

*Astro 448*

Lecture Notes *Set 1*

Wayne Hu

# Recombination

- Equilibrium number density distribution of a non-relativistic species

$$n_i = g_i \left( \frac{m_i T}{2\pi} \right)^{3/2} e^{-m_i/T}$$

- Apply to the  $e^- + p \leftrightarrow H$  system: Saha Equation

$$\begin{aligned} \frac{n_e n_p}{n_H n_b} &= \frac{x_e^2}{1 - x_e} \\ &= \frac{1}{n_b} \left( \frac{m_e T}{2\pi} \right)^{3/2} e^{-B/T} \end{aligned}$$

where  $B = m_e + m_p - m_H = 13.6\text{eV}$

- Naive guess of  $T = B$  for recombination would put  $z_* \approx 45000$ .

# Recombination

- But the photon-baryon ratio is very low

$$\eta_{b\gamma} \equiv n_b/n_\gamma \approx 3 \times 10^{-8} \Omega_b h^2$$

- Eliminate in favor of  $\eta_{b\gamma}$  and  $B/T$  through

$$n_\gamma = 0.244T^3, \quad \frac{m_e}{B} = 3.76 \times 10^4$$

- Big coefficient

$$\frac{x_e^2}{1 - x_e} = 3.16 \times 10^{15} \left( \frac{B}{T} \right)^{3/2} e^{-B/T}$$

$$T = 1/3\text{eV} \rightarrow x_e = 0.7, \quad T = 0.3\text{eV} \rightarrow x_e = 0.2$$

- Further delayed by inability to maintain equilibrium since net is through  $2\gamma$  process and redshifting out of line

# Thomson Scattering

- Thomson scattering of photons off of free electrons is the most important CMB process with a cross section (averaged over polarization states) of

$$\sigma_T = \frac{8\pi\alpha^2}{3m_e^2} = 6.65 \times 10^{-25} \text{cm}^2$$

- Density of free electrons in a fully ionized  $x_e = 1$  universe

$$n_e = (1 - Y_p/2)x_e n_b \approx 10^{-5} \Omega_b h^2 (1+z)^3 \text{cm}^{-3},$$

where  $Y_p \approx 0.24$  is the Helium mass fraction, creates a high (comoving) Thomson **opacity**

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

where dots are conformal time  $\eta \equiv \int dt/a$  derivatives and  $\tau$  is the optical depth.

# Temperature Fluctuations

- Observe blackbody radiation with a temperature that differs at  $10^{-5}$  coming from the surface of last scattering, with distribution function (specific intensity  $I_\nu = 4\pi\nu^3 f(\nu)$  each polarization)

$$f(\nu) = [\exp(2\pi\nu/T(\hat{\mathbf{n}})) - 1]^{-1}$$

- Decompose the temperature perturbation in spherical harmonics

$$T(\hat{\mathbf{n}}) = \sum_{\ell m} T_{\ell m} Y_{\ell m}(\hat{\mathbf{n}})$$

- For Gaussian random fluctuations, the statistical properties of the temperature field are determined by the power spectrum

$$\langle T_{\ell m}^* T_{\ell' m'} \rangle = \delta_{\ell\ell'} \delta_{mm'} C_\ell$$

where the  $\delta$ -function comes from statistical isotropy

# Spatial vs Angular Power

- Take the radiation distribution at last scattering to also be described by an isotropic temperature field  $T(\mathbf{x})$  and recombination to be instantaneous

$$T(\hat{\mathbf{n}}) = \int dD T(\mathbf{x}) \delta(D - D_*)$$

where  $D$  is the comoving distance and  $D_*$  denotes recombination.

- Describe the temperature field by its Fourier moments

$$T(\mathbf{x}) = \int \frac{d^3k}{(2\pi)^3} T(\mathbf{k}) e^{i\mathbf{k}\cdot\mathbf{x}}$$

with a power spectrum

$$\langle T(\mathbf{k})^* T(\mathbf{k}') \rangle = (2\pi)^3 \delta(\mathbf{k} - \mathbf{k}') P_T(k)$$

# Spatial vs Angular Power

- Note that the variance of the field

$$\begin{aligned}\langle T(\mathbf{x})T(\mathbf{x}) \rangle &= \int \frac{d^3k}{(2\pi)^3} P(k) \\ &= \int d \ln k \frac{k^3 P(k)}{2\pi^2} \equiv \int d \ln k \Delta_T^2(k)\end{aligned}$$

so it is more convenient to think in the log power spectrum  $\Delta_T^2(k)$

- Temperature field

$$T(\hat{\mathbf{n}}) = \int \frac{d^3k}{(2\pi)^3} T(\mathbf{k}) e^{i\mathbf{k} \cdot D_* \hat{\mathbf{n}}}$$

- Expand out plane wave in spherical coordinates

$$e^{i\mathbf{k} D_* \cdot \hat{\mathbf{n}}} = 4\pi \sum_{\ell m} i^\ell j_\ell(k D_*) Y_{\ell m}^*(\mathbf{k}) Y_{\ell m}(\hat{\mathbf{n}})$$

# Spatial vs Angular Power

- Multipole moments

$$T_{\ell m} = \int \frac{d^3 k}{(2\pi)^3} T(\mathbf{k}) 4\pi i^\ell j_\ell(kD_*) Y_{\ell m}(\mathbf{k})$$

- Power spectrum

$$\begin{aligned} \langle T_{\ell m}^* T_{\ell' m'} \rangle &= \int \frac{d^3 k}{(2\pi)^3} (4\pi)^2 (i)^{\ell-\ell'} j_\ell(kD_*) j_{\ell'}(kD_*) Y_{\ell m}^*(\mathbf{k}) Y_{\ell' m'}(\mathbf{k}) P_T(k) \\ &= \delta_{\ell\ell'} \delta_{mm'} 4\pi \int d \ln k j_\ell^2(kD_*) \Delta_T^2(k) \end{aligned}$$

with  $\int_0^\infty j_\ell^2(x) d \ln x = 1/(2\ell(\ell + 1))$ , slowly varying  $\Delta_T^2$

$$C_\ell = \frac{4\pi \Delta_T^2(\ell/D_*)}{2\ell(\ell + 1)} = \frac{2\pi}{\ell(\ell + 1)} \Delta_T^2(\ell/D_*)$$

so  $\ell(\ell + 1)C_\ell/2\pi = \Delta_T^2$  is commonly used log power



# Tight Coupling Approximation

- Near recombination  $z \approx 10^3$  and  $\Omega_b h^2 \approx 0.02$ , the (comoving) mean free path of a photon

$$\lambda_C \equiv \frac{1}{\dot{\tau}} \sim 2.5 \text{Mpc}$$

small by cosmological standards!

- On scales  $\lambda \gg \lambda_C$  photons are **tightly coupled** to the electrons by Thomson scattering which in turn are tightly coupled to the baryons by Coulomb interactions
- Specifically, their bulk velocities are defined by a **single fluid velocity**  $v_\gamma = v_b$  and the photons carry **no anisotropy** in the rest frame of the baryons
- $\rightarrow$  No **heat conduction** or **viscosity** (anisotropic stress) in fluid

# Zeroth Order Approximation

- Momentum density of a fluid is  $(\rho + p)v$ , where  $p$  is the pressure
- Neglect the momentum density of the **baryons**

$$R \equiv \frac{(\rho_b + p_b)v_b}{(\rho_\gamma + p_\gamma)v_\gamma} = \frac{\rho_b + p_b}{\rho_\gamma + p_\gamma} = \frac{3\rho_b}{4\rho_\gamma}$$
$$\approx 0.6 \left( \frac{\Omega_b h^2}{0.02} \right) \left( \frac{a}{10^{-3}} \right)$$

since  $\rho_\gamma \propto T^4$  is fixed by the CMB temperature  $T = 2.73(1 + z)\text{K}$   
– OK substantially **before recombination**

- Neglect **radiation** in the **expansion**

$$\frac{\rho_m}{\rho_r} = 3.6 \left( \frac{\Omega_m h^2}{0.15} \right) \left( \frac{a}{10^{-3}} \right)$$

# Number Continuity

- Photons are **not created** or destroyed. Without expansion

$$\dot{n}_\gamma + \nabla \cdot (n_\gamma \mathbf{v}_\gamma) = 0$$

but the **expansion** or Hubble flow causes  $n_\gamma \propto a^{-3}$  or

$$\dot{n}_\gamma + 3n_\gamma \frac{\dot{a}}{a} + \nabla \cdot (n_\gamma \mathbf{v}_\gamma) = 0$$

- **Linearize**  $\delta n_\gamma = n_\gamma - \bar{n}_\gamma$

$$(\delta n_\gamma)^\cdot = -3\delta n_\gamma \frac{\dot{a}}{a} - n_\gamma \nabla \cdot \mathbf{v}_\gamma$$

$$\left( \frac{\delta n_\gamma}{n_\gamma} \right)^\cdot = -\nabla \cdot \mathbf{v}_\gamma$$

# Continuity Equation

- Number density  $n_\gamma \propto T^3$  so define temperature fluctuation  $\Theta$

$$\frac{\delta n_\gamma}{n_\gamma} = 3 \frac{\delta T}{T} \equiv 3\Theta$$

- Real space continuity equation

$$\dot{\Theta} = -\frac{1}{3} \nabla \cdot \mathbf{v}_\gamma$$

- Fourier space

$$\dot{\Theta} = -\frac{1}{3} i\mathbf{k} \cdot \mathbf{v}_\gamma$$

# Momentum Conservation

- No expansion:  $\dot{\mathbf{q}} = \mathbf{F}$
- De Broglie wavelength stretches with the expansion

$$\dot{\mathbf{q}} + \frac{\dot{a}}{a}\mathbf{q} = \mathbf{F}$$

for photons this the **redshift**, for non-relativistic particles **expansion drag** on peculiar velocities

- Collection of particles: momentum  $\rightarrow$  **momentum density**  
 $(\rho_\gamma + p_\gamma)\mathbf{v}_\gamma$  and force  $\rightarrow$  **pressure gradient**

$$[(\rho_\gamma + p_\gamma)\mathbf{v}_\gamma]^\cdot = -4\frac{\dot{a}}{a}(\rho_\gamma + p_\gamma)\mathbf{v}_\gamma - \nabla p_\gamma$$

$$\frac{4}{3}\rho_\gamma\dot{\mathbf{v}}_\gamma = \frac{1}{3}\nabla\rho_\gamma$$

$$\dot{\mathbf{v}}_\gamma = -\nabla\Theta$$

# Euler Equation

- Fourier space

$$\dot{\mathbf{v}}_\gamma = -ik\Theta$$

- Pressure gradients (any gradient of a scalar field) generates a curl-free flow
- For convenience define velocity amplitude:

$$\mathbf{v}_\gamma \equiv -iv_\gamma \hat{\mathbf{k}}$$

- Euler Equation:

$$\dot{v}_\gamma = k\Theta$$

- Continuity Equation:

$$\dot{\Theta} = -\frac{1}{3}kv_\gamma$$

# Oscillator: Take One

- Combine these to form the simple harmonic oscillator equation

$$\ddot{\Theta} + c_s^2 k^2 \Theta = 0$$

where the adiabatic sound speed is defined through

$$c_s^2 \equiv \frac{\dot{p}_\gamma}{\dot{\rho}_\gamma}$$

here  $c_s^2 = 1/3$  since we are photon-dominated

- General solution:

$$\Theta(\eta) = \Theta(0) \cos(k s) + \frac{\dot{\Theta}(0)}{k c_s} \sin(k s)$$

where the sound horizon is defined as  $s \equiv \int c_s d\eta$

# Harmonic Extrema

- All modes are **frozen** in at recombination (denoted with a subscript \*) yielding temperature perturbations of **different amplitude** for different modes. For the adiabatic (curvature mode)  $\dot{\Theta}(0) = 0$

$$\Theta(\eta_*) = \Theta(0) \cos(k s_*)$$

- Modes caught in the **extrema** of their oscillation will have enhanced fluctuations

$$k_n s_* = n\pi$$

yielding a **fundamental scale** or frequency, related to the inverse **sound horizon**

$$k_A = \pi / s_*$$

and a **harmonic relationship** to the other extrema as 1 : 2 : 3...



# Peak Location

- The fundamental **physical scale** is translated into a fundamental **angular scale** by simple projection according to the angular diameter distance  $D_A$

$$\theta_A = \lambda_A / D_A$$

$$\ell_A = k_A D_A$$

- In a flat universe, the distance is simply  $D_A = D \equiv \eta_0 - \eta_* \approx \eta_0$ , the horizon distance, and  $k_A = \pi / s_* = \sqrt{3}\pi / \eta_*$  so

$$\theta_A \approx \frac{\eta_*}{\eta_0}$$

- In a **matter-dominated** universe  $\eta \propto a^{1/2}$  so  $\theta_A \approx 1/30 \approx 2^\circ$  or

$$\ell_A \approx 200$$

# Curvature

- In a **curved universe**, the apparent or **angular diameter distance** is no longer the conformal distance  $D_A = R \sin(D/R) \neq D$
- Objects in a **closed universe** are **further** than they appear!  
gravitational **lensing** of the background...
- Curvature scale of the universe must be substantially **larger than current horizon**
- **Flat universe** indicates critical density and implies missing energy given local measures of the matter density “**dark energy**”
- $D$  also depends on **dark energy density**  $\Omega_{\text{DE}}$  and **equation of state**  $w = p_{\text{DE}}/\rho_{\text{DE}}$ .
- Expansion rate at recombination or **matter-radiation ratio** enters into calculation of  $k_A$ .

# Doppler Effect

- Bulk motion of fluid changes the observed temperature via Doppler shifts

$$\left(\frac{\Delta T}{T}\right)_{\text{dop}} = \hat{\mathbf{n}} \cdot \mathbf{v}_\gamma$$

- Averaged over directions

$$\left(\frac{\Delta T}{T}\right)_{\text{rms}} = \frac{v_\gamma}{\sqrt{3}}$$

- Acoustic solution

$$\begin{aligned} \frac{v_\gamma}{\sqrt{3}} &= -\frac{\sqrt{3}}{k} \dot{\Theta} = \frac{\sqrt{3}}{k} k c_s \Theta(0) \sin(ks) \\ &= \Theta(0) \sin(ks) \end{aligned}$$

# Doppler Peaks?

- Doppler effect for the photon dominated system is of equal amplitude and  $\pi/2$  out of phase: extrema of temperature are turning points of velocity
- Effects add in quadrature:

$$\left(\frac{\Delta T}{T}\right)^2 = \Theta^2(0)[\cos^2(ks) + \sin^2(ks)] = \Theta^2(0)$$

- No peaks in  $k$  spectrum! However the Doppler effect carries an angular dependence that changes its projection on the sky

$$\hat{\mathbf{n}} \cdot \mathbf{v}_\gamma \propto \hat{\mathbf{n}} \cdot \hat{\mathbf{k}}$$

- Coordinates where  $\hat{\mathbf{z}} \parallel \hat{\mathbf{k}}$

$$Y_{10}Y_{\ell 0} \rightarrow Y_{\ell \pm 1 0}$$

recoupling  $j'_\ell Y_{\ell 0}$ : no peaks in Doppler effect

# Restoring Gravity

- Take a simple **photon dominated** system **with gravity**
- **Continuity** altered since a gravitational potential represents a **stretching** of the **spatial fabric** that dilutes number densities – formally a spatial **curvature perturbation**
- Think of this as a perturbation to the **scale factor**  $a \rightarrow a(1 + \Phi)$  so that the cosmological redshift is generalized to

$$\frac{\dot{a}}{a} \rightarrow \frac{\dot{a}}{a} + \dot{\Phi}$$

$$(\delta n_\gamma)' = -3\delta n_\gamma \left( \frac{\dot{a}}{a} + \dot{\Phi} \right) - n_\gamma \nabla \cdot \mathbf{v}_\gamma$$

so that the **continuity equation** becomes

$$\dot{\Theta} = -\frac{1}{3}k v_\gamma - \dot{\Phi}$$

# Restoring Gravity

- Gravitational force in momentum conservation  $\mathbf{F} = -m\nabla\Psi$  generalized to momentum density modifies the Euler equation to

$$\dot{v}_\gamma = k(\Theta + \Psi)$$

- General relativity says that  $\Phi$  and  $\Psi$  are the relativistic analogues of the Newtonian potential and that  $\Phi \approx -\Psi$ .
- In our matter-dominated approximation,  $\Phi$  represents matter density fluctuations through the cosmological Poisson equation

$$k^2\Phi = 4\pi G a^2 \rho_m \Delta_m$$

where the difference comes from the use of comoving coordinates for  $k$  ( $a^2$  factor), the removal of the background density into the background expansion ( $\rho\Delta_m$ ) and finally a coordinate subtlety that enters into the definition of  $\Delta_m$

# Constant Potentials

- In the matter dominated epoch potentials are constant because infall generates velocities as  $v_m \sim k\eta\Psi$
- Velocity divergence generates density perturbations as  $\Delta_m \sim -k\eta v_m \sim -(k\eta)^2\Psi$
- And density perturbations generate potential fluctuations as  $\Phi \sim \Delta_m/(k\eta)^2 \sim -\Psi$ , keeping them constant. Note that because of the expansion, density perturbations must grow to keep potentials constant.
- Here we have used the Friedman equation  $H^2 = 8\pi G\rho_m/3$  and  $\eta = \int d\ln a/(aH) \sim 1/(aH)$
- More generally, if stress perturbations are negligible compared with density perturbations ( $\delta p \ll \delta\rho$ ) then potential will remain roughly constant – more specifically a variant called the Bardeen or comoving curvature  $\zeta$  is constant

# Oscillator: Take Two

- Combine these to form the **simple harmonic oscillator** equation

$$\ddot{\Theta} + c_s^2 k^2 \Theta = -\frac{k^2}{3} \Psi - \ddot{\Phi}$$

- In a **CDM dominated** expansion  $\dot{\Phi} = \dot{\Psi} = 0$ . Also for **photon domination**  $c_s^2 = 1/3$  so the oscillator equation becomes

$$\ddot{\Theta} + \ddot{\Psi} + c_s^2 k^2 (\Theta + \Psi) = 0$$

- Solution is just an **offset version** of the original

$$[\Theta + \Psi](\eta) = [\Theta + \Psi](0) \cos(ks)$$

- $\Theta + \Psi$  is also the **observed temperature fluctuation** since photons lose energy climbing out of **gravitational potentials** at recombination



# Effective Temperature

- Photons climb out of potential wells at last scattering
- Lose energy to gravitational redshifts
- Observed or effective temperature

$$\Theta + \Psi$$

- Effective temperature oscillates around zero with amplitude given by the initial conditions
- Note: initial conditions are set when the perturbation is outside of horizon, need inflation or other modification to matter-radiation FRW universe.
- GR says that initial temperature is given by initial potential

# Sachs-Wolfe Effect and the Magic 1/3

- A gravitational potential is a perturbation to the temporal coordinate [formally a gauge transformation]

$$\frac{\delta t}{t} = \Psi$$

- Convert this to a perturbation in the scale factor,

$$t = \int \frac{da}{aH} \propto \int \frac{da}{a\rho^{1/2}} \propto a^{3(1+w)/2}$$

where  $w \equiv p/\rho$  so that during matter domination

$$\frac{\delta a}{a} = \frac{2}{3} \frac{\delta t}{t}$$

- CMB temperature is cooling as  $T \propto a^{-1}$  so

$$\Theta + \Psi \equiv \frac{\delta T}{T} + \Psi = -\frac{\delta a}{a} + \Psi = \frac{1}{3}\Psi$$

# Baryon Loading

- Baryons add extra **mass** to the photon-baryon fluid
- Controlling parameter is the **momentum density ratio**:

$$R \equiv \frac{p_b + \rho_b}{p_\gamma + \rho_\gamma} \approx 30\Omega_b h^2 \left( \frac{a}{10^{-3}} \right)$$

of order **unity** at recombination

- Momentum density of the **joint system** is conserved

$$\begin{aligned} (\rho_\gamma + p_\gamma)v_\gamma + (\rho_b + p_b)v_b &\approx (p_\gamma + p_\gamma + \rho_b + \rho_\gamma)v_\gamma \\ &= (1 + R)(\rho_\gamma + p_\gamma)v_{\gamma b} \end{aligned}$$

where the controlling parameter is the **momentum density ratio**:

$$R \equiv \frac{p_b + \rho_b}{p_\gamma + \rho_\gamma} \approx 30\Omega_b h^2 \left( \frac{a}{10^{-3}} \right)$$

of order **unity** at recombination

# New Euler Equation

- Momentum density ratio enters as

$$\begin{aligned} [(1 + R)(\rho_\gamma + p_\gamma)\mathbf{v}_{\gamma b}]^\cdot &= -4\frac{\dot{a}}{a}(1 + R)(\rho_\gamma + p_\gamma)\mathbf{v}_{\gamma b} \\ &\quad - \nabla p_\gamma - (1 + R)(\rho_\gamma + p_\gamma)\nabla\Psi \end{aligned}$$

same as before except for  $(1 + R)$  terms so

$$[(1 + R)v_{\gamma b}]^\cdot = k\Theta + (1 + R)k\Psi$$

- Photon continuity remains the same

$$\dot{\Theta} = -\frac{k}{3}v_{\gamma b} - \dot{\Phi}$$

- Modification of oscillator equation

$$[(1 + R)\dot{\Theta}]^\cdot + \frac{1}{3}k^2\Theta = -\frac{1}{3}k^2(1 + R)\Psi - [(1 + R)\dot{\Phi}]^\cdot$$

# Oscillator: Take Three

- Combine these to form the not-quite-so simple harmonic oscillator equation

$$c_s^2 \frac{d}{d\eta} (c_s^{-2} \dot{\Theta}) + c_s^2 k^2 \Theta = -\frac{k^2}{3} \Psi - c_s^2 \frac{d}{d\eta} (c_s^{-2} \dot{\Phi})$$

where  $c_s^2 \equiv \dot{p}_{\gamma b} / \dot{\rho}_{\gamma b}$

$$c_s^2 = \frac{1}{3} \frac{1}{1 + R}$$

- In a CDM dominated expansion  $\dot{\Phi} = \dot{\Psi} = 0$  and the adiabatic approximation  $\dot{R}/R \ll \omega = kc_s$

$$[\Theta + (1 + R)\Psi](\eta) = [\Theta + (1 + R)\Psi](0) \cos(k s)$$

# Baryon Peak Phenomenology

- Photon-baryon ratio enters in **three ways**
- Overall larger **amplitude**:

$$[\Theta + (1 + R)\Psi](0) = \frac{1}{3}(1 + 3R)\Psi(0)$$

- Even-odd peak **modulation** of effective temperature

$$[\Theta + \Psi]_{\text{peaks}} = [\pm(1 + 3R) - 3R] \frac{1}{3} \Psi(0)$$

$$[\Theta + \Psi]_1 - [\Theta + \Psi]_2 = [-6R] \frac{1}{3} \Psi(0)$$

- Shifting of the **sound horizon** down or  $\ell_A$  up

$$\ell_A \propto \sqrt{1 + R}$$

- Actual effects **smaller** since  $R$  evolves

# Photon Baryon Ratio Evolution

- Oscillator equation has time evolving mass

$$c_s^2 \frac{d}{d\eta} (c_s^{-2} \dot{\Theta}) + c_s^2 k^2 \Theta = 0$$

- Effective mass is  $m_{\text{eff}} = 3c_s^{-2} = (1 + R)$
- Adiabatic invariant

$$\frac{E}{\omega} = \frac{1}{2} m_{\text{eff}} \omega A^2 = \frac{1}{2} 3c_s^{-2} k c_s A^2 \propto A^2 (1 + R)^{1/2} = \text{const.}$$

- Amplitude of oscillation  $A \propto (1 + R)^{-1/4}$  decays adiabatically as the photon-baryon ratio changes

# Oscillator: Take Three and a Half

- The not-quite-so simple harmonic oscillator equation is a forced harmonic oscillator

$$c_s^2 \frac{d}{d\eta} (c_s^{-2} \dot{\Theta}) + c_s^2 k^2 \Theta = -\frac{k^2}{3} \Psi - c_s^2 \frac{d}{d\eta} (c_s^{-2} \Phi)$$

changes in the gravitational potentials alter the form of the acoustic oscillations

- If the forcing term has a temporal structure that is related to the frequency of the oscillation, this becomes a driven harmonic oscillator
- Term involving  $\Psi$  is the ordinary gravitational force
- Term involving  $\Phi$  involves the  $\dot{\Phi}$  term in the continuity equation as a (curvature) perturbation to the scale factor



# Potential Decay

- Matter-to-radiation ratio

$$\frac{\rho_m}{\rho_r} \approx 24\Omega_m h^2 \left( \frac{a}{10^{-3}} \right)$$

of order **unity** at recombination in a low  $\Omega_m$  universe

- Radiation is not stress free and so **impedes** the growth of structure

$$k^2\Phi = 4\pi G a^2 \rho_r \Delta_r$$

$\Delta_r \sim 4\Theta$  **oscillates** around a constant value,  $\rho_r \propto a^{-4}$  so the Newtonian **curvature decays**.

- General rule: potential decays if the dominant energy component has substantial stress fluctuations, i.e. below the generalized sound horizon or Jeans scale

# Radiation Driving

- Decay is timed precisely to **drive** the oscillator - close to fully coherent

$$\begin{aligned} [\Theta + \Psi](\eta) &= [\Theta + \Psi](0) + \Delta\Psi - \Delta\Phi \\ &= \frac{1}{3}\Psi(0) - 2\Psi(0) = \frac{5}{3}\Psi(0) \end{aligned}$$

- **5**× the amplitude of the Sachs-Wolfe effect!
- Coherent approximation is **exact** for a photon-baryon fluid but reality is reduced to  $\sim 4$ × because of **neutrino contribution** to radiation
- Actual **initial conditions** are  $\Theta + \Psi = \Psi/2$  for radiation domination but comparison to matter dominated SW correct

# External Potential Approach

- Solution to homogeneous equation

$$(1 + R)^{-1/4} \cos(ks), \quad (1 + R)^{-1/4} \sin(ks)$$

- Give the general solution for an external potential by propagating impulsive forces

$$(1 + R)^{1/4} \Theta(\eta) = \Theta(0) \cos(ks) + \frac{\sqrt{3}}{k} \left[ \dot{\Theta}(0) + \frac{1}{4} \dot{R}(0) \Theta(0) \right] \sin ks \\ + \frac{\sqrt{3}}{k} \int_0^\eta d\eta' (1 + R')^{3/4} \sin[ks - ks'] F(\eta')$$

where

$$F = -\ddot{\Phi} - \frac{\dot{R}}{1 + R} \dot{\Phi} - \frac{k^2}{3} \Psi$$

- Useful if general form of potential evolution is known

# Damping

- Tight coupling equations assume a perfect fluid: no viscosity, no heat conduction
- Fluid imperfections are related to the mean free path of the photons in the baryons

$$\lambda_C = \dot{\tau}^{-1} \quad \text{where} \quad \dot{\tau} = n_e \sigma_T a$$

is the conformal opacity to Thompson scattering

- Dissipation is related to the diffusion length: random walk approximation

$$\lambda_D = \sqrt{N} \lambda_C = \sqrt{\eta / \lambda_C} \lambda_C = \sqrt{\eta \lambda_C}$$

the geometric mean between the horizon and mean free path

- $\lambda_D / \eta_* \sim \text{few } \%$ , so expect the peaks  $> 3$  to be affected by dissipation

# Equations of Motion

- Continuity

$$\dot{\Theta} = -\frac{k}{3}v_\gamma - \dot{\Phi}, \quad \dot{\delta}_b = -kv_b - 3\dot{\Phi}$$

where the photon equation remains unchanged and the baryons follow number conservation with  $\rho_b = m_b n_b$

- Euler

$$\begin{aligned}\dot{v}_\gamma &= k(\Theta + \Psi) - \frac{k}{6}\pi_\gamma - \dot{\tau}(v_\gamma - v_b) \\ \dot{v}_b &= -\frac{\dot{a}}{a}v_b + k\Psi + \dot{\tau}(v_\gamma - v_b)/R\end{aligned}$$

where the photons gain an anisotropic stress term  $\pi_\gamma$  from radiation viscosity and a momentum exchange term with the baryons and are compensated by the opposite term in the baryon Euler equation

# Viscosity

- Viscosity is generated from radiation streaming from hot to cold regions
- Expect

$$\pi_\gamma \sim v_\gamma \frac{k}{\dot{\tau}}$$

generated by streaming, suppressed by scattering in a wavelength of the fluctuation. Radiative transfer says

$$\pi_\gamma \approx 2A_v v_\gamma \frac{k}{\dot{\tau}}$$

where  $A_v = 16/15$

$$\dot{v}_\gamma = k(\Theta + \Psi) - \frac{k}{3} A_v \frac{k}{\dot{\tau}} v_\gamma$$

# Oscillator: Penultimate Take

- Adiabatic approximation ( $\omega \gg \dot{a}/a$ )

$$\dot{\Theta} \approx -\frac{k}{3}v_\gamma$$

- Oscillator equation contains a  $\dot{\Theta}$  damping term

$$c_s^2 \frac{d}{d\eta} (c_s^{-2} \dot{\Theta}) + \frac{k^2 c_s^2}{\dot{\tau}} A_v \dot{\Theta} + k^2 c_s^2 \Theta = -\frac{k^2}{3} \Psi - c_s^2 \frac{d}{d\eta} (c_s^{-2} \dot{\Phi})$$

- Heat conduction term similar in that it is proportional to  $v_\gamma$  and is suppressed by scattering  $k/\dot{\tau}$ . Expansion of Euler equations to leading order in  $k\dot{\tau}$  gives

$$A_h = \frac{R^2}{1 + R}$$

since the effects are only significant if the baryons are dynamically important

# Oscillator: Final Take

- Final oscillator equation

$$c_s^2 \frac{d}{d\eta} (c_s^{-2} \dot{\Theta}) + \frac{k^2 c_s^2}{\dot{\tau}} [A_v + A_h] \dot{\Theta} + k^2 c_s^2 \Theta = -\frac{k^2}{3} \Psi - c_s^2 \frac{d}{d\eta} (c_s^{-2} \dot{\Phi})$$

- Solve in the adiabatic approximation

$$\Theta \propto \exp(i \int \omega d\eta)$$

$$-\omega^2 + \frac{k^2 c_s^2}{\dot{\tau}} (A_v + A_h) i\omega + k^2 c_s^2 = 0 \quad (1)$$



# Dispersion Relation

- Solve

$$\begin{aligned}\omega^2 &= k^2 c_s^2 \left[ 1 + i \frac{\omega}{\dot{\tau}} (A_v + A_h) \right] \\ \omega &= \pm k c_s \left[ 1 + \frac{i}{2} \frac{\omega}{\dot{\tau}} (A_v + A_h) \right] \\ &= \pm k c_s \left[ 1 \pm \frac{i}{2} \frac{k c_s}{\dot{\tau}} (A_v + A_h) \right]\end{aligned}$$

- Exponentiate

$$\begin{aligned}\exp(i \int \omega d\eta) &= e^{\pm i k s} \exp\left[-k^2 \int d\eta \frac{1}{2} \frac{c_s^2}{\dot{\tau}} (A_v + A_h)\right] \\ &= e^{\pm i k s} \exp\left[-(k/k_D)^2\right]\end{aligned}\tag{2}$$

- Damping is **exponential** under the scale  $k_D$

# Diffusion Scale

- Diffusion wavenumber

$$k_D^{-2} = \int d\eta \frac{1}{\dot{\tau}} \frac{1}{6(1+R)} \left( \frac{16}{15} + \frac{R^2}{(1+R)} \right)$$

- Limiting forms

$$\lim_{R \rightarrow 0} k_D^{-2} = \frac{1}{6} \frac{16}{15} \int d\eta \frac{1}{\dot{\tau}}$$

$$\lim_{R \rightarrow \infty} k_D^{-2} = \frac{1}{6} \int d\eta \frac{1}{\dot{\tau}}$$

- Geometric mean between horizon and mean free path as expected from a **random walk**

$$\lambda_D = \frac{2\pi}{k_D} \sim \frac{2\pi}{\sqrt{6}} (\eta \dot{\tau}^{-1})^{1/2}$$