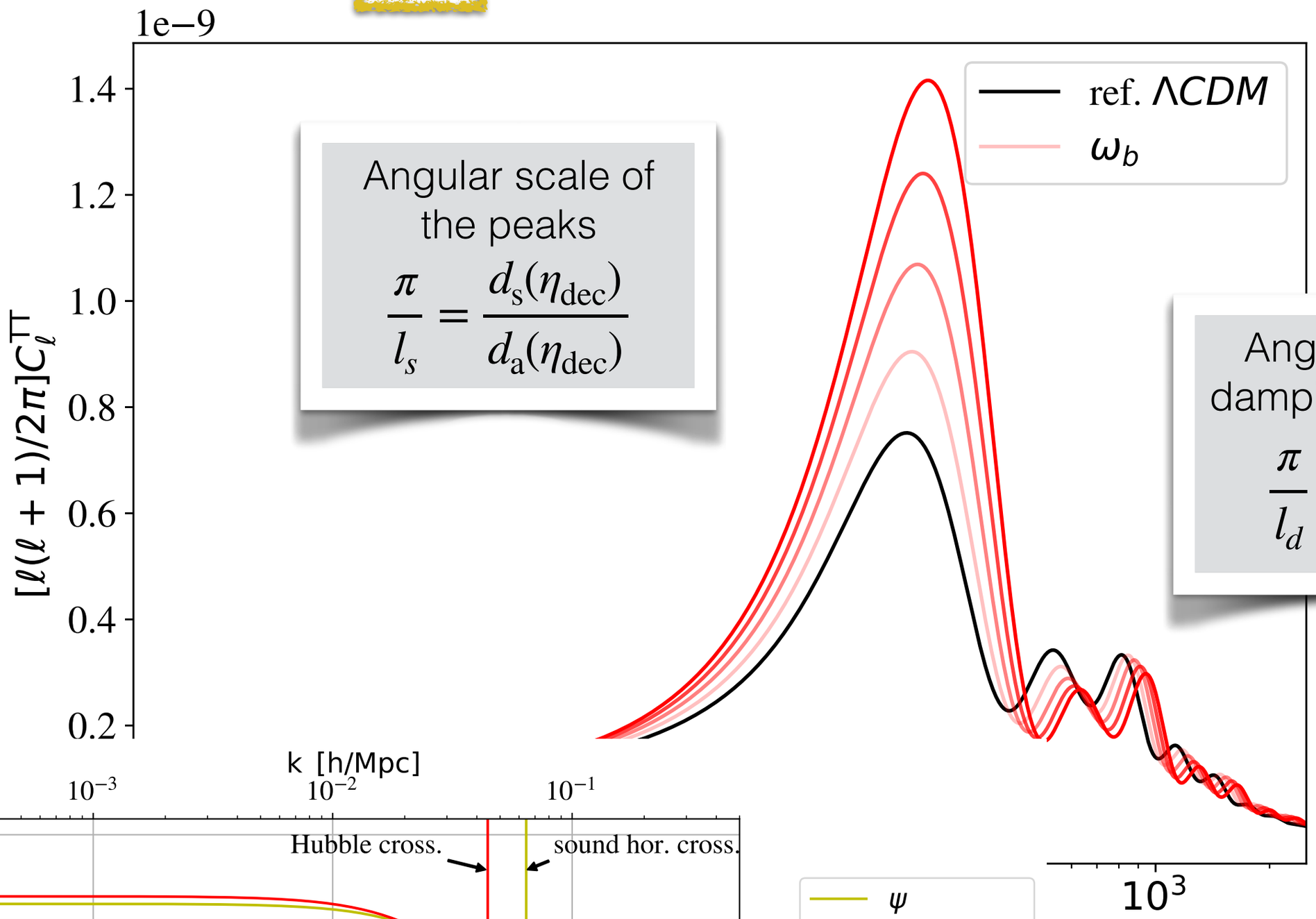
Angular scale of damping enveloppe

$$\frac{\pi}{l_d} = \frac{\lambda_{\rm d}(\eta_{\rm dec})}{d_{\rm a}(\eta_{\rm dec})}$$

zero-point of oscillations

$$-(1+R)\,\psi$$

$$\{\omega_b, \omega_m, \Omega_\Lambda, \tau_{\rm reio}, A_s, n_s\}$$



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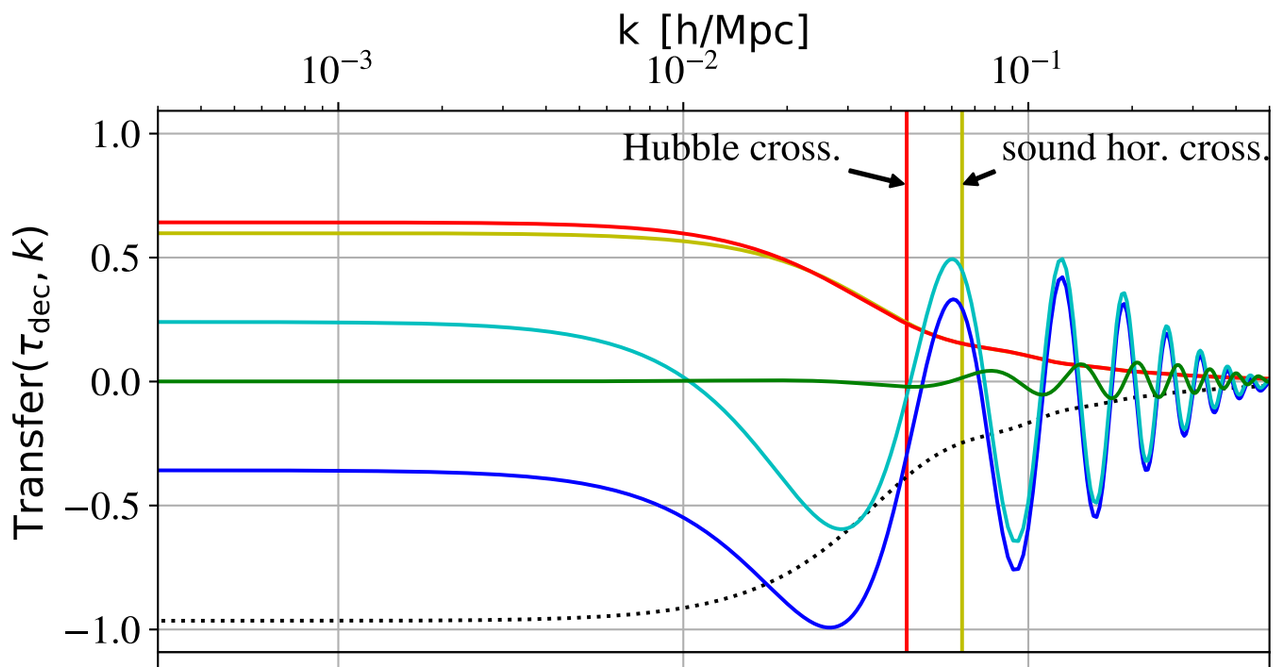

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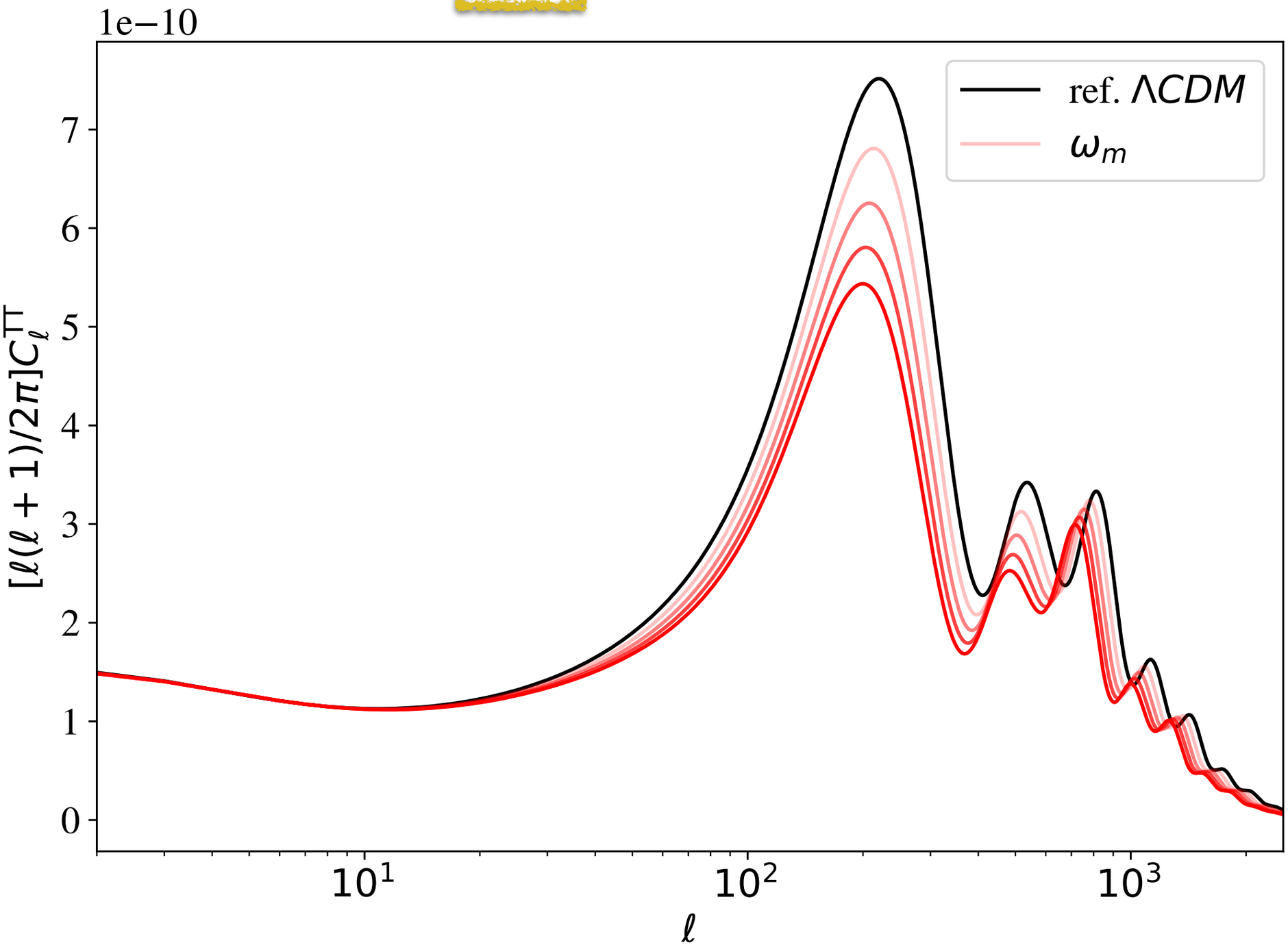

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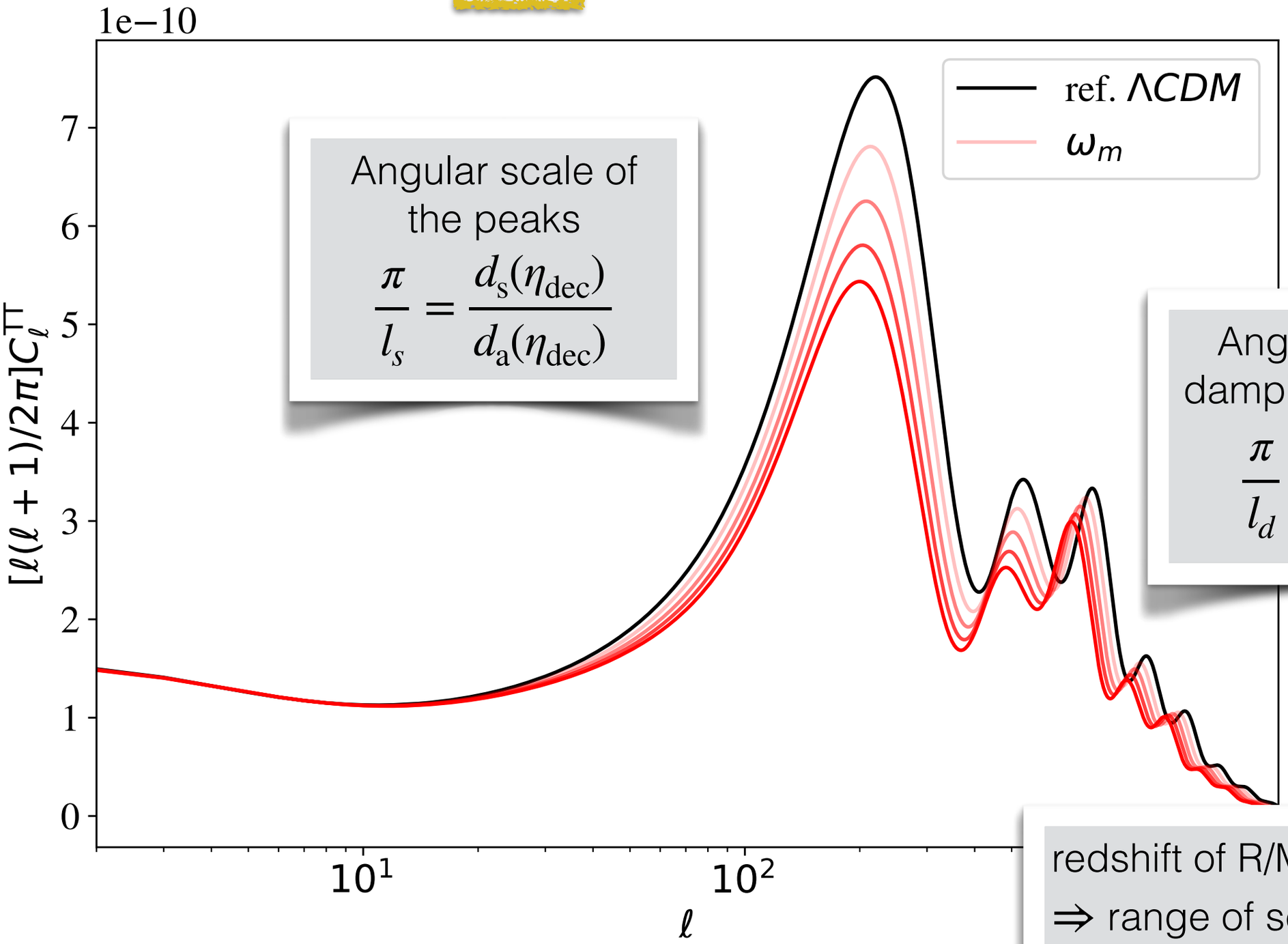

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redshift of R/M equality $z_{\rm eq}$:

⇒ range of scales affected by gravitational boost

⇒ early ISW

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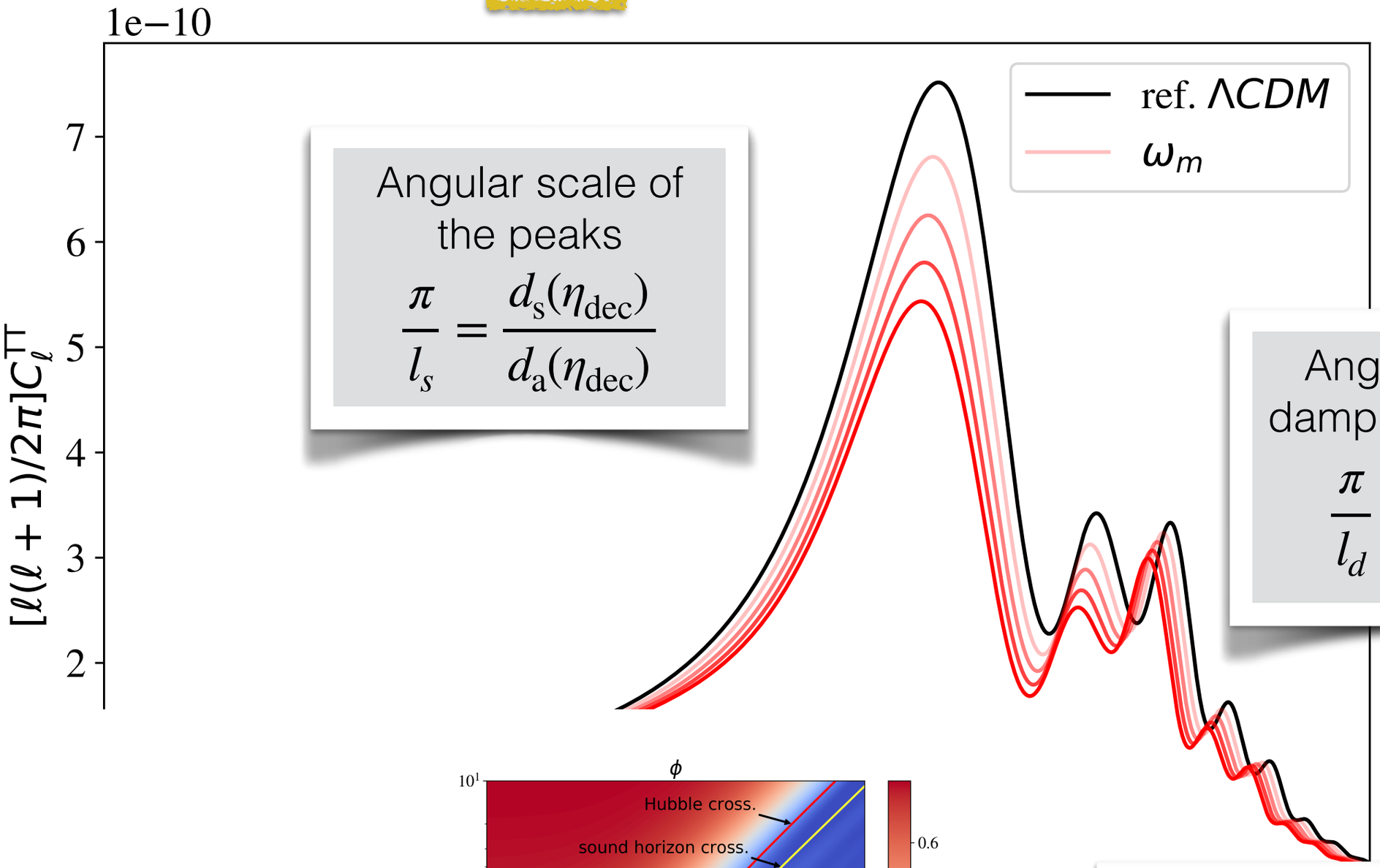
$$\{\omega_b, \omega_m, \Omega_\Lambda, \tau_{\rm reio}, A_s, n_s\}$$



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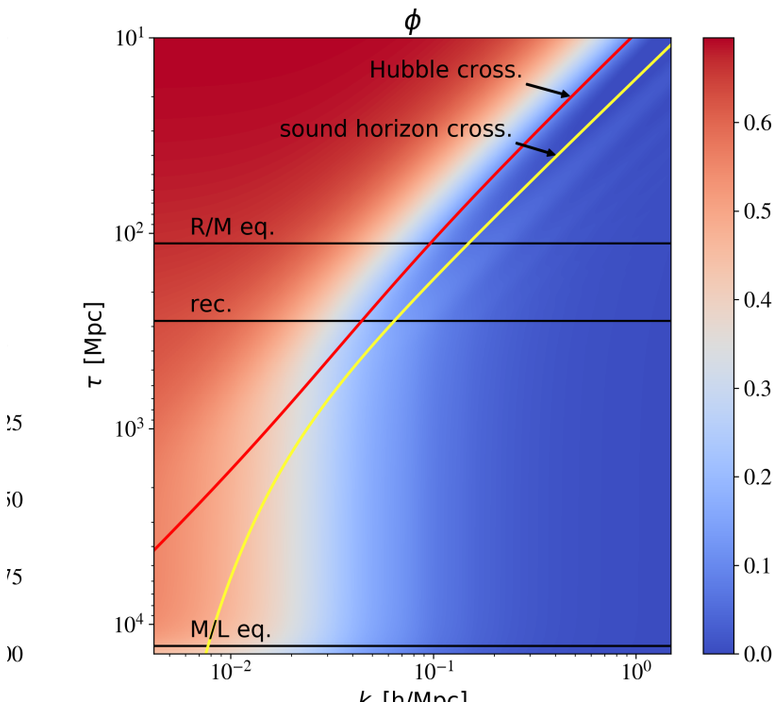

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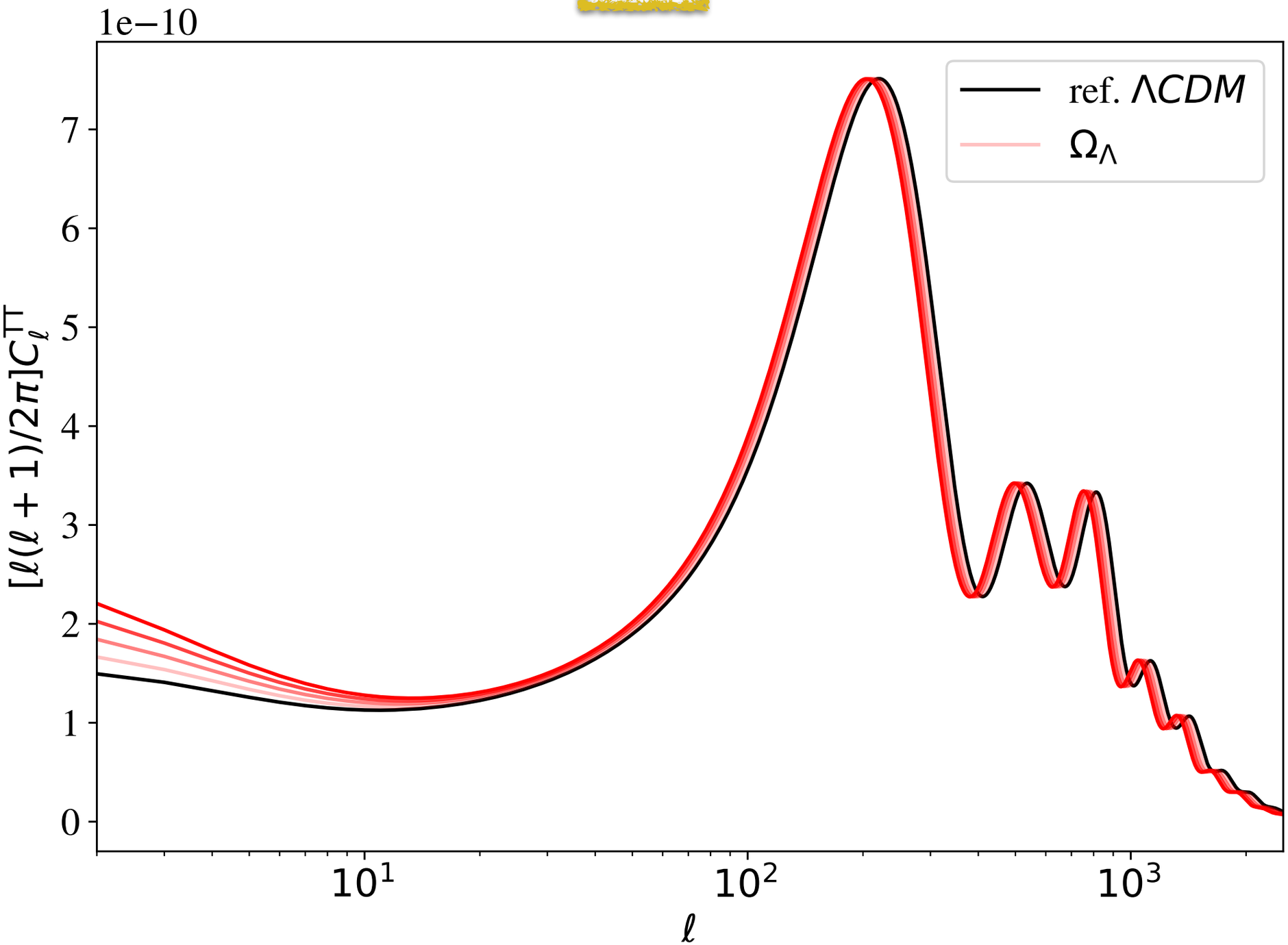
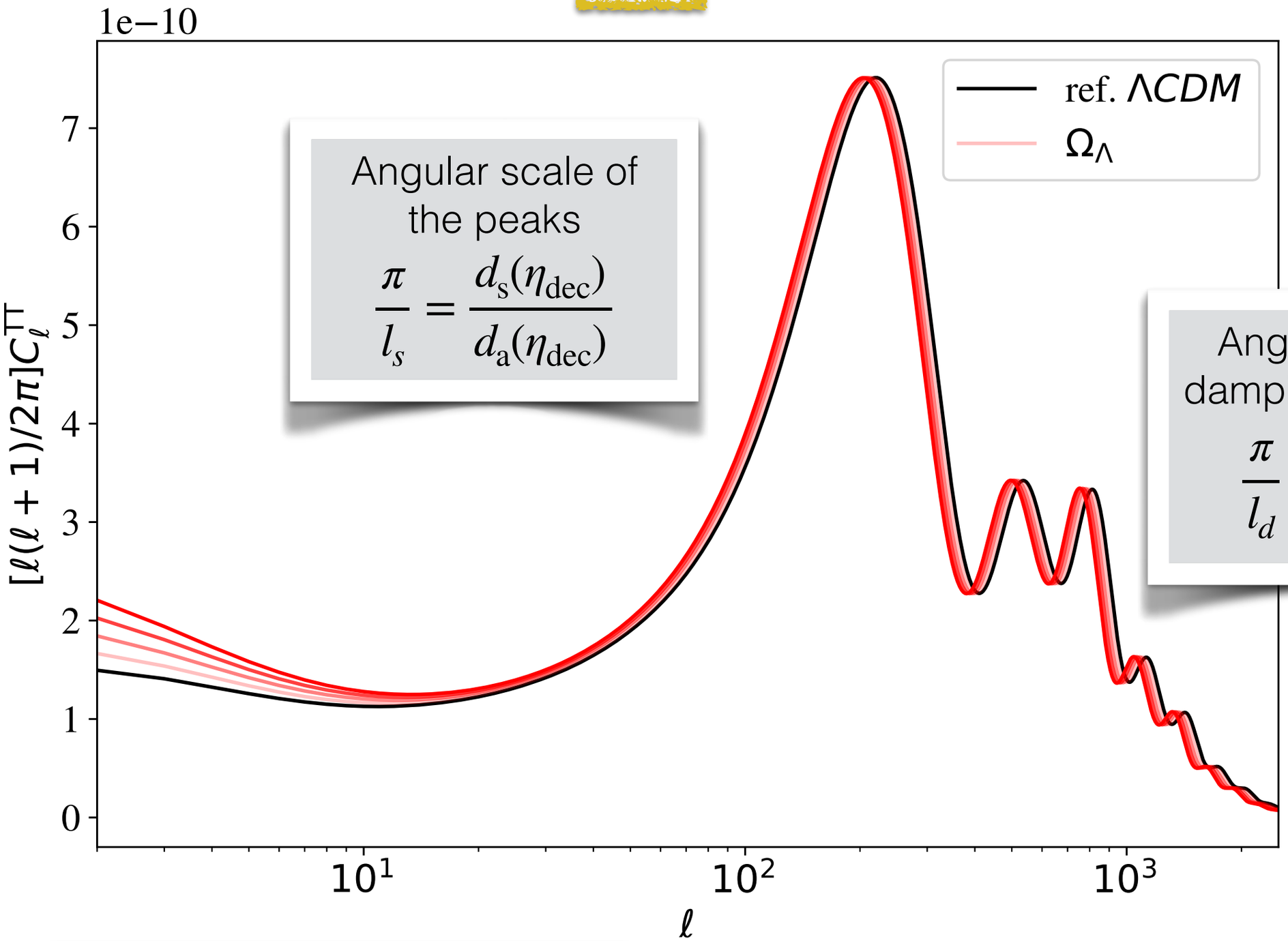


$$\{\omega_b, \omega_m, \Omega_\Lambda, \tau_{\rm reio}, A_s, n_s\}$$



Angular scale of the peaks

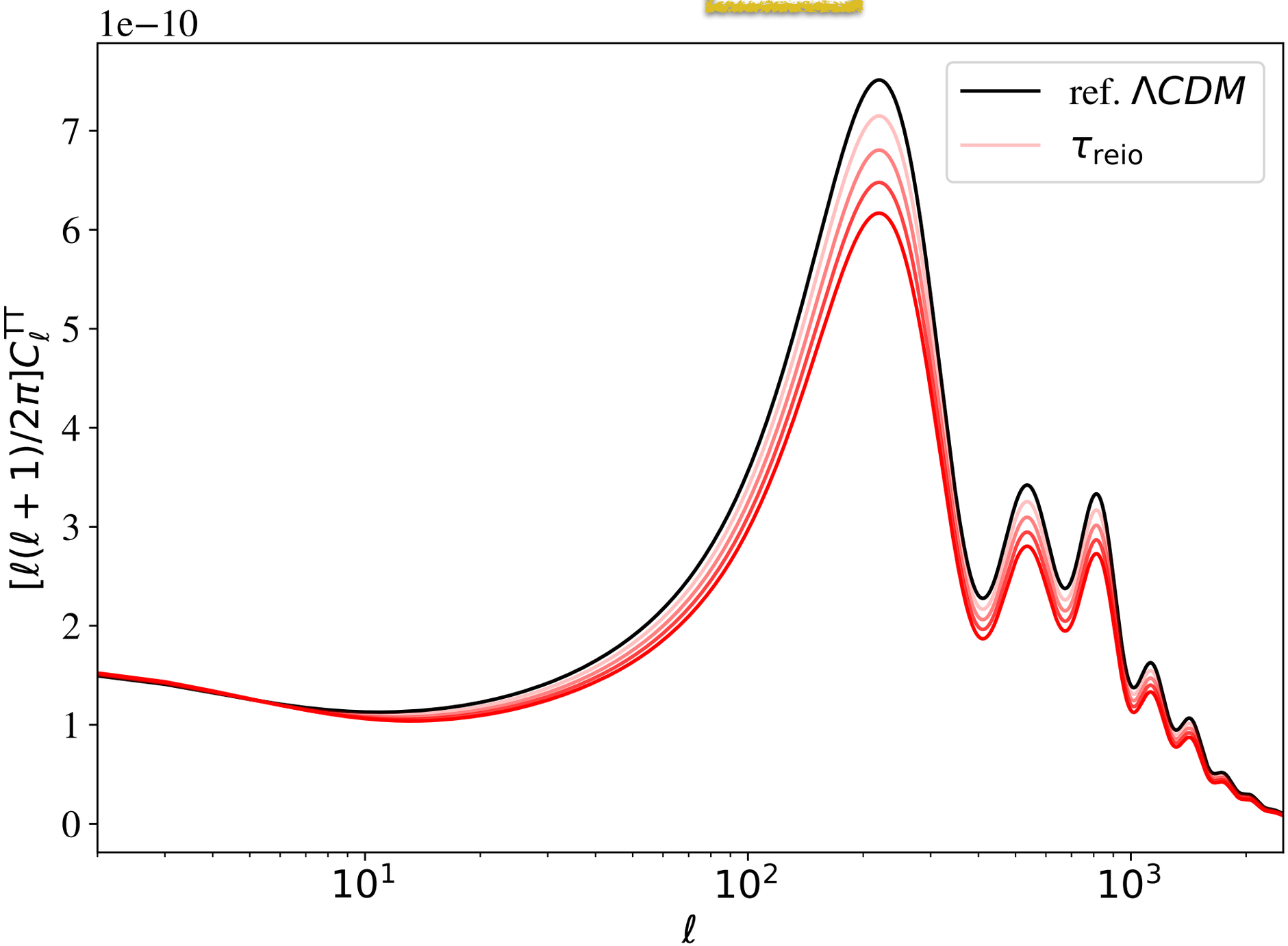
$$\frac{\pi}{l_s} = \frac{d_{\rm s}(\eta_{\rm dec})}{d_{\rm a}(\eta_{\rm dec})}$$

Angular scale of damping enveloppe

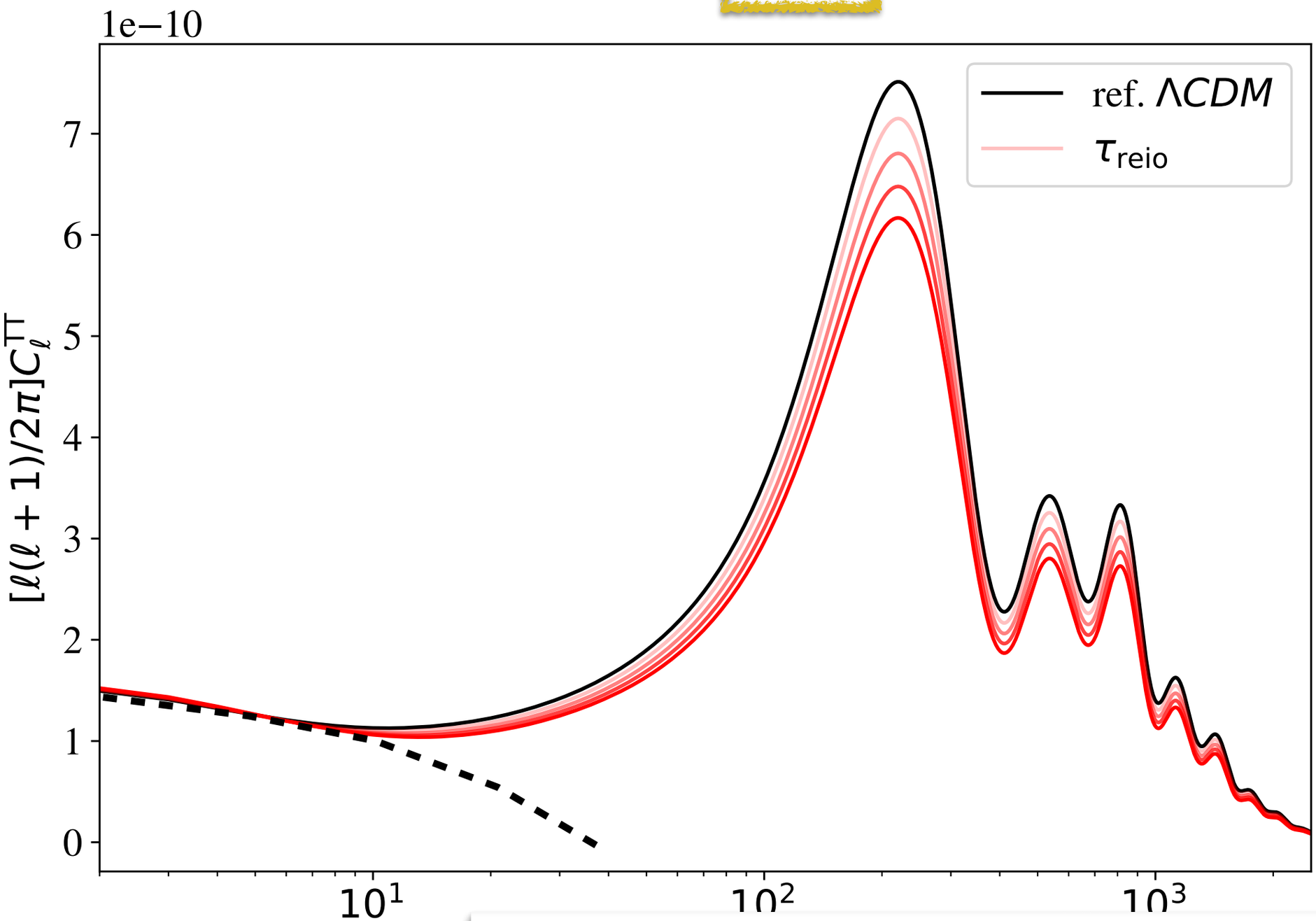
$$\frac{\pi}{l_d} = \frac{\lambda_{\rm d}(\eta_{\rm dec})}{d_{\rm a}(\eta_{\rm dec})}$$

redshift of M/Λ equality $z_{\rm eq}$:
⇒ late ISW

$$\{\omega_b, \omega_m, \Omega_\Lambda, \tau_{\rm reio}, A_s, n_s\}$$



$$\{\omega_b, \omega_m, \Omega_\Lambda, \tau_{\rm reio}, A_s, n_s\}$$

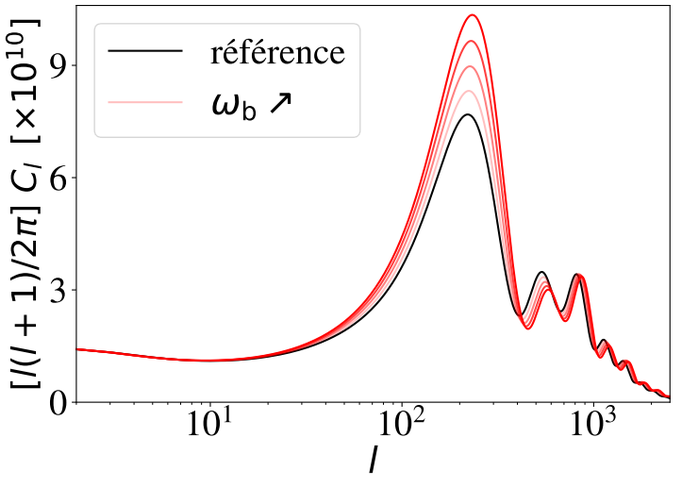


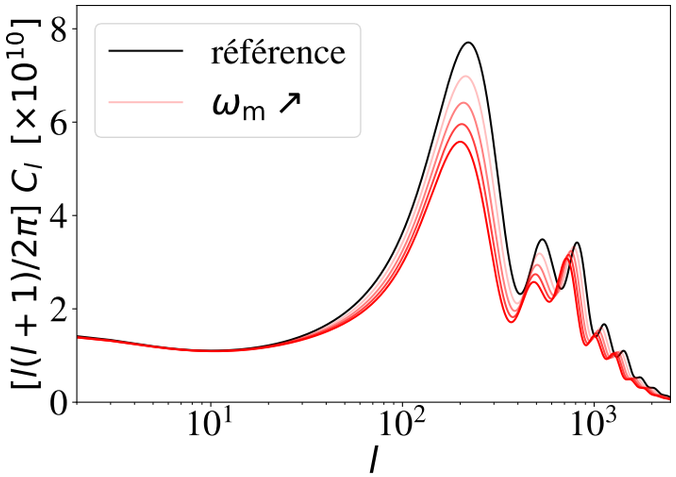
Visibility function

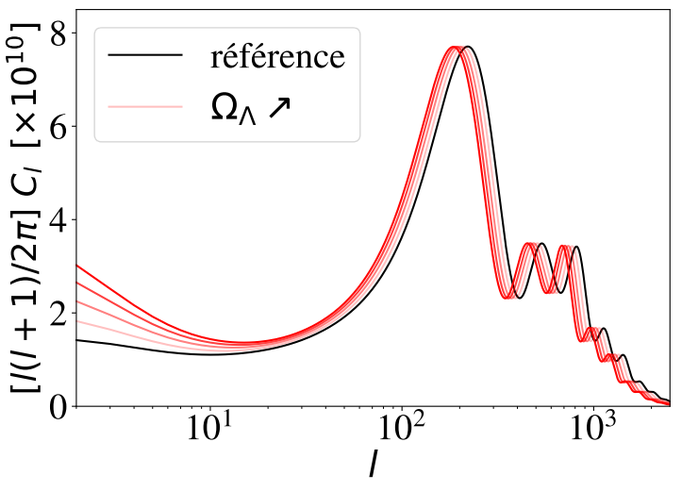
$$g(\eta) \simeq \delta(\eta - \eta_{\rm dec})$$

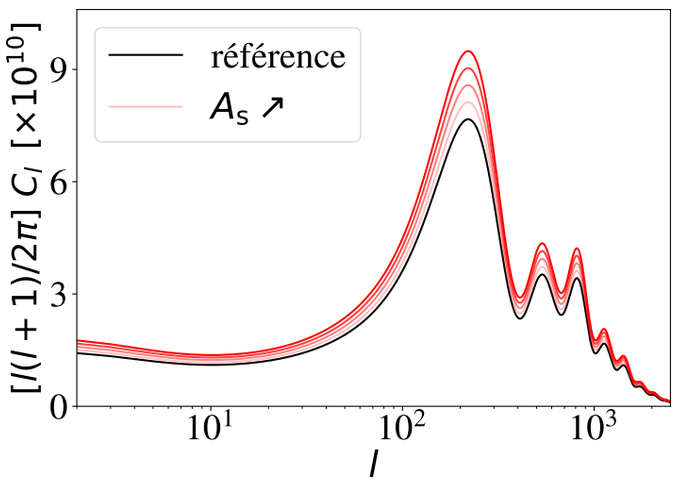
$$\downarrow$$

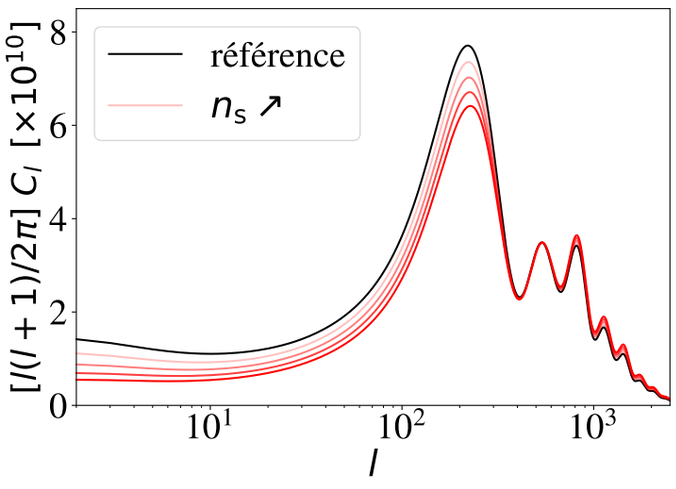
$$g(\eta) \simeq e^{-\tau_{\rm reio}}\,\delta(\eta - \eta_{\rm dec}) + (1 - e^{-\tau_{\rm reio}})\,\delta(\eta - \eta_{\rm reio})$$

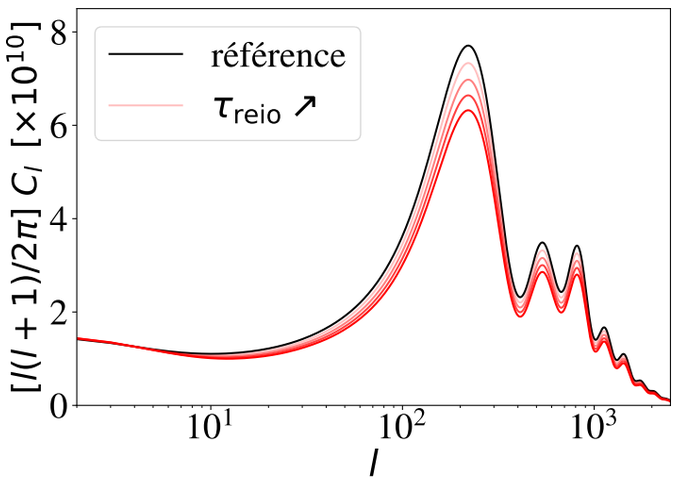












8 physical governing C_l's shape

- C1: angular scale of the peaks, θ_s
- C2: gravity/pressure at rec., R_{rec}
- C3: interval between z_{eq} and z_{dec}
- C4: angular scale of damping, θ_d
- C5: global amplitude
- C6: global tilt
- C7: plateau tilting by late ISW
- C8: reionisation steplike suppression

but all tight to 6 parameters in ΛCDM

Extended cosmologies? … more parameters … but also more effects …