Constraints on $f(R)$ gravity and neutrino mass from large scale structure

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Approaches to cosmic acceleration problem

- ΛCDM model

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}(R - 2\Lambda) + S_m$$

- Modified matter (modify r.h.s. of Einstein eq.)

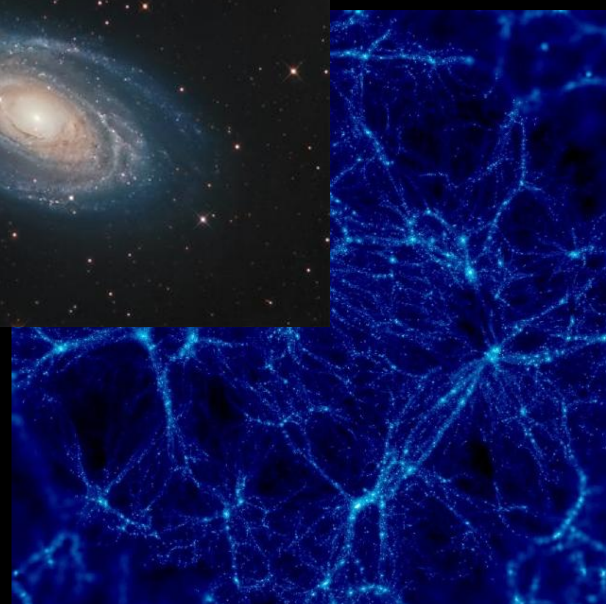
$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}R + S_\phi + S_m$$

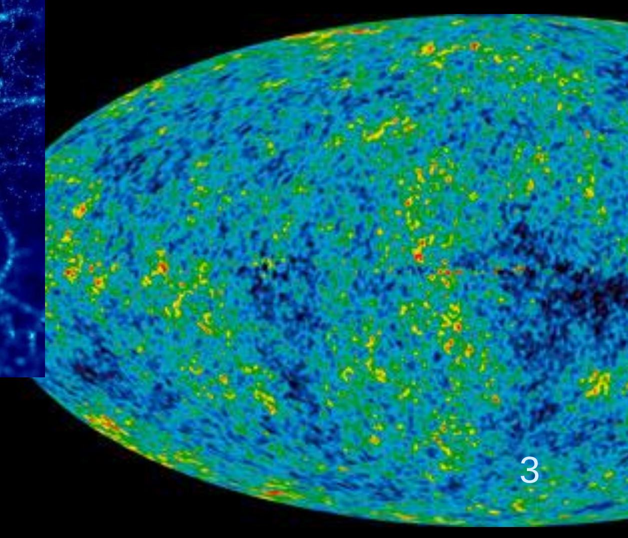
- Modified gravity (modify l.h.s. of Einstein eq.)

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}f(R) + S_m$$

- Inhomogeneous model (modify cosmological principle)

Testing modified gravity





Local scale

$\sim 1\mathrm{AU}$:

Solar system test

Intermediate scale

$\sim 100\mathrm{Mpc}$:

Large scale structure

Cosmological scale

$\sim 1\mathrm{Gpc}$:

Expansion history

The evolution equation for density fluctuations

- ΛCDM model

$$\ddot{\delta}_{\mathbf{k}} + 2H\dot{\delta}_{\mathbf{k}} - 4\pi G\rho\delta_{\mathbf{k}} = 0$$

- f(R) gravity + subhorizon limit Tsujikawa (2007)

$$\ddot{\delta}_{\mathbf{k}} + 2H\dot{\delta}_{\mathbf{k}} - 4\pi G_{\text{eff}}(k)\rho\delta_{\mathbf{k}} = 0$$

Effective gravitational coefficient

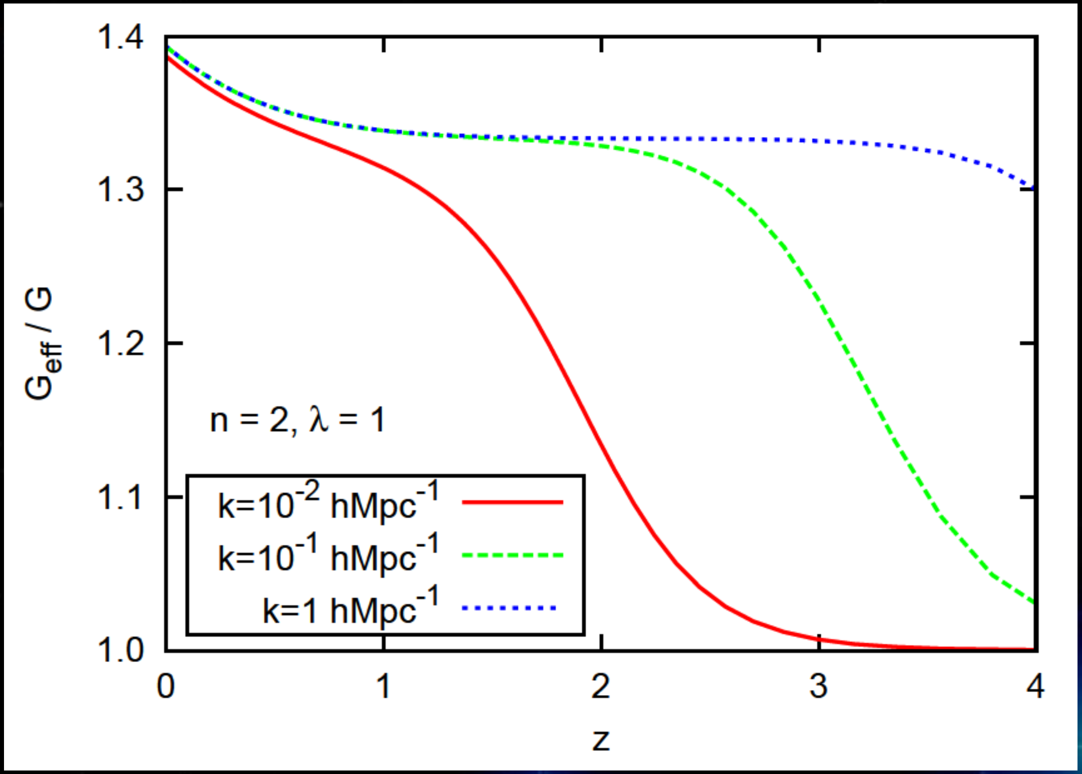
$$G_{\text{eff}}(k) = \frac{G}{F}\left[1 + \frac{1}{3}\frac{\frac{k^2}{a^2}\frac{3F'}{F}}{1 + \frac{k^2}{a^2}\frac{3F'}{F}}\right]$$

$$\simeq \begin{cases} G/F & (3k^2F'/a^2F \ll 1) \\ 4G/3F & (3k^2F'/a^2F \gg 1) \end{cases}$$

Time evolution of $G_{\rm eff}$

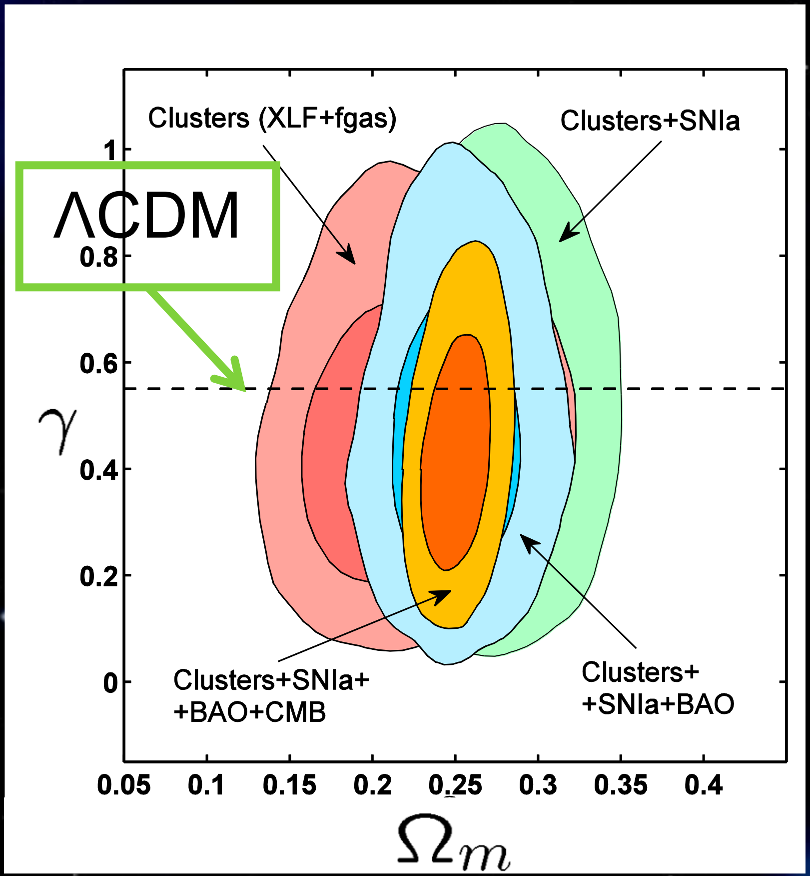
$$f(R) = R + \lambda R_s \left[\left(1 + \frac{R^2}{R_s^2} \right)^{-n} - 1 \right]$$

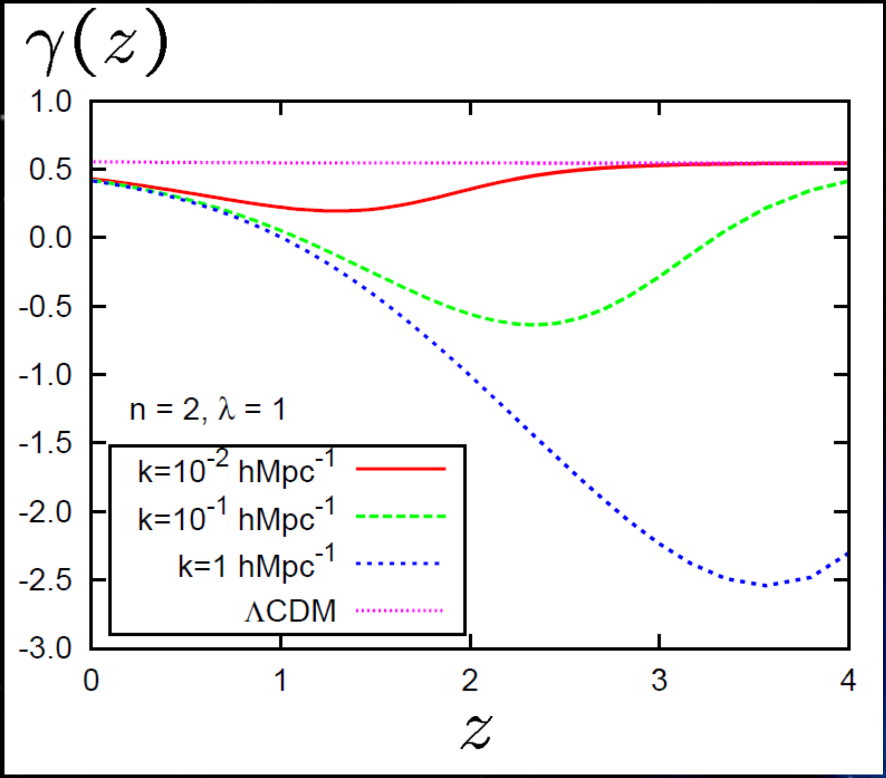
Starobinsky (2007)



Growth index $\gamma(z)$ $\frac{d \log \delta}{d \log a} = \Omega_m(z)^{\gamma(z)}$

growth index $\gamma(z)$ (ΛCDM: almost constant $\gamma(z) \simeq 6/11$)





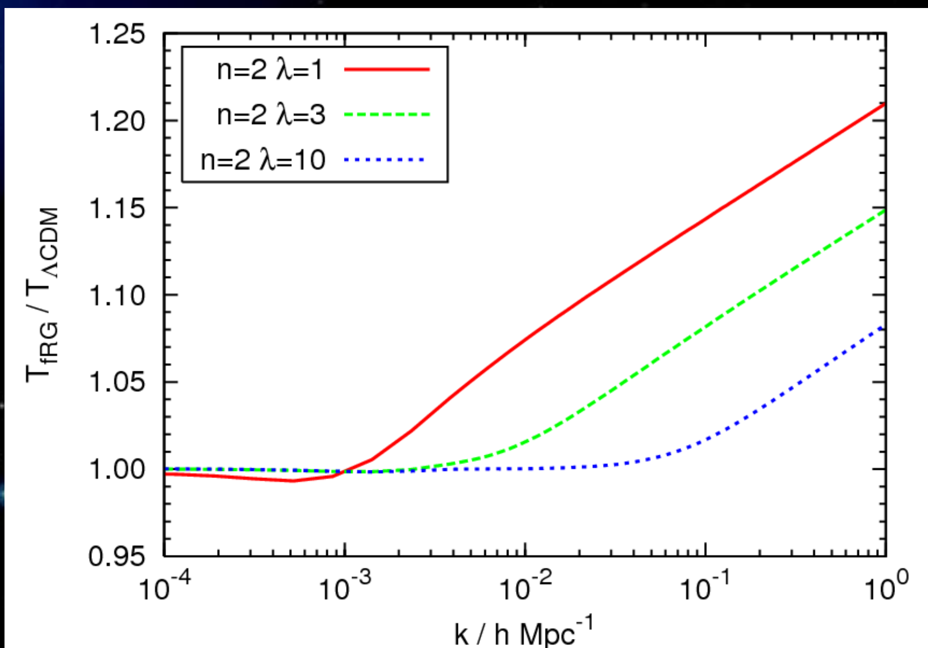
Rapetti et al. (2010)

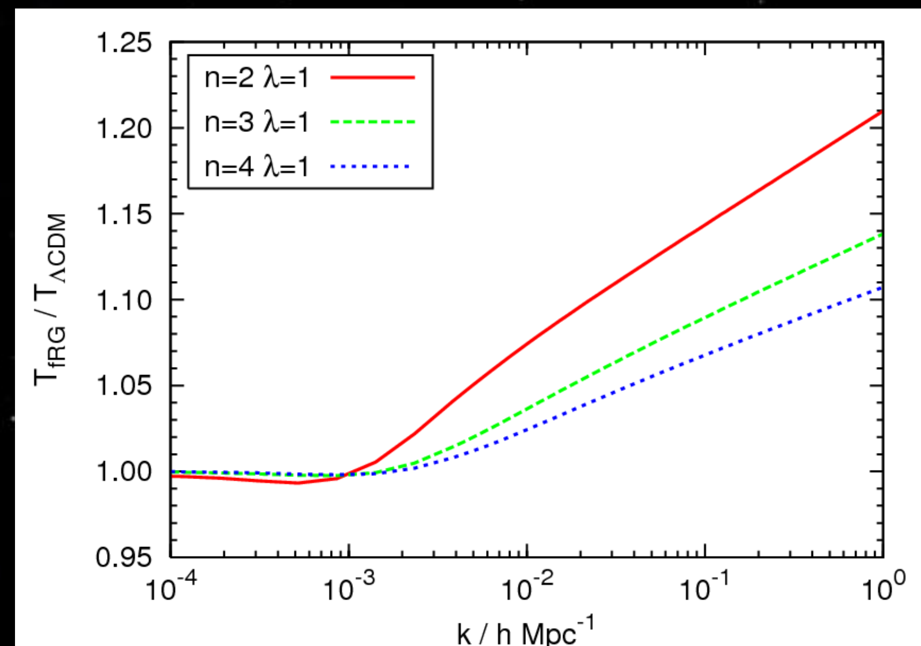
H.M., Yokoyama, Starobinsky (2010)

Transfer function in $f(R)$ gravity

Scale and time dependence for G_{eff}

= Additional transfer function





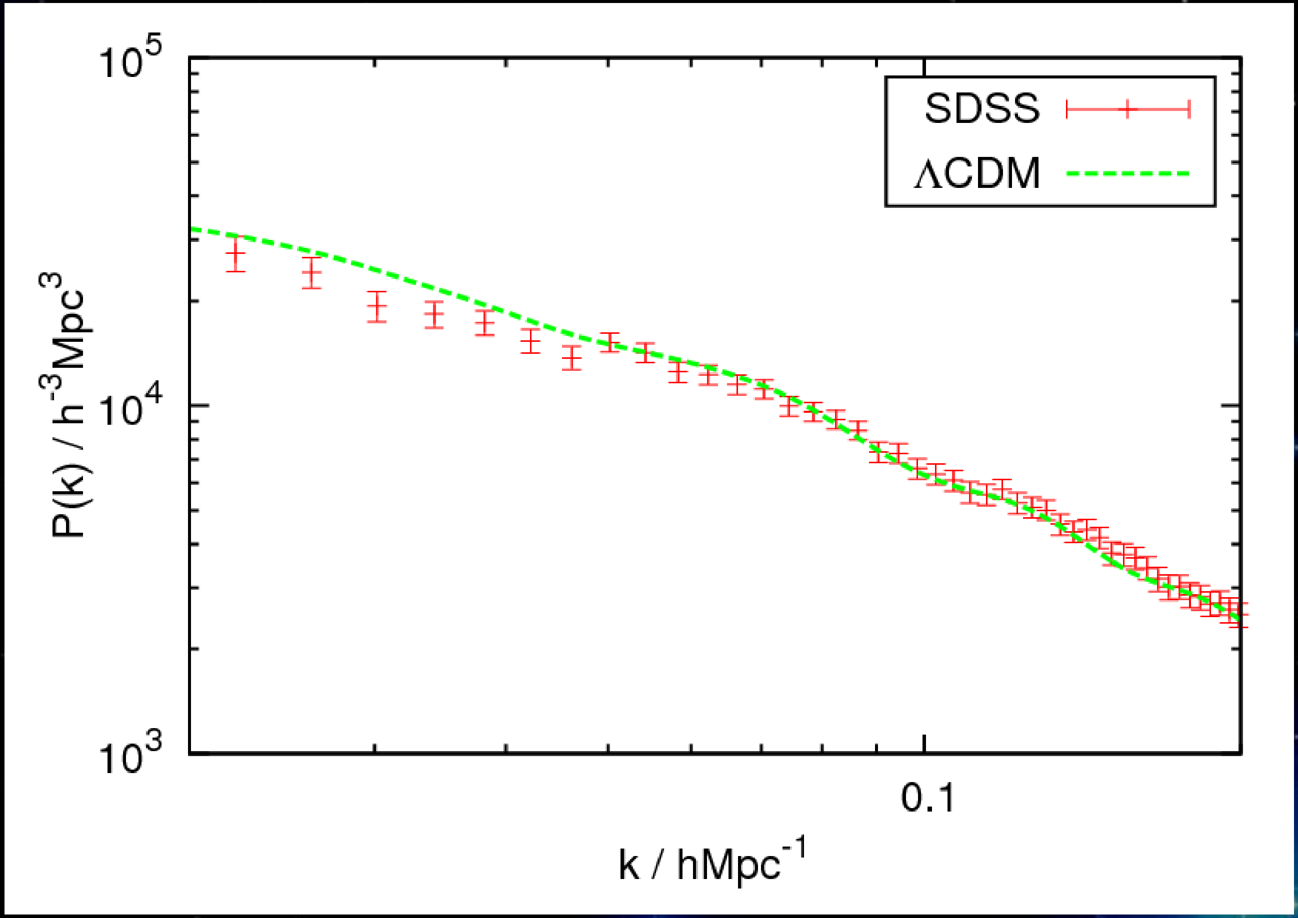
It gives scale dependent enhancement in power spectrum.

→ compare it observational data from SDSS DR7.

$P(k)$: ΛCDM model

Reid et al. (2009)
Komatsu et al. (2010)

- Matter power spectrum in ΛCDM model
  (Cosmological parameters: WMAP7)



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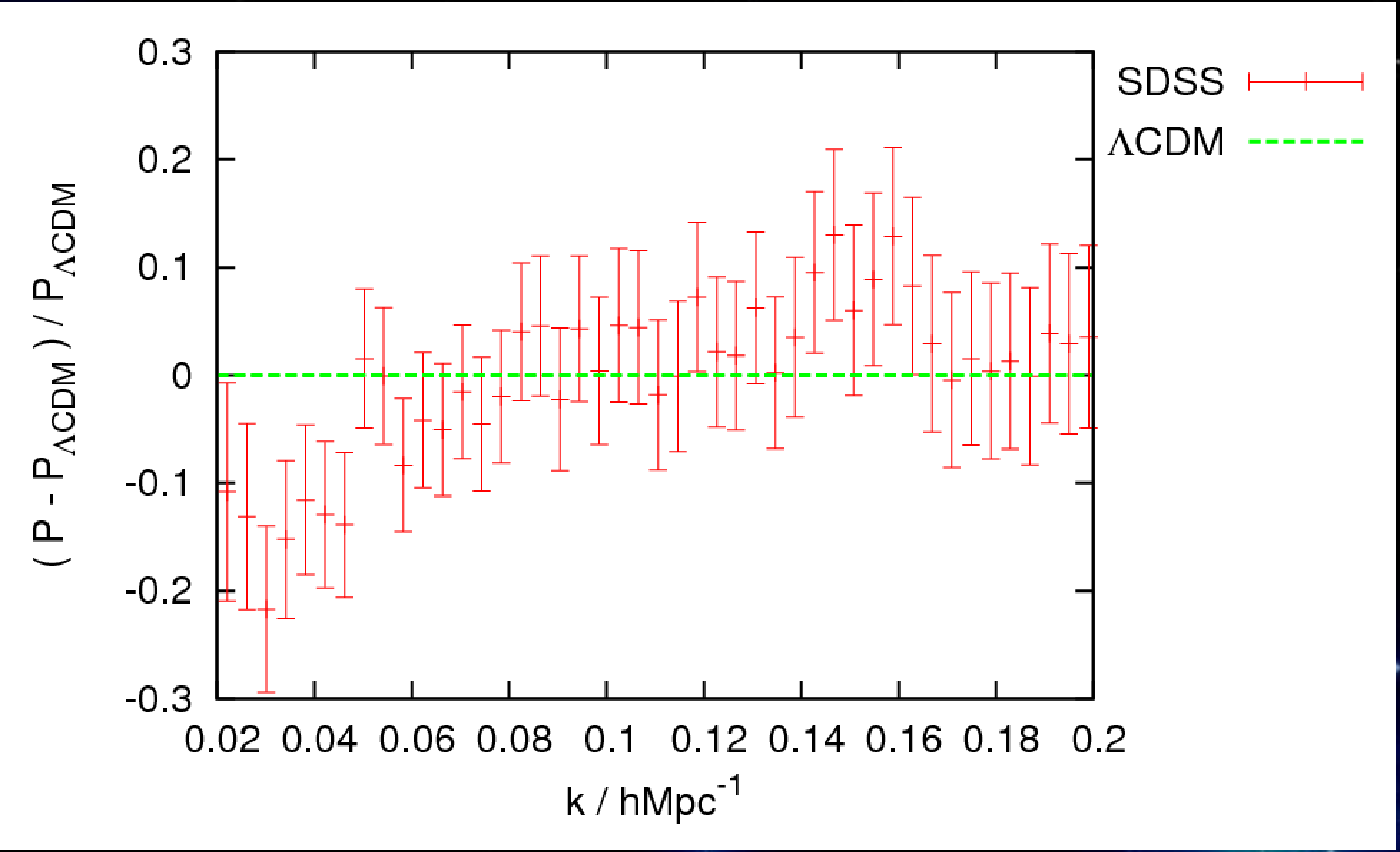


Massive neutrinos

- Free streaming scale

$$k_{\rm fs}(z) \simeq \frac{0.35}{(1+z)^{1/2}} \left(\frac{m_\nu}{1\ \rm eV}\right) \left(\frac{\Omega_m}{0.27}\right)^{1/2} h\ \rm Mpc^{-1}$$

Massive neutrinos break the structure below $k_{\rm fs}$.

- Bounds for total neutrino mass

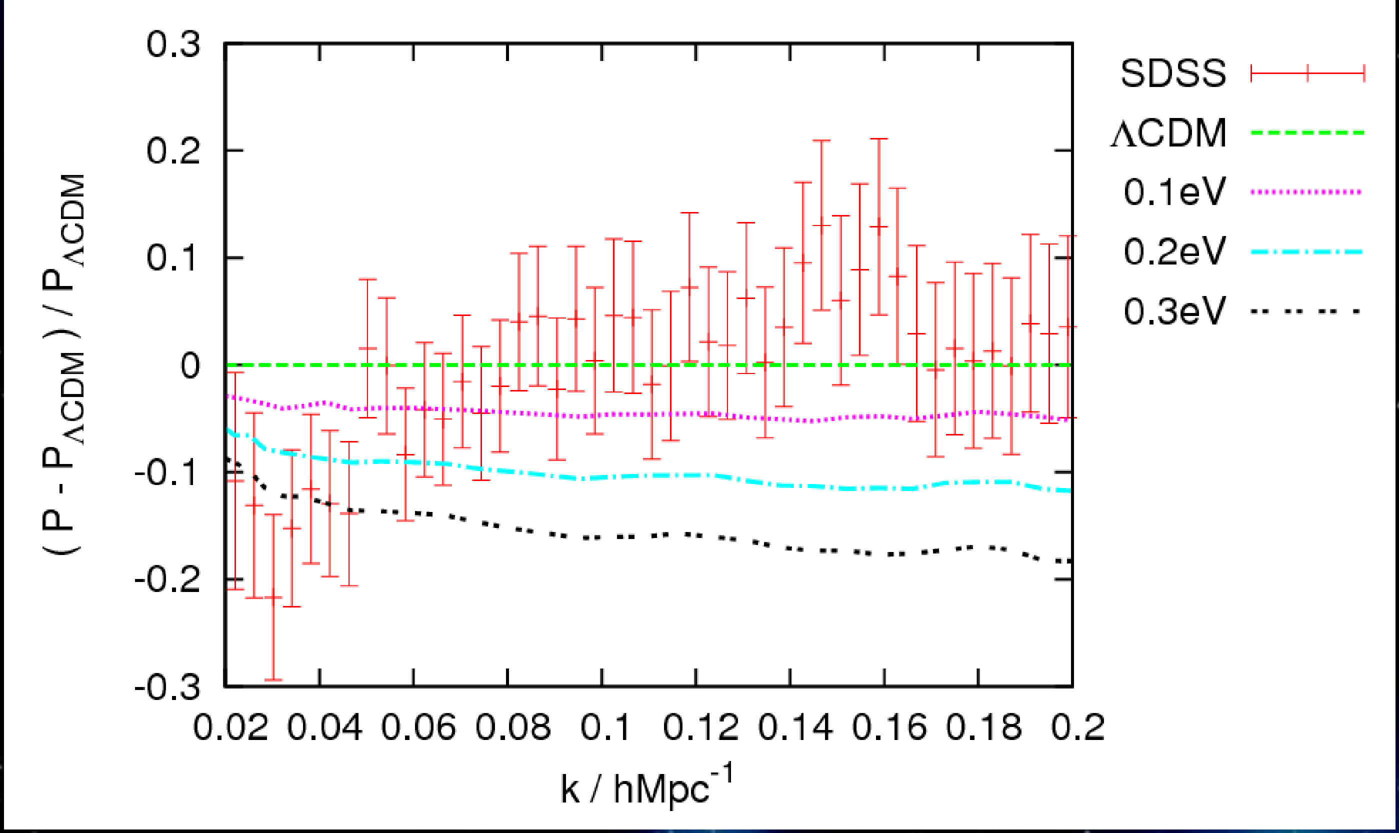
0.058 eV < $\sum m_\nu$ < 0.3 – 0.6 eV

< 0.58 eV (WMAP7 only)

$$\Omega_\nu h^2 = \frac{\sum m_\nu}{94.1 \rm eV}$$

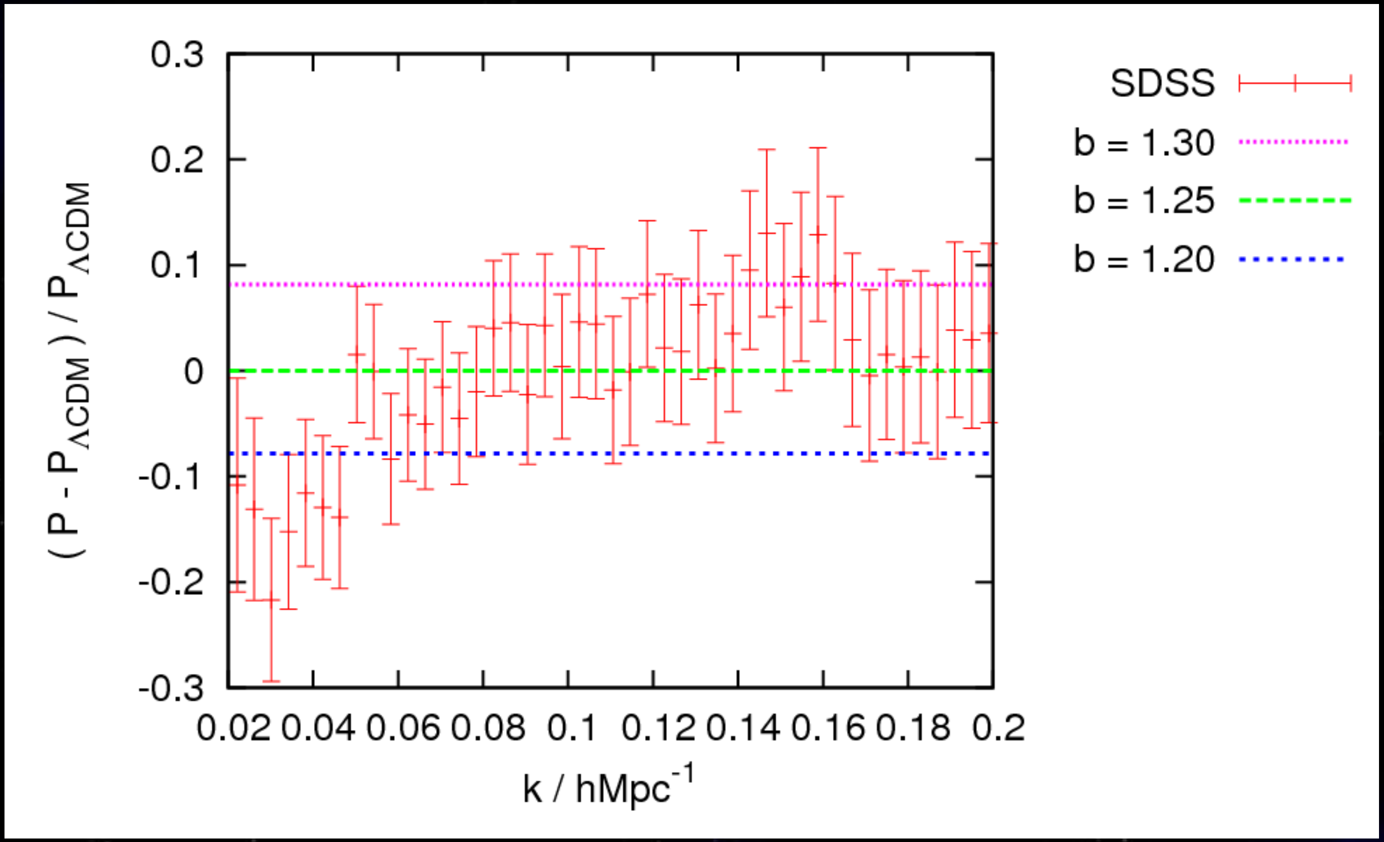
Massive neutrinos

$\sum m_\nu$ suppresses $P(k)$ and fit becomes worse.



Bias parameter $b\ (=\mathrm{const.})$

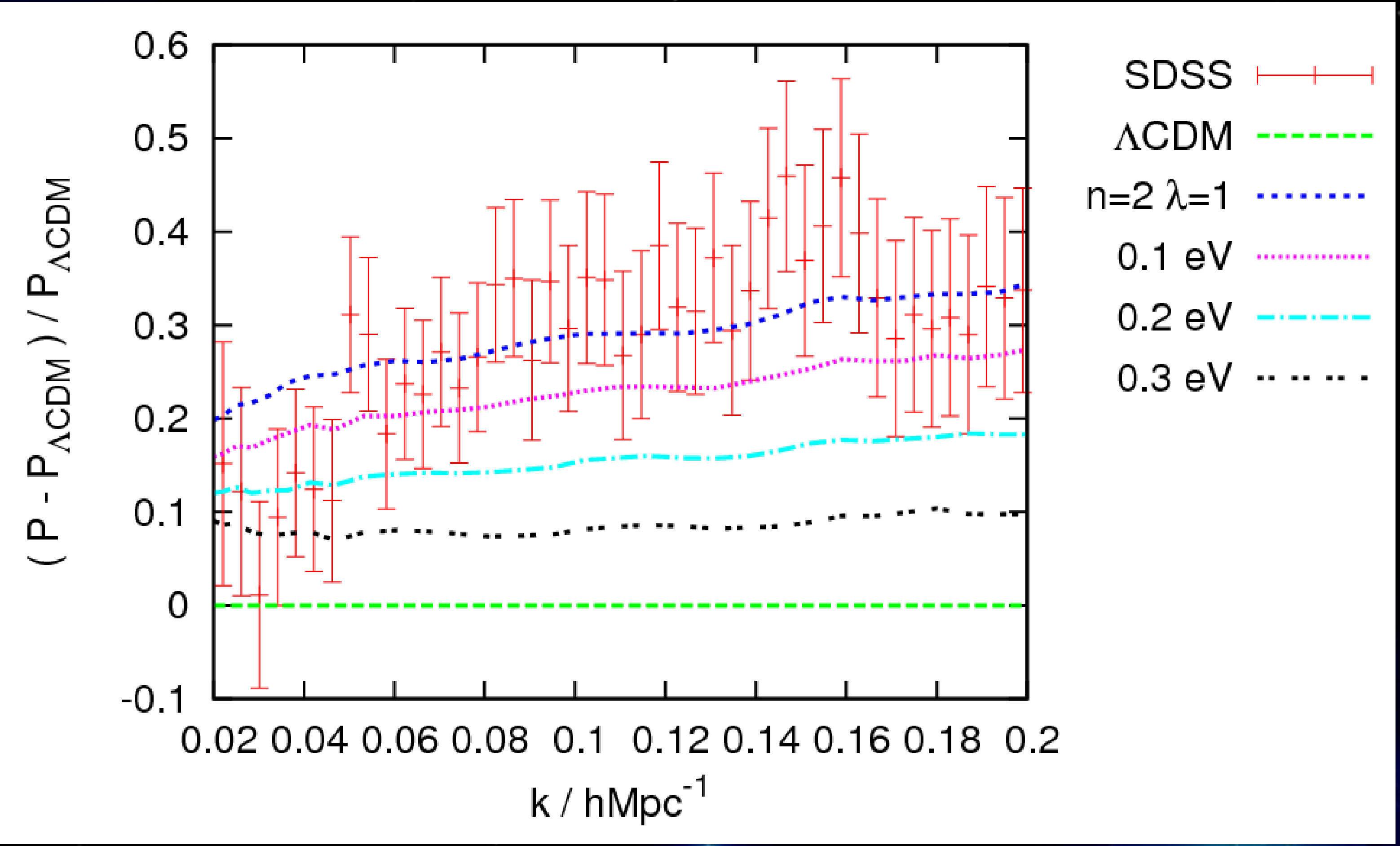
b makes only parallel translation.



- scale dep. bias $b(k)$, nonlinear bias
- $f(R)$ gravity

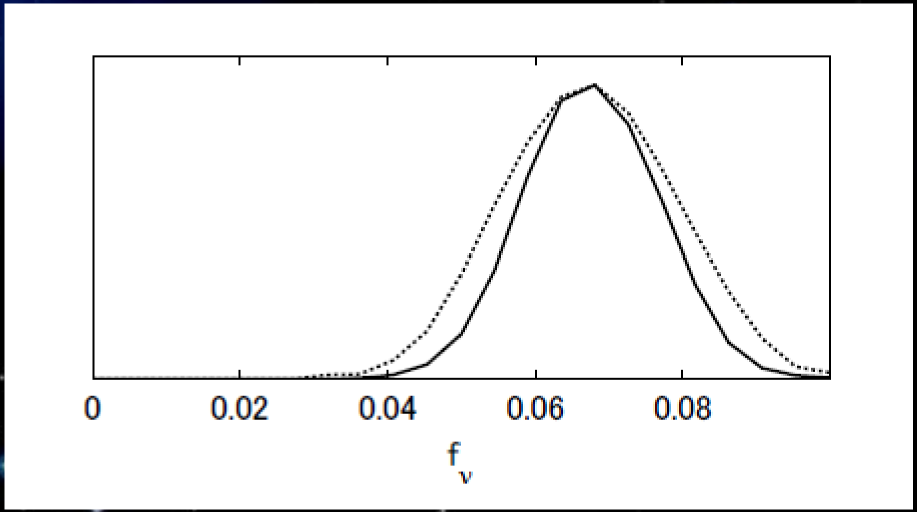
$P(k): f(R)$ gravity

- $P(k)$ increases with k.
- $f(R)$ gravity allows the suppression by massive neutrinos.



MCMC analysis: ΛCDM

$$f_\nu = \frac{\Omega_\nu}{\Omega_m}$$



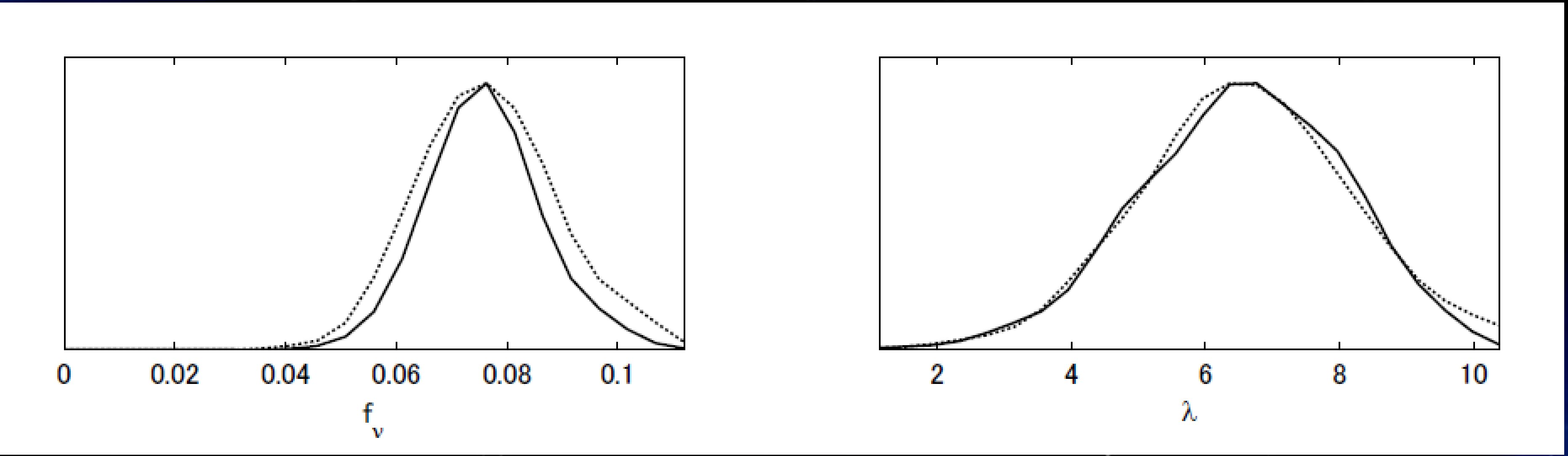
$$f_{\nu,\mathrm{mean}} = 0.0672$$

(Cosmological parameters: WMAP7)

MCMC analysis: $f(R)$ gravity

- $f(R)$ gravity relaxes the upper bound on neutrino mass.

H.M., Yokoyama, Starobinsky (in preparation)



$$f_{\nu,\mathrm{mean}} = 0.0754 \qquad \lambda_{\mathrm{mean}} = 6.59$$

(Cosmological parameters: WMAP7, $n = 2$)

See also: Hojjati, Pogosian, Zhao (2011)

Summary & Future works

Summary

- $f(R)$ gravity enhances the structure formation.
- $\gamma(z)$ (G_{eff}) depends on time and scale.
- The upper bound on $\sum m_\nu$ is relaxed in $f(R)$ gravity.

Future works

- MCMC analysis of background evolution.
- Gauge issues on density fluctuations.