

# Effect of Modified Gravity On CMB

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# Modification to Einstein equations: $\mu, \gamma$

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

$$k^2\Phi = -4\pi Ga^2\rho\Delta,$$

$$k^2(\Phi - \Psi) = 12\pi Ga^2(\rho + P)\sigma.$$



$$k^2\Psi = -4\pi Ga^2\mu[\rho\Delta + 3(\rho + P)\sigma],$$

$$k^2[\Phi - \gamma\Psi] = 12\pi Ga^2\mu(\rho + P)\sigma,$$

# Boltzmann Equations

- Remain UNCHANGED!

# Conservation of comoving curvature

$$\dot{\mathcal{R}} = \alpha \left\{ 3\mathcal{H} \frac{\delta P}{\delta \rho} \frac{1}{\mu} [(1-\gamma)\Psi + \Phi] + \frac{1}{1+\alpha} \left[ \Gamma - \left[ \dot{\Phi} + \mathcal{H}(\Psi - \sigma) \right] \right] \right\}, \quad (3)$$

$$\mathcal{H}\mathcal{R} = -\frac{1}{(3/2)(1+w)} \left\{ \frac{3}{2}(1+w)\mathcal{H}\Phi + \frac{1}{1+\alpha} \left[ \left[ \dot{\Phi} + \mathcal{H}(\Psi - \sigma) \right] + \alpha\Gamma \right] \right\}$$

$$\alpha = \frac{k^2}{(3/2)\mathcal{H}^2 \times 3(1+w)},$$

$$\Gamma = \frac{1}{\mu} \left[ \dot{\Phi} + (1-\gamma)\dot{\Psi} - \dot{\gamma}\Psi + \left( \mathcal{H} - \frac{\dot{\mu}}{\mu} \right) (\Phi + (1-\gamma)\Psi) \right]$$

# Conservation of comoving curvature

$$\text{GR: } \frac{k^2}{\mathcal{H}^2} \times \frac{(\delta P/\delta\rho)}{(3/2)(1+w) + [1 + \dot{\Phi}/(\mathcal{H}\Phi)]} \ll 1.$$

$$\gamma = 1, \sigma = 0$$

$$\frac{k^2}{3\mathcal{H}^2} \left| \frac{3\mathcal{H} \frac{\delta P}{\delta\rho} \frac{1}{\mu} + \frac{1}{1+\alpha} \left[ \left(\frac{1}{\mu} - 1\right) \frac{\dot{\Phi}}{\Phi} + \left(\frac{1}{\mu} - 1\right) \mathcal{H} - \frac{\dot{\mu}}{\mu^2} \right]}{\frac{3}{2}(1+w)\mathcal{H} + \frac{1}{1+\alpha} \left[ \left(\frac{\dot{\Phi}}{\Phi} + \mathcal{H}\right) + \alpha \frac{1}{\mu} \left(\frac{\dot{\Phi}}{\Phi} + \mathcal{H} - \frac{\dot{\mu}}{\mu}\right) \right]} \right| \ll 1.$$

$$\mu = 1, \sigma = 0$$

$$\frac{k^2}{3\mathcal{H}^2} \left| \frac{3\mathcal{H} \frac{\delta P}{\delta\rho} [(1-\gamma)\Psi + \Phi] + \frac{1}{1+\alpha} [\dot{\Psi} - \dot{\Phi}]}{\frac{3}{2}(1+w)\mathcal{H}\Phi + \frac{1}{1+\alpha} [\dot{\Phi} + \mathcal{H}\Psi + \alpha(\dot{\Psi} + \mathcal{H}\Psi)]} \right| \ll 1.$$

# Initial Conditions

- Correction terms due to  $\mu$  &  $\gamma$

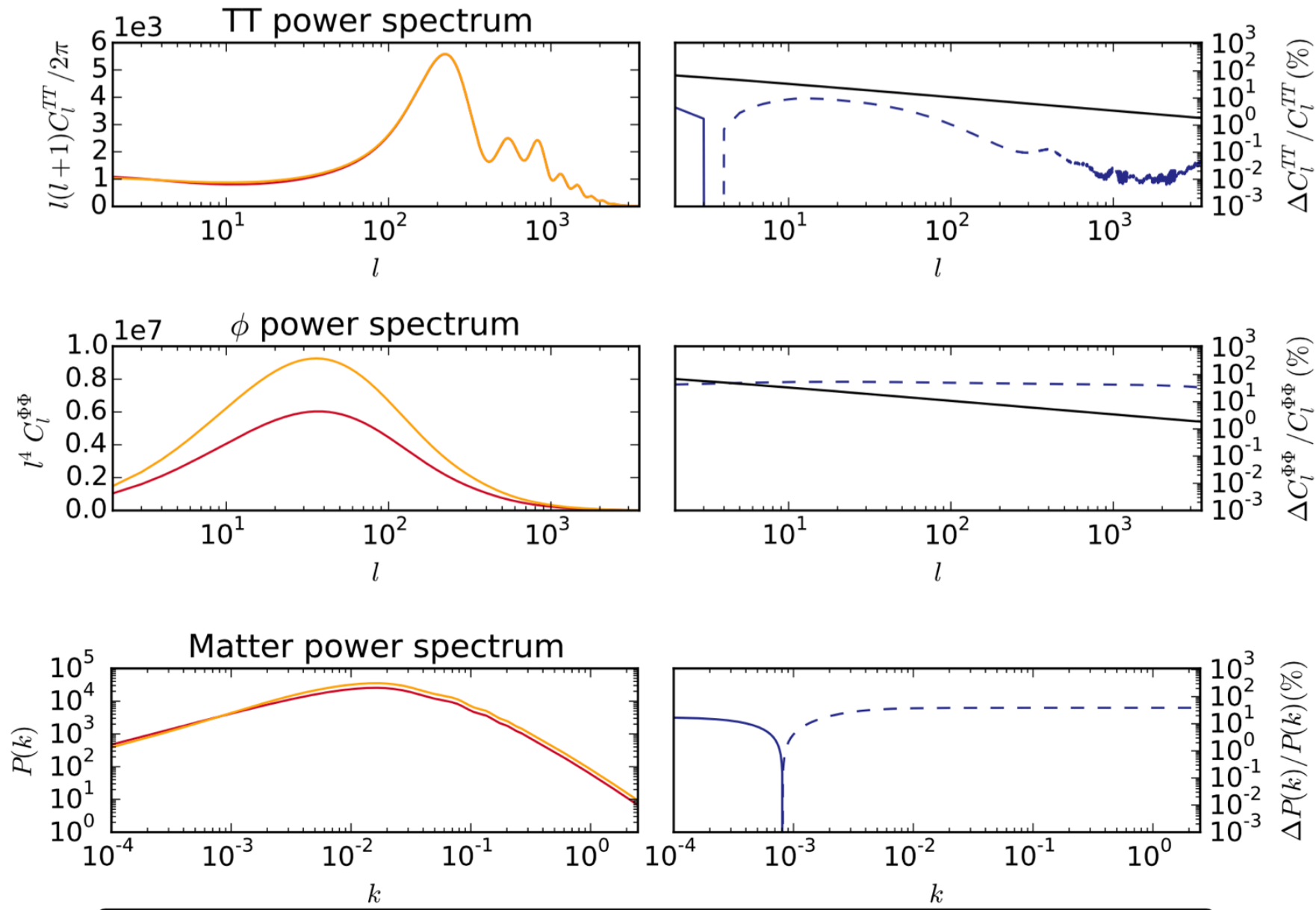
$$C_{\Psi} = -\frac{10}{10\gamma + 5 + 4\mu R_{\nu}} \mathcal{R}.$$

$$\Phi = \left(\gamma + \frac{2}{5}\mu R_{\nu}\right) C_{\Psi}$$

# Numerical Code

- **RCAMB**: modification to CMAB
- Parameters:  $w_{DE}, \mu, \gamma$
- Mode 0: GR+LCDM
  - ( $w_{DE} = -1, \mu = \gamma = 1, c_T = 1$ )
- Mode 1: wCDM
  - ( $w_{DE} \neq -1, \mu = \gamma = 1, c_T = 1$ )
- **Mode 2**: Modified Gravity
  - ( $\mu \neq 1$  or  $\gamma \neq 1$ )
- Mode 3:  $c_T \neq 1$
- .....

# 1\_GR VS 10\_steplogMGini\_mu1 comparison of scalar Cls

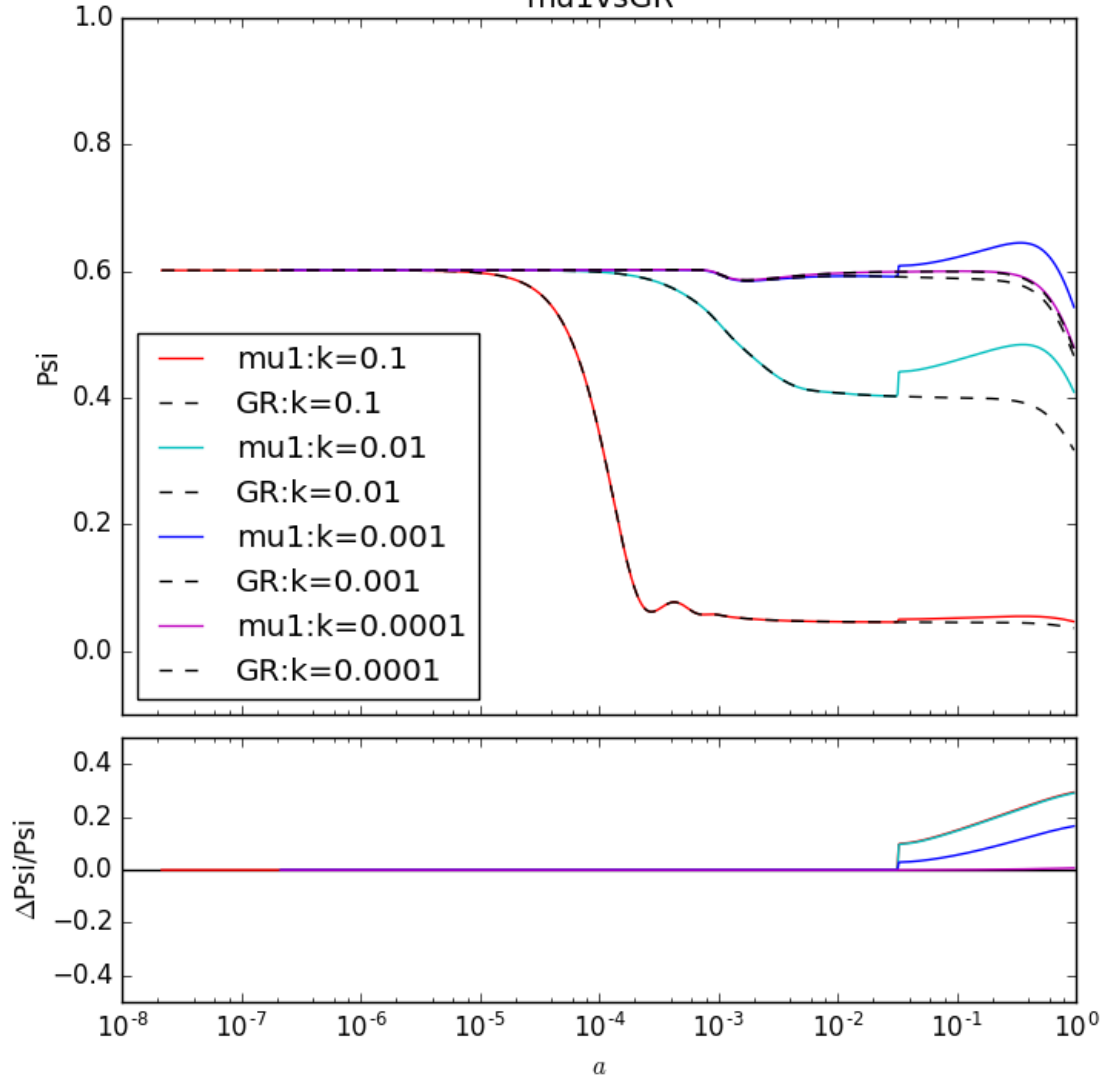


Late time:  $\mu=1.1$

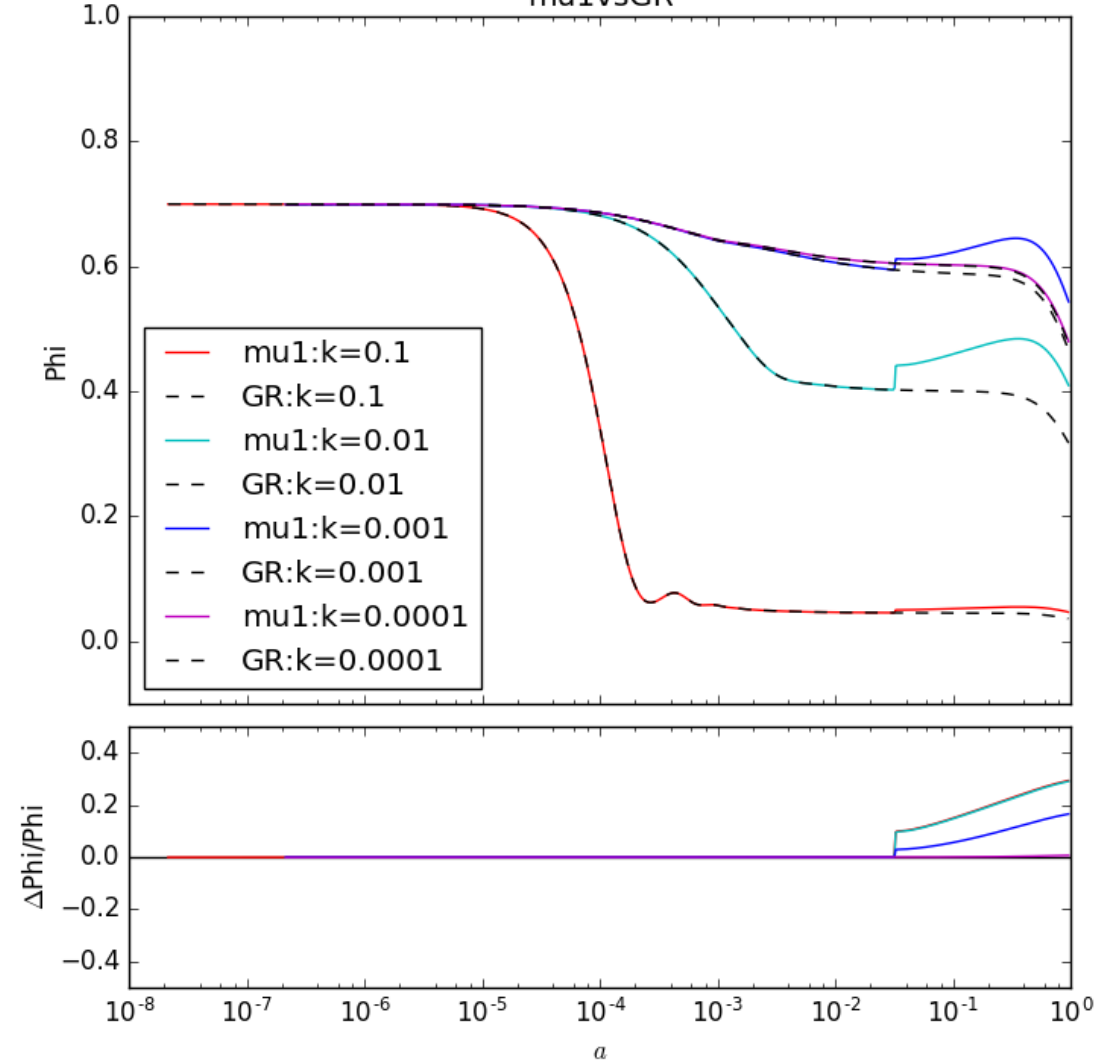


# Late time: $\mu=1.1$

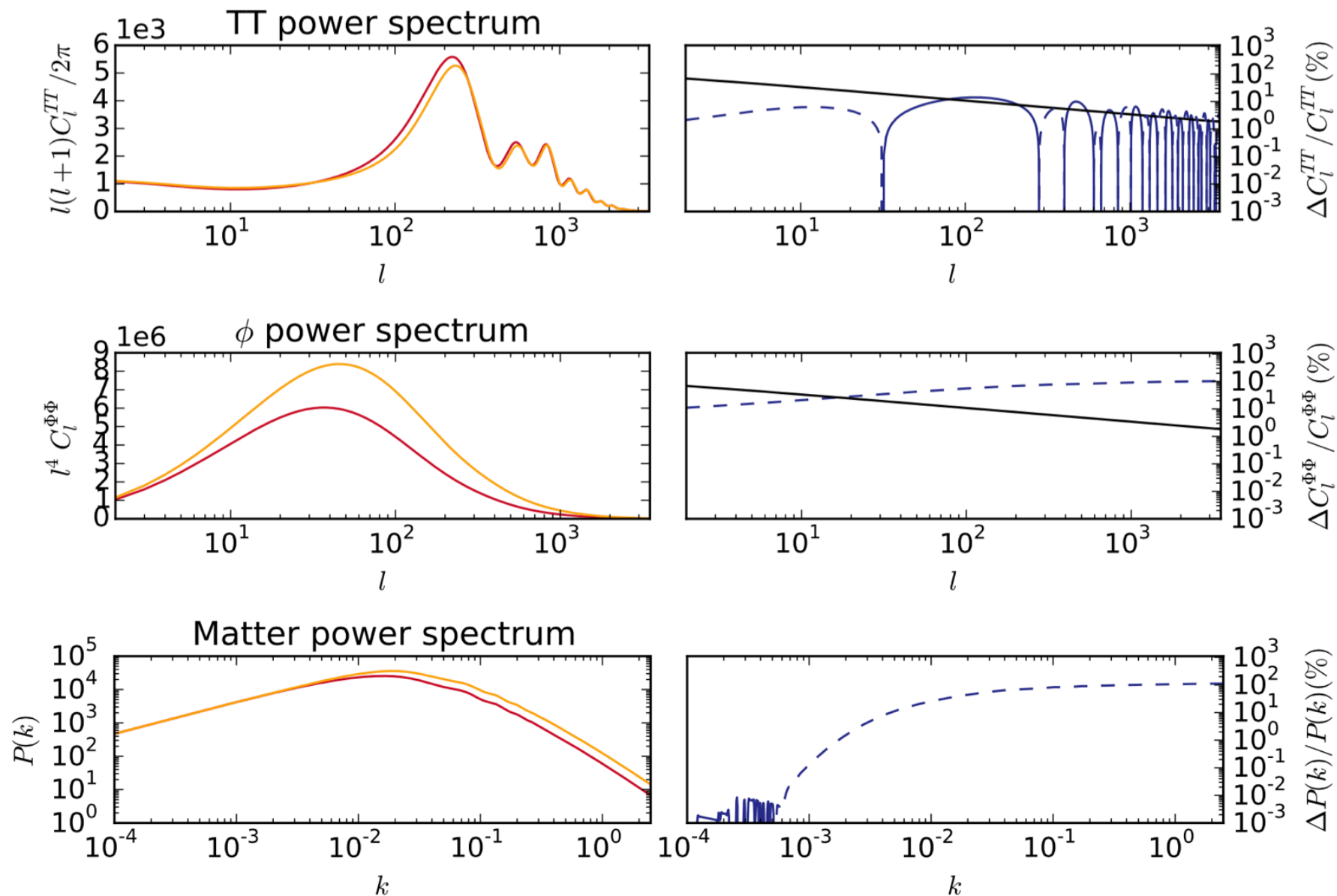
mu1vsGR



mu1vsGR



# 1\_GR VS 10\_steplogMGini\_mu2 comparison of scalar Cls

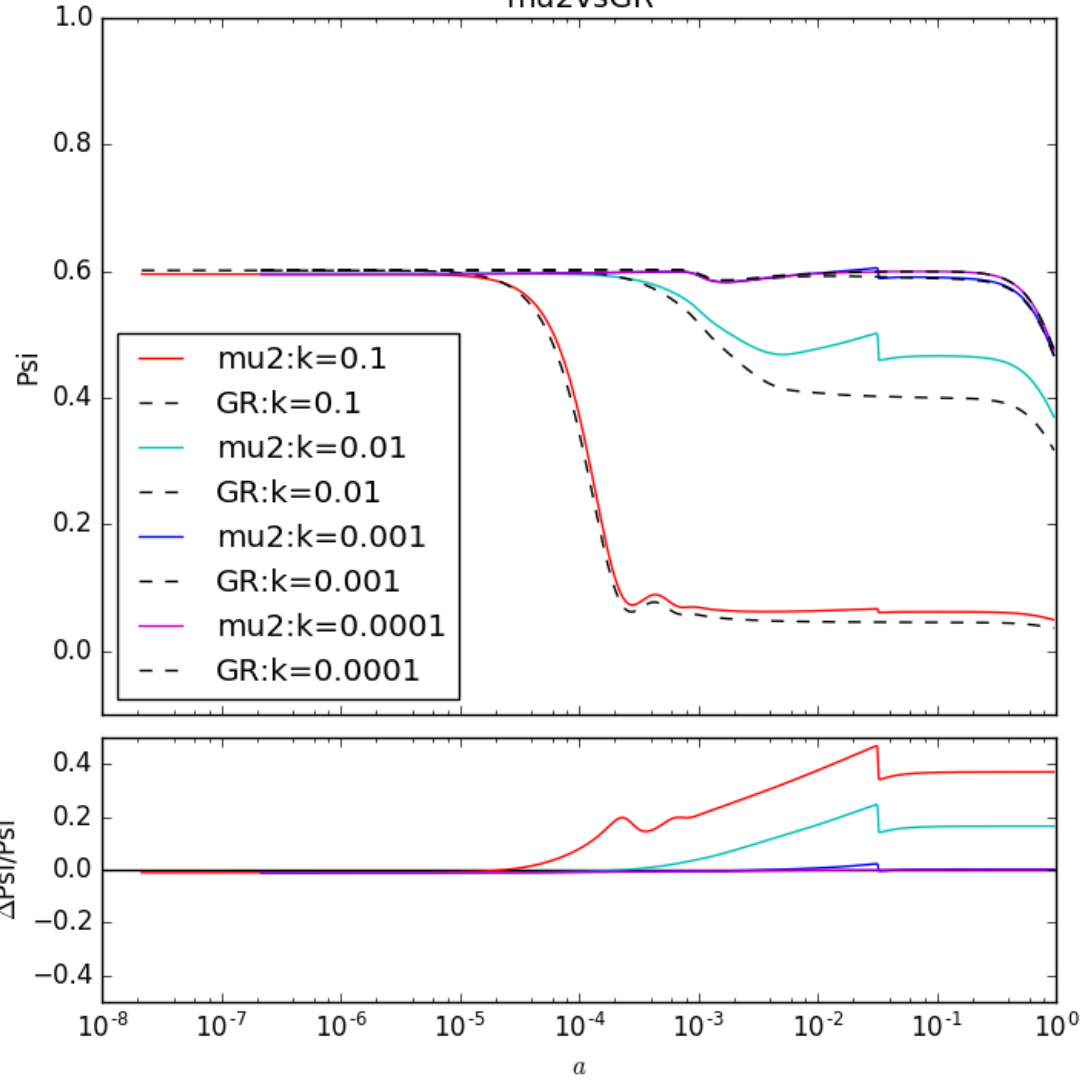


— 1\_GR   
 — 10\_steplogMGini\_mu2   
 — Cosmic variance

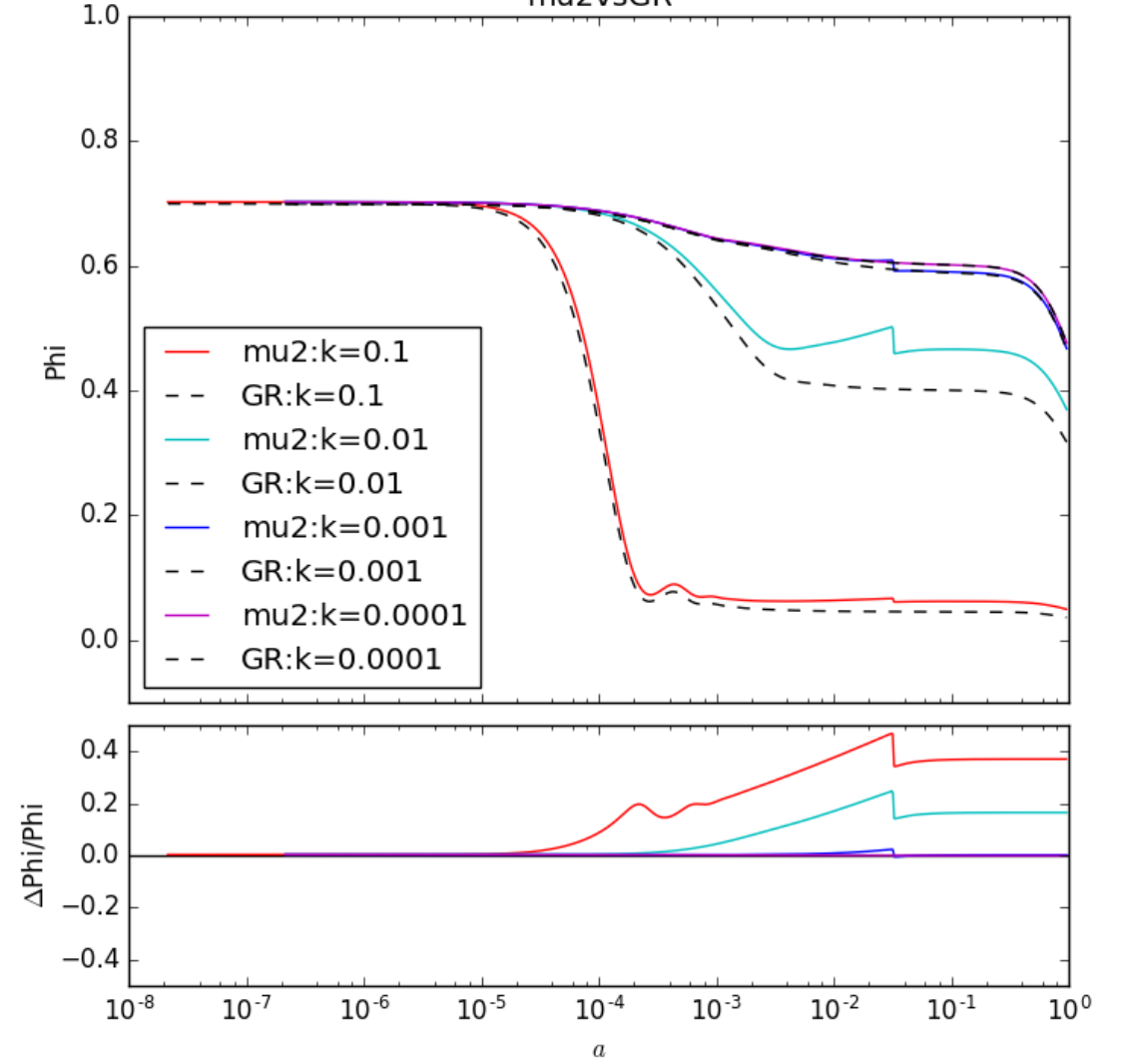
Early time:  $\mu=1.1$

# Early time: $\mu=1.1$

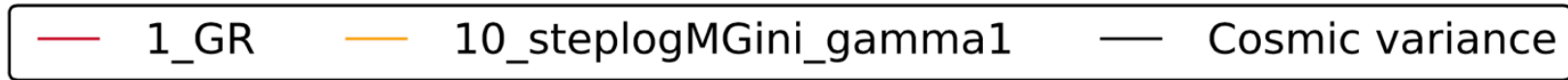
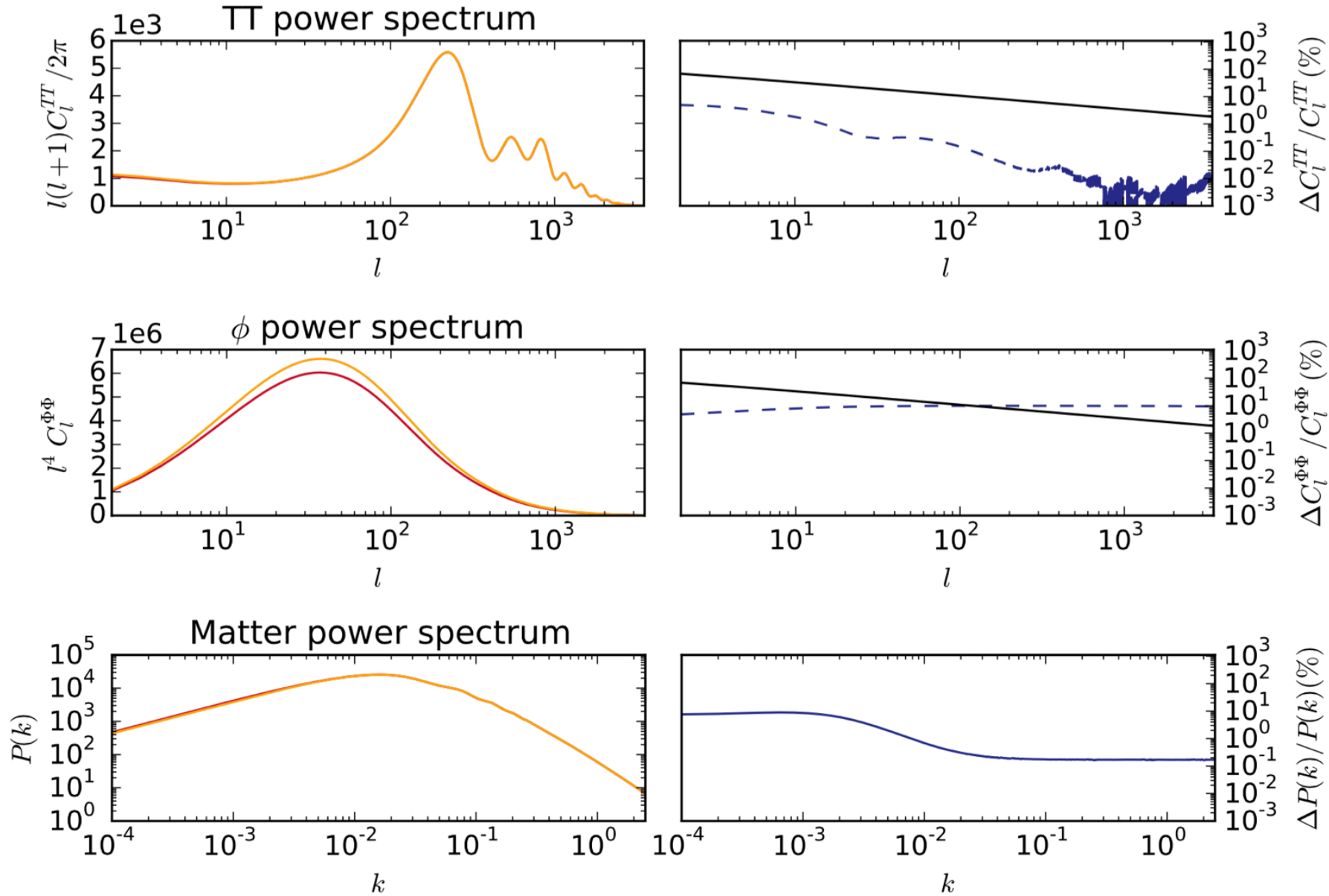
mu2vsGR



mu2vsGR



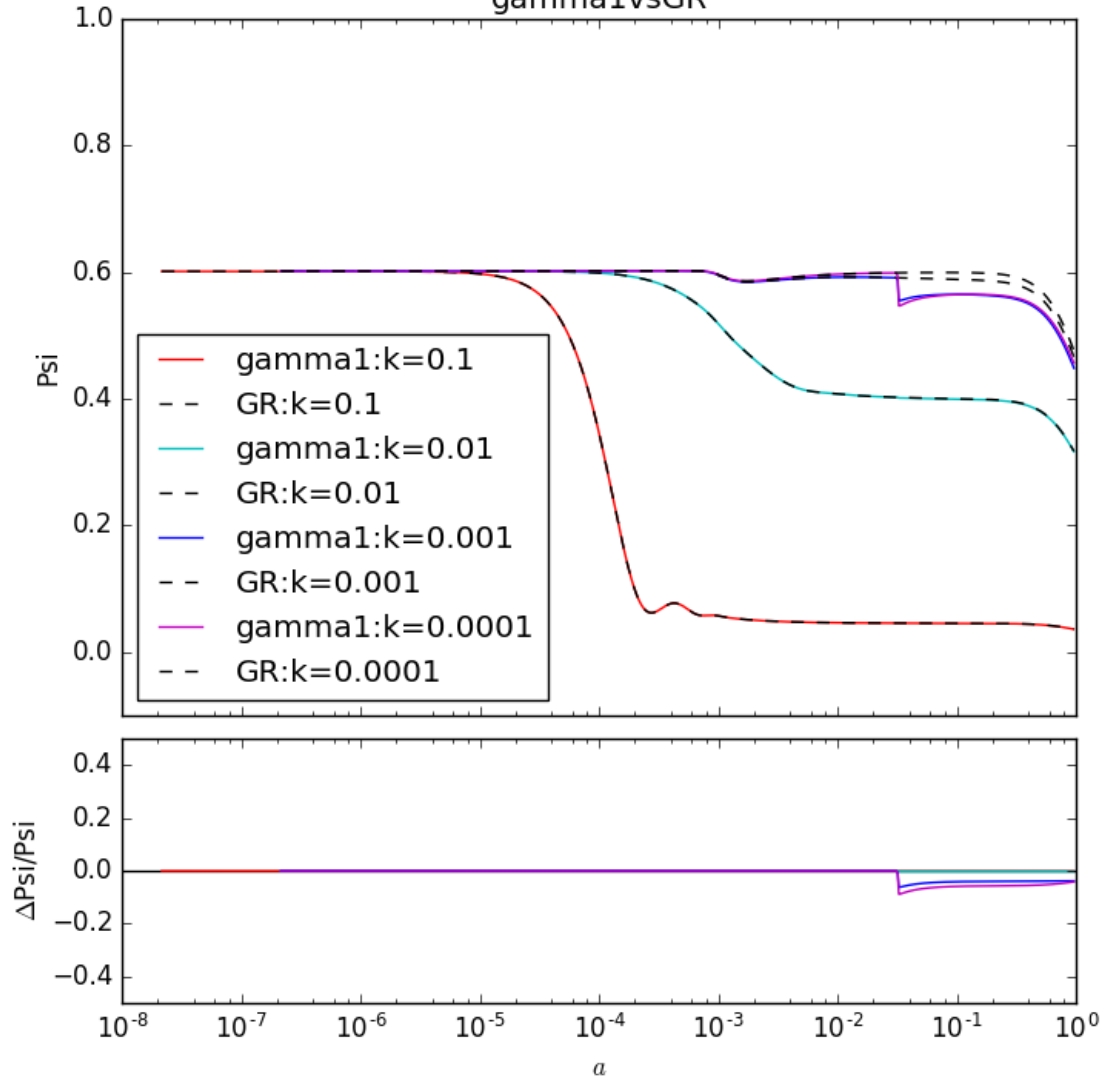
# 1\_GR VS 10\_steplogMGini\_gamma1 comparison of scalar Cls



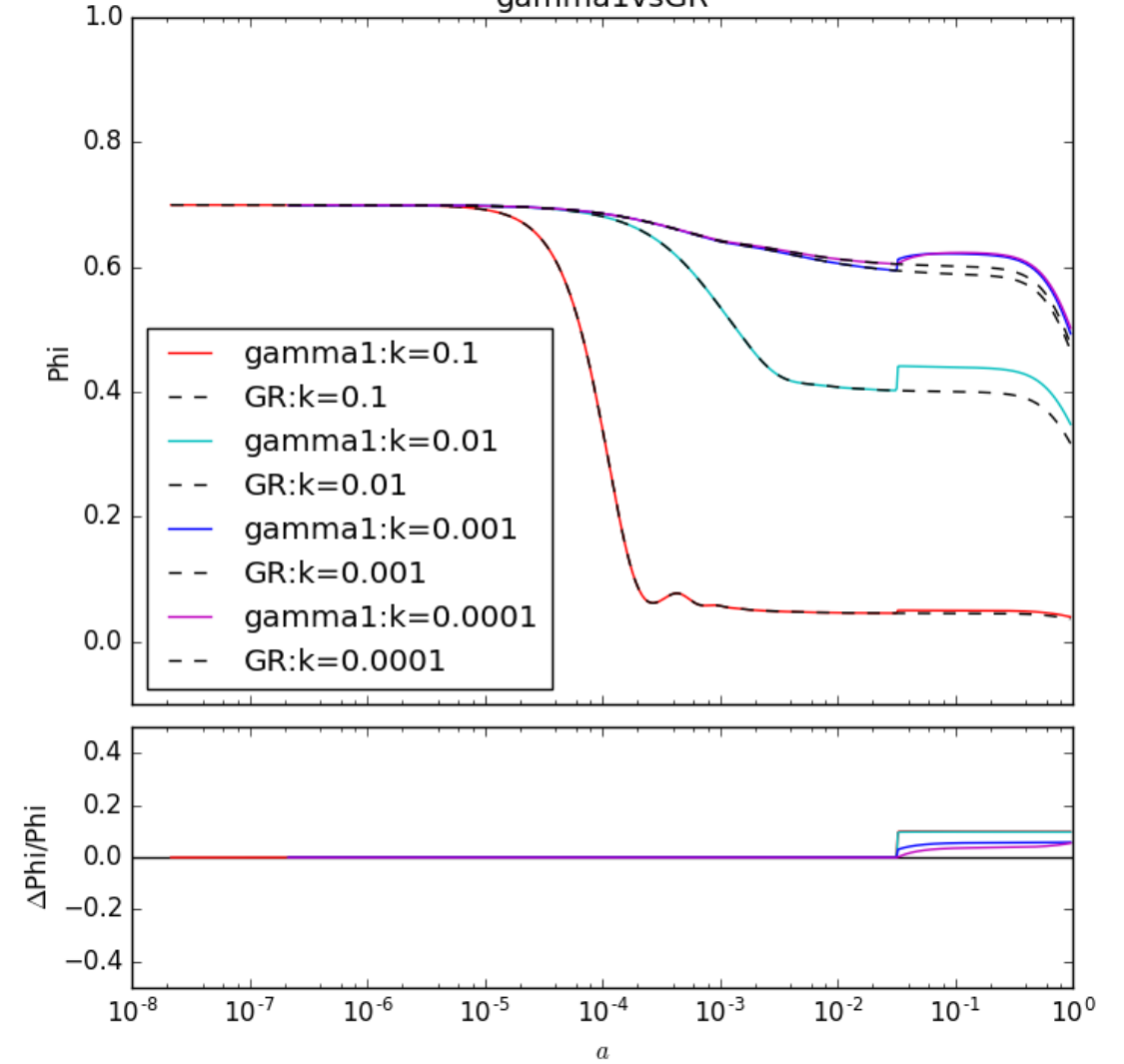
Late time: gamma=1.1

# Late time: $\gamma=1.1$

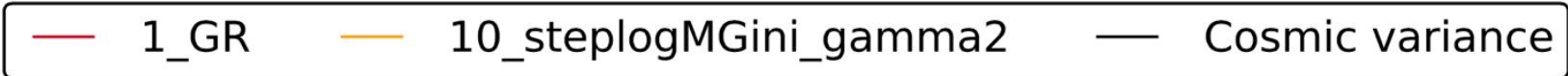
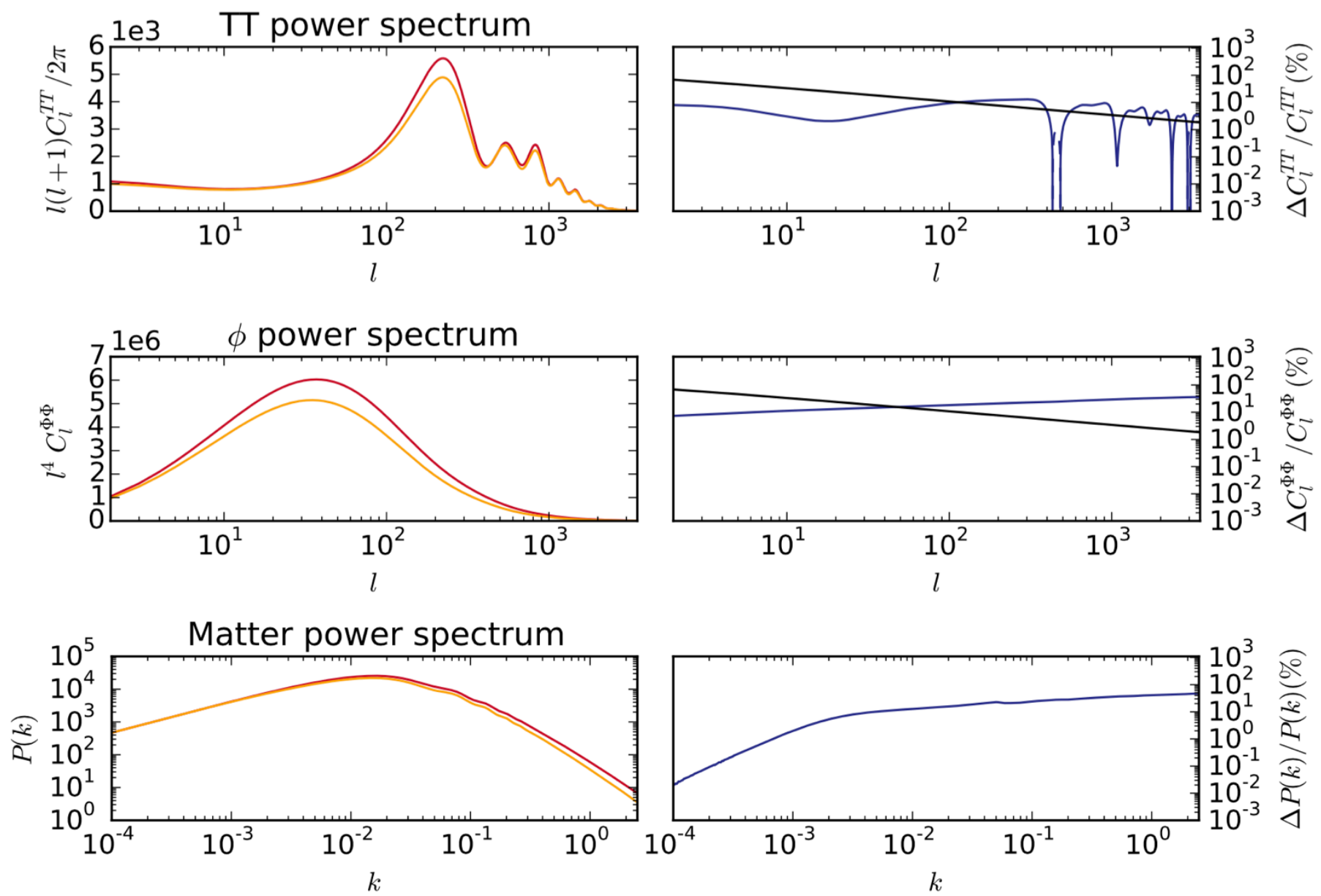
gamma1vsGR



gamma1vsGR



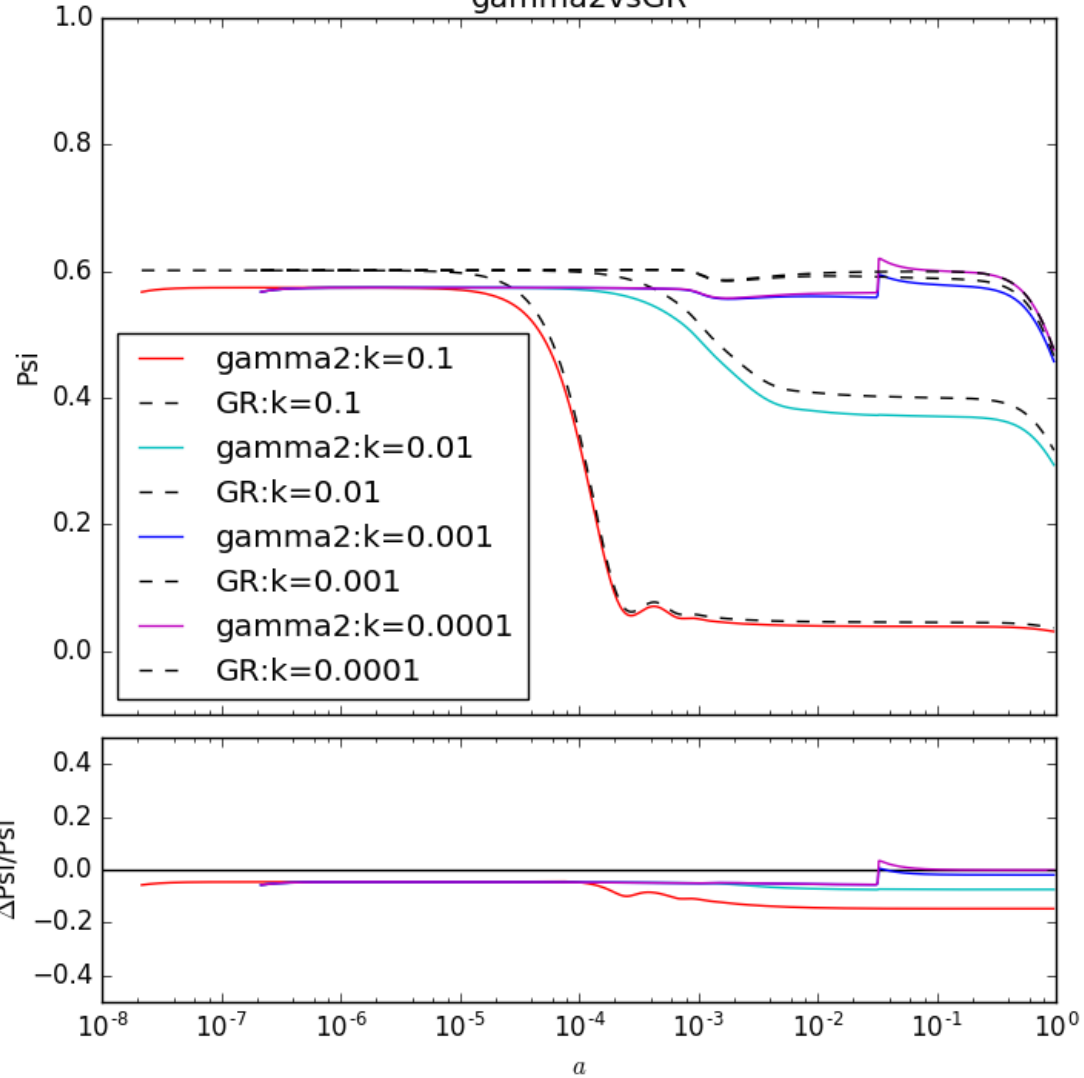
# 1\_GR VS 10\_steplogMGini\_gamma2 comparison of scalar Cls



Early time: gamma=1.1

# Early time: gamma=1.1

gamma2vsGR



gamma2vsGR

