Constraints on deviation from Newton's law of gravity from large-scale structure

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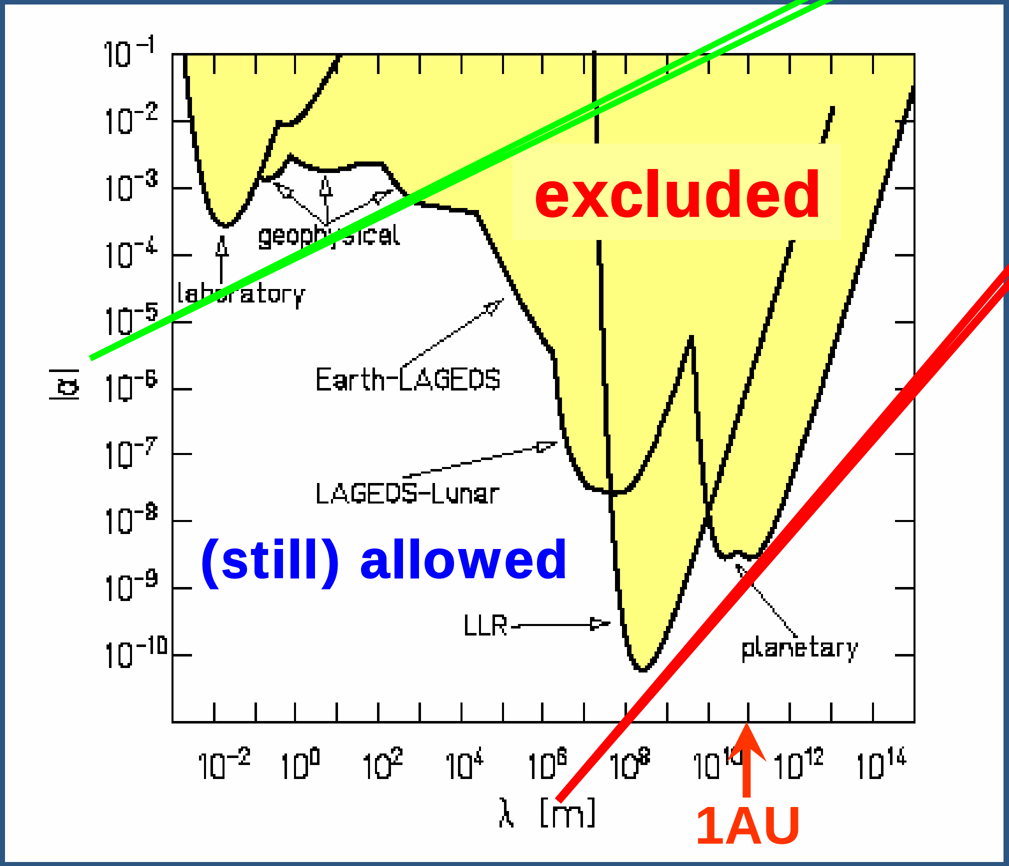
Current constraints on deviations from Newton's law of gravity

Assume the Yukawa-type deviation:

$$V(r) = -G\frac{m_1 m_2}{r}\left\{1+\alpha\exp\left(-\frac{r}{\lambda}\right)\right\}$$



weak, if any, constraints on cosmological scales so far…

E.G. Adelberger et al. Ann.Rev.Nucl.Part.Sci. 53 (2003) 77

Recent inspirations from brane-world scenario on modified gravity

cosmic acceleration:

induced by dark energy or by extra-dimension ?
matter content or law of physics ?

an example: the DGP model; gravity leaking to extra dimensions

"modified" Friedmann equation **(M.Longair in this meeting)**

$$H^2 = H_0^2\left[\Omega_k(1+z)^2 + \left\{\sqrt{\Omega_M(1+z)^3+\Omega_{rc}} + \sqrt{\Omega_{rc}}\right\}^2\right]$$

$$\Omega_{rc} \equiv \frac{1}{4r_c^2 H_0^2}$$

"modified" Newton Potential

$$V(r) = -\frac{G_{(4)}}{r}\left[1+\frac{2}{\pi}\left\{-1+\gamma+\ln\left(\frac{r}{r_c}\right)\right\}\left(\frac{r}{r_c}\right)+O(r^2)\right] \; : \; r << r_c \sim \frac{1}{H_0}$$

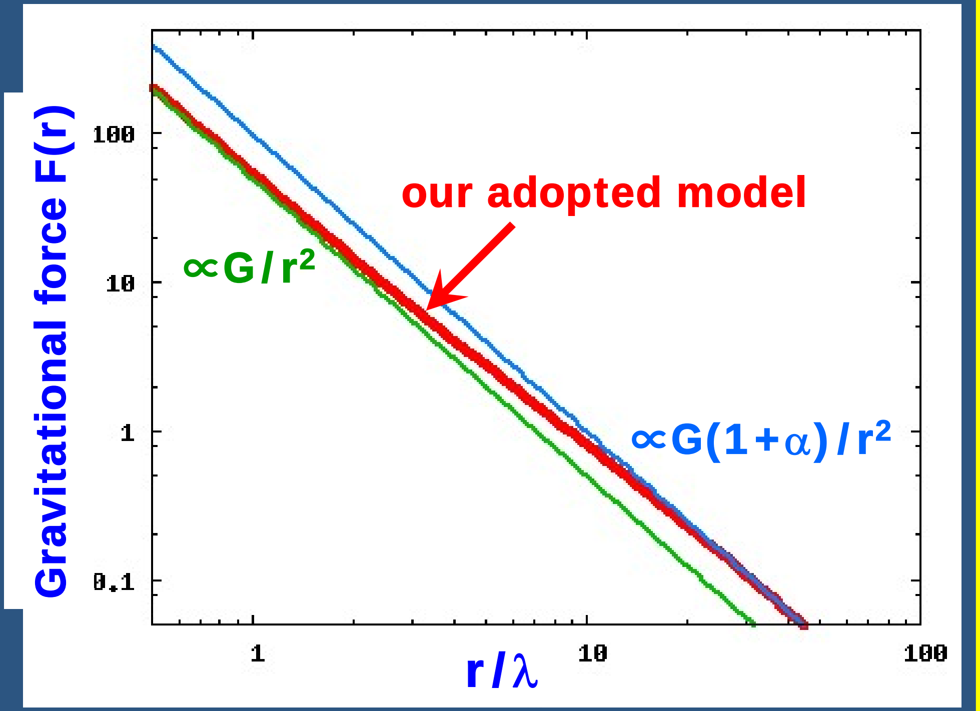
Dvali, Gabadadze & Porrati , PLB 485 (2000) 208
Deffayet, Dvali & Gabadadze, PRD 65 (2002) 044023

Empirical constraints on deviations from Newton's law of gravity via SDSS galaxy P(k)

- ad-hoc and empirical approach (Shirata et al. 2005; Sealfon et al. 2005)
  - adopt the standard Friedmann model (i.e, ΛCDM) but with ***an additional Yukawa term*** to gravity
  - adopt the standard interpretation of CMB anisotropy as the initial condition for the primordial fluctuations
  - assume ***scale-independent bias of SDSS galaxies***
- we are currently repeating the similar analysis for the DGP model (Shirata et al. in preparation)
- See also Frieman & Gradwohl (1991), Gradwohl & Frieman (1992), and Nusser, Gubser & Peebles (2005)

Yukawa-type additional gravitational potential

$$V(r) = -G\int d^3r' \frac{\rho(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|}\left[1+\alpha\left(1-e^{-\frac{|\mathbf{r}-\mathbf{r}'|}{\lambda}}\right)\right]$$



small-scale: Newtonian gravity

$r \ll \lambda$:

$$V(r) \to -G\int d^3r' \frac{\rho(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|}$$

large-scale: G ⇒ G(1+α)

$r \gg \lambda$:

$$V(r) \to -G(1+\alpha)\int d^3r' \frac{\rho(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|}$$

stronger (weaker) gravity on large scales if $\alpha>0$ ($\alpha<0$), while cosmic expansion is dictated by "correct" G

Method (Shirata et al. 2005)

1) directly solve the linear perturbation equation under the modified Newtonian potential:

$$\ddot{\delta}_{\mathbf{k}} + 2H\dot{\delta}_{\mathbf{k}} - 4\pi G\bar{\rho}\delta_{\mathbf{k}}\left[1+\alpha\frac{(a/k\lambda)^2}{1+(a/k\lambda)^2}\right] = 0$$

assuming the initial conditions of

$$\delta_{\mathbf{k}}(a_{ini}) = \delta_{\mathbf{k},\Lambda CDM}(a_{ini}), \quad \left.\frac{d\delta_{\mathbf{k}}}{da}\right|_{a=a_{ini}} = \left.\frac{d\delta_{\mathbf{k},\Lambda CDM}}{da}\right|_{a=a_{ini}}$$

2) apply the nonlinear correction using the Peacock-Dodds formula

3) Compare the model predictions with SDSS galaxy P(k) assuming linear bias ($0.01<k[h^{-1}\mathrm{Mpc}]<0.3$)

the exact solution in the Einstein-de Sitter model

$$\ddot{\delta}_{\mathrm{k}} + 2H\dot{\delta}_{\mathrm{k}} - 4\pi G\bar{\rho}\delta_{\mathrm{k}}\left[1 + \alpha\frac{(a/k\lambda)^2}{1+(a/k\lambda)^2}\right] = 0$$

(α : amplitude, λ : scale, of the additional Yukawa term)

$$\lambda = 0 \quad \Rightarrow \quad \delta_k \propto a^{-\frac{1}{4}\pm\frac{\sqrt{1+24(1+\alpha)}}{4}}$$

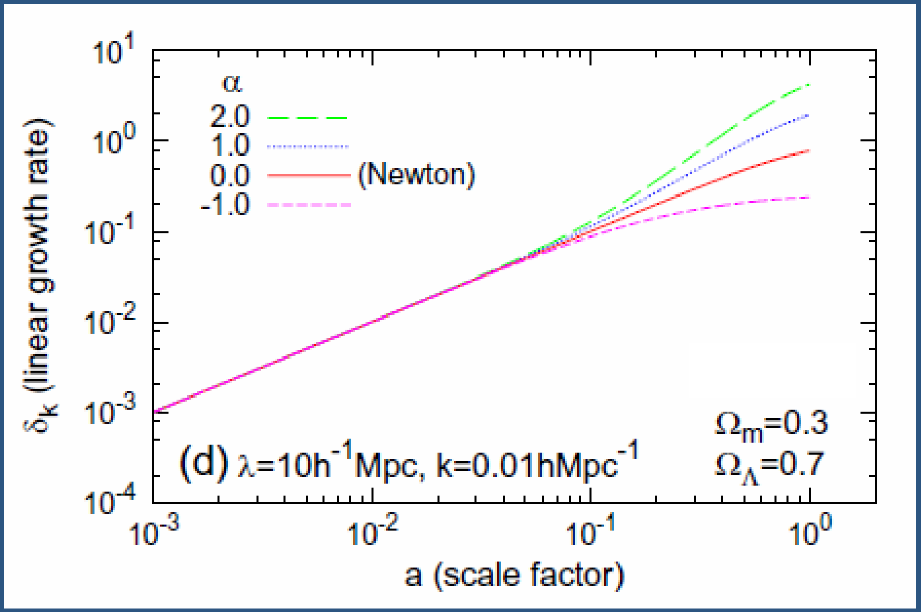
$$\lambda \neq 0$$

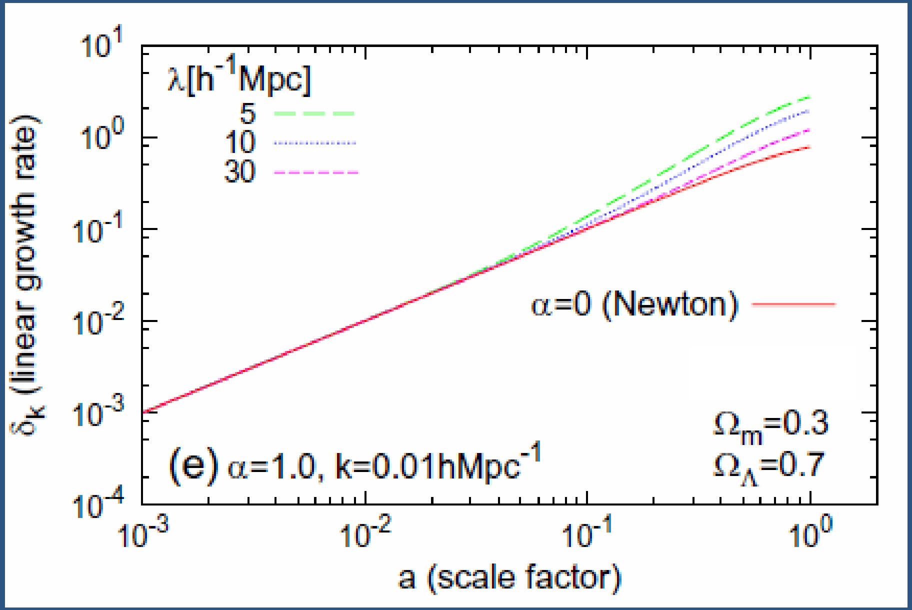
$$\Rightarrow \delta_k = C_1 \frac{a}{k\lambda} \, {}_2F_1\left(\frac{5}{8} - \frac{1}{8}\sqrt{25+24\alpha}, \frac{5}{8} + \frac{1}{8}\sqrt{25+24\alpha}, \frac{9}{4}, -\left(\frac{a}{k\lambda}\right)^2\right)$$

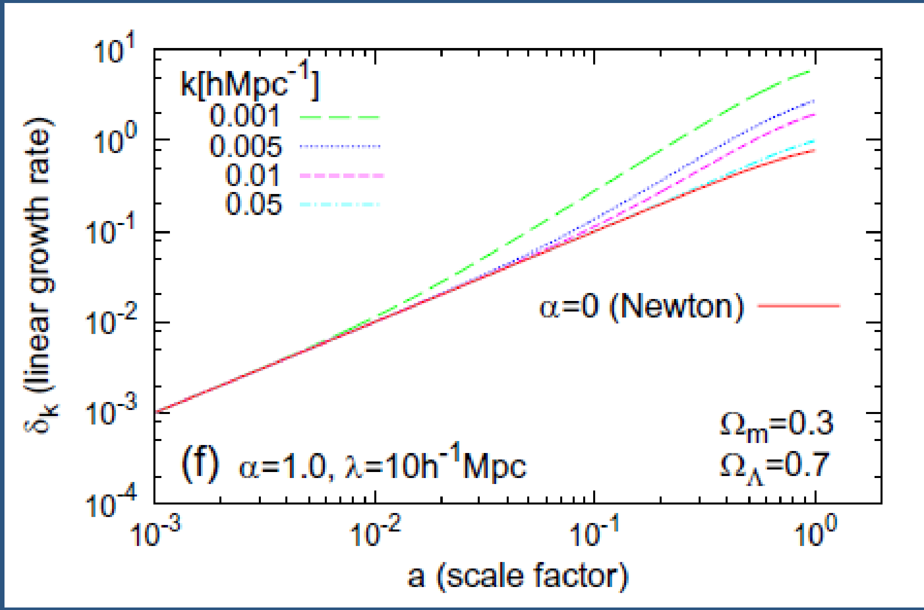
$$+ C_2\left(\frac{a}{k\lambda}\right)^{-3/2} {}_2F_1\left(-\frac{5}{8} - \frac{1}{8}\sqrt{25+24\alpha}, -\frac{5}{8} + \frac{1}{8}\sqrt{25+24\alpha}, -\frac{1}{4}, -\left(\frac{a}{k\lambda}\right)^2\right)$$

k-dependent linear growth rate of density fluctuations

$$V(r) = -G\int d^3r' \frac{\rho(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|} \times\left[1+\alpha\left(1-e^{-\frac{|\mathbf{r}-\mathbf{r}'|}{\lambda}}\right)\right]$$

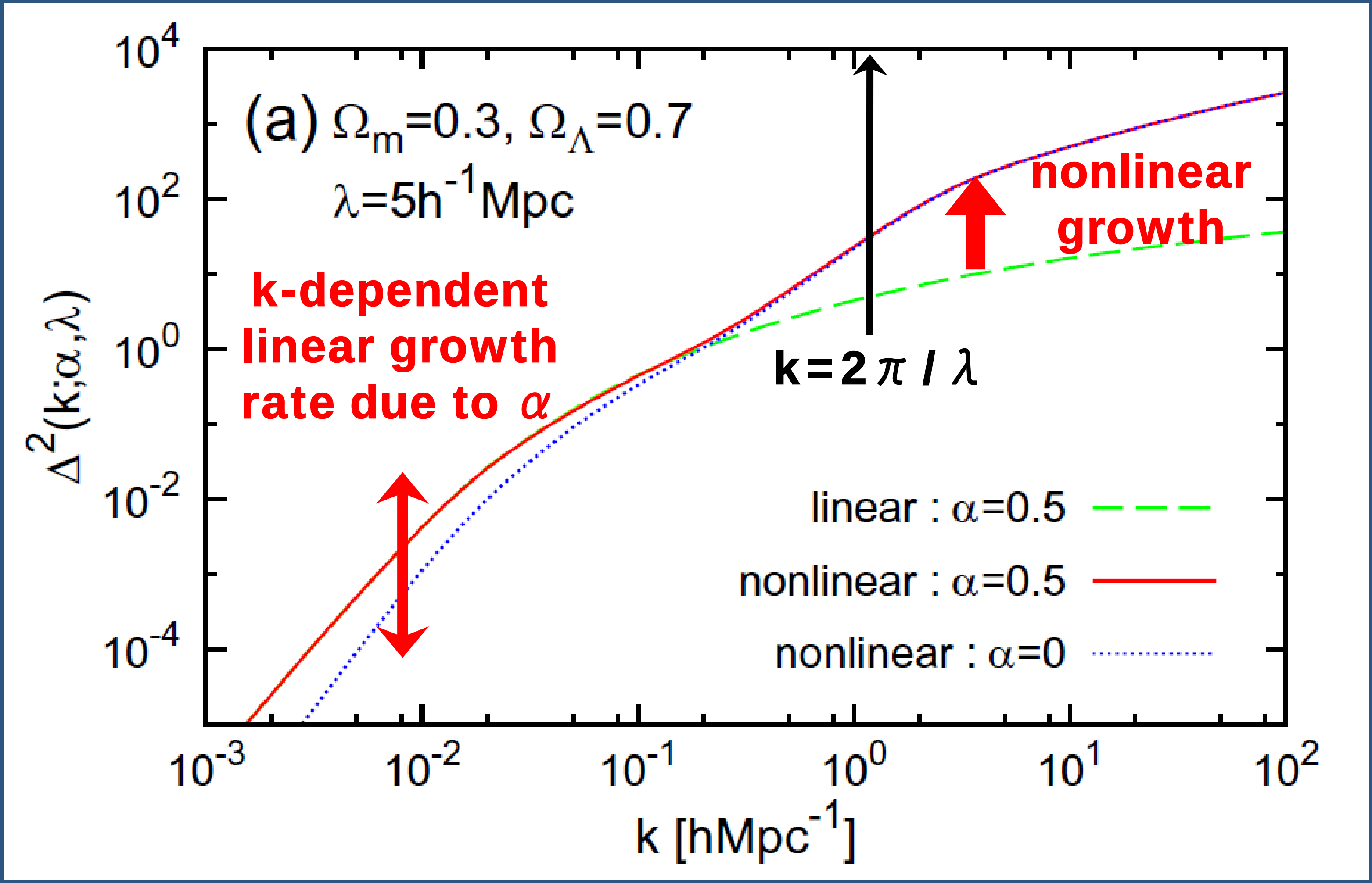






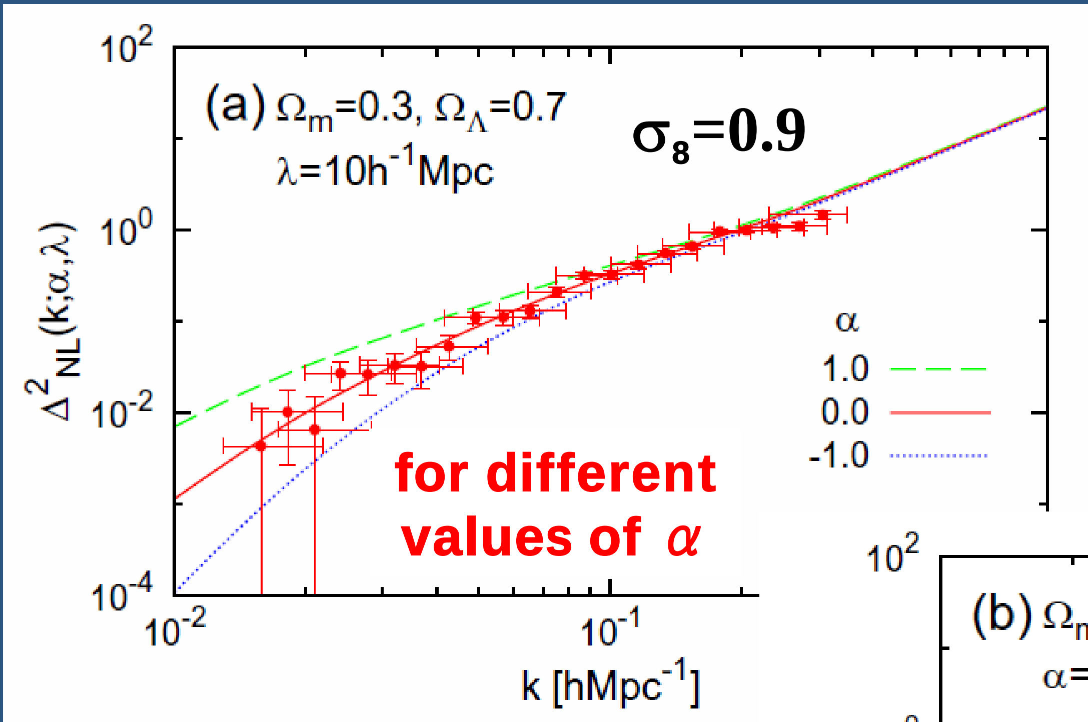
Shirata, Shiromizu, Yoshida & Suto: Phys.Rev.D 71(2005) 064030

Nonlinear correction for power spectrum applying the Peacock-Dodds fit

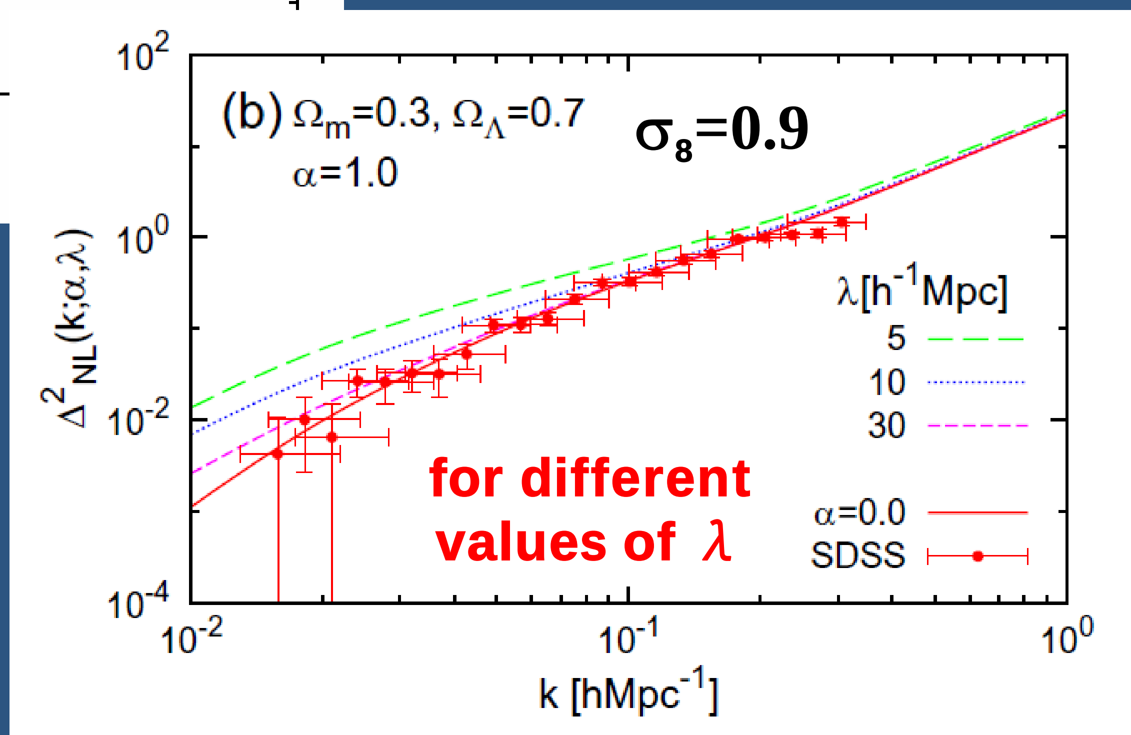


Shirata, Shiromizu, Yoshida & Suto: Phys.Rev.D 71(2005) 064030

Comparison with SDSS galaxy P(k)



● SDSS galaxy P(k) corrected for redshift-space distortion (Tegmark et al. 2004)

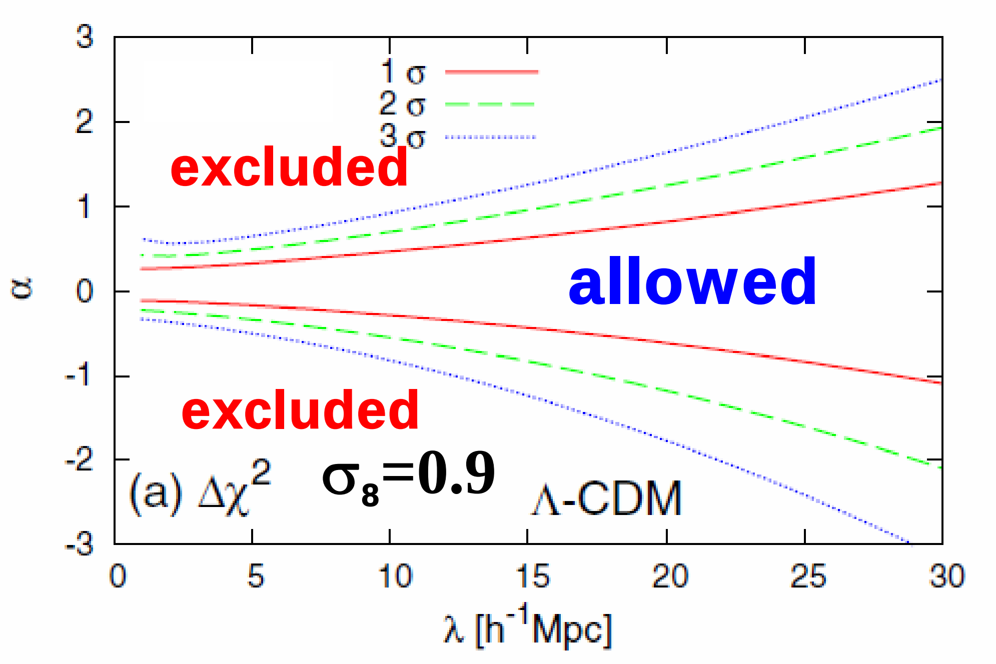


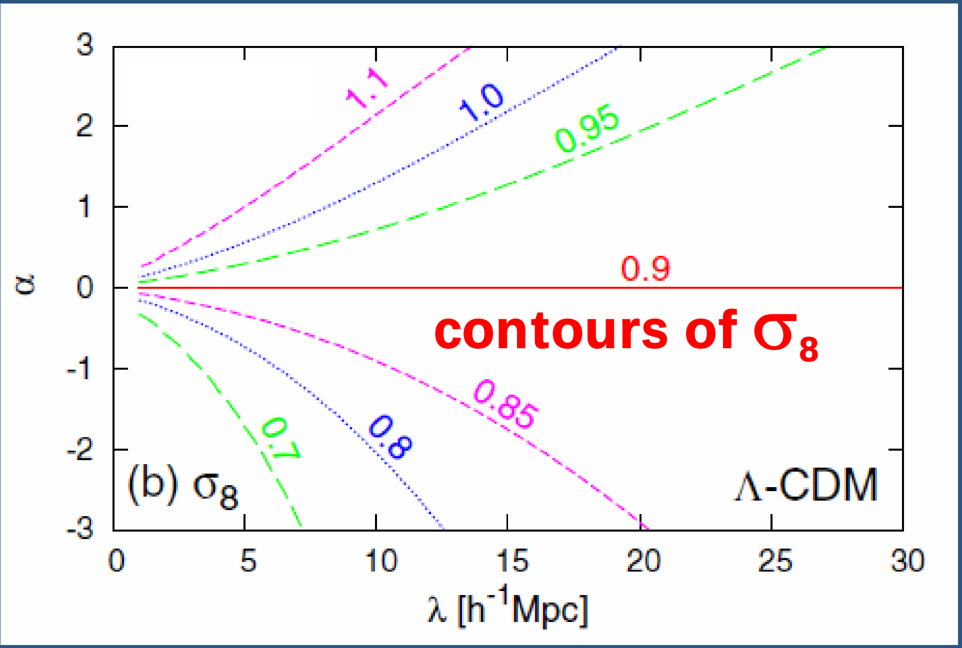
lines: model predictions by Shirata et al. (2005) for

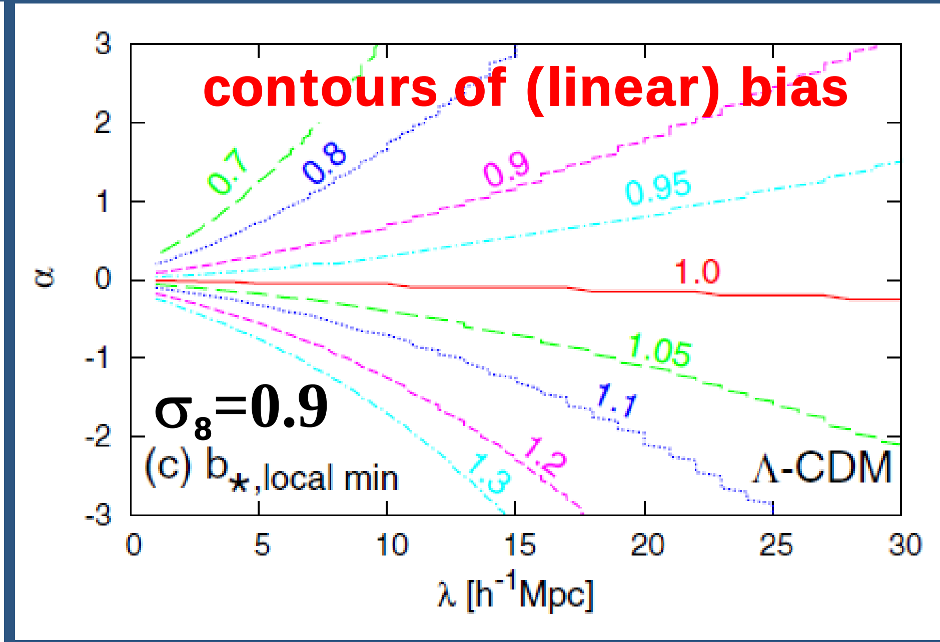
$$V(r) = -G\int d^3r' \frac{\rho(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|} \times\left[1+\alpha\left(1-e^{-\frac{|\mathbf{r}-\mathbf{r}'|}{\lambda}}\right)\right]$$

Constraints on model parameters

$$V(r) = -G\int d^3r' \frac{\rho(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|} \times \left[1+\alpha\left(1-e^{-\frac{|\mathbf{r}-\mathbf{r}'|}{\lambda}}\right)\right]$$





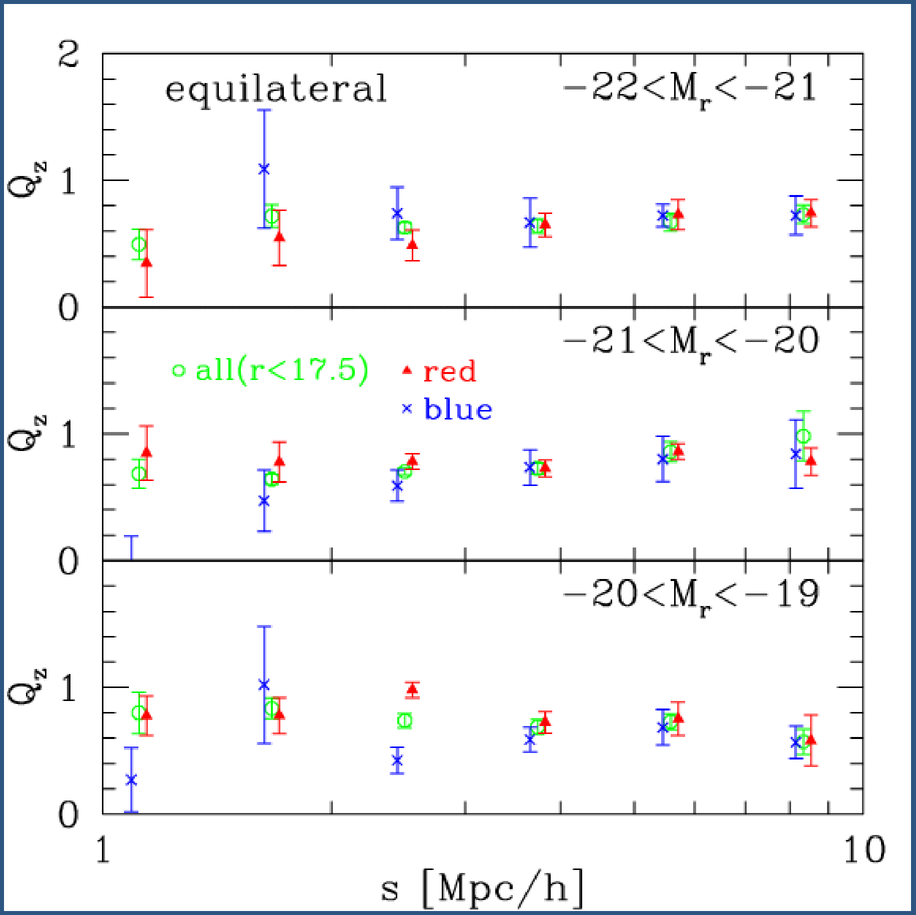


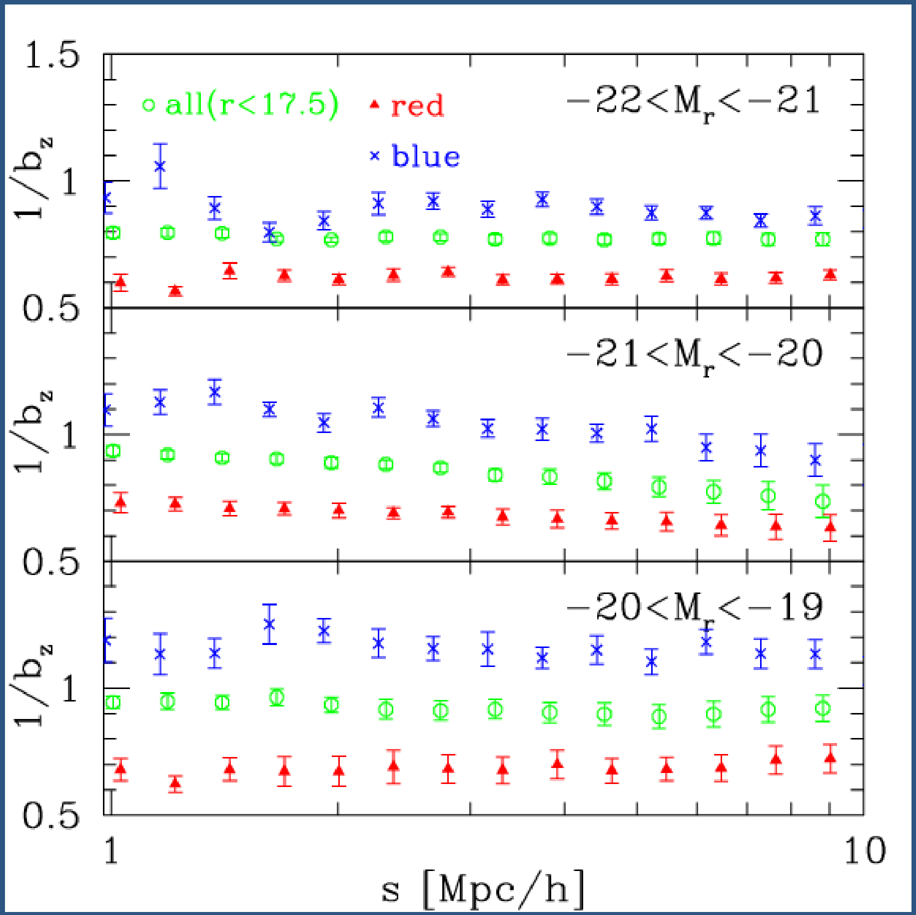
Shirata, Shiromizu, Yoshida & Suto: Phys.Rev.D 71(2005) 064030

Summary and outlook

- The SDSS galaxy clustering can constrain the possible deviations from the Newtonian gravity with an empirical Yukawa term correction
- currently we are repeating the analysis using a self-consistently modified model of cosmic expansion ***and*** local gravity law (Dvali et al. 2000)
- **Constraints on the Yukawa-type term**
  - $\lambda =$ 5h^{-1}Mpc $\Rightarrow$ $-0.5 < \alpha < 0.6$ (3σ limits)
  - $\lambda =$10h^{-1}Mpc $\Rightarrow$ $-0.8 < \alpha < 0.9$ (3σ limits)
- More stringent limits will be obtained by considering
  - fully nonlinear effect using N-body simulation
  - *higher-order statistics (e.g., 3pt functions, bi-spectrum)*

3pt correlation functions of SDSS galaxies *in redshift space*

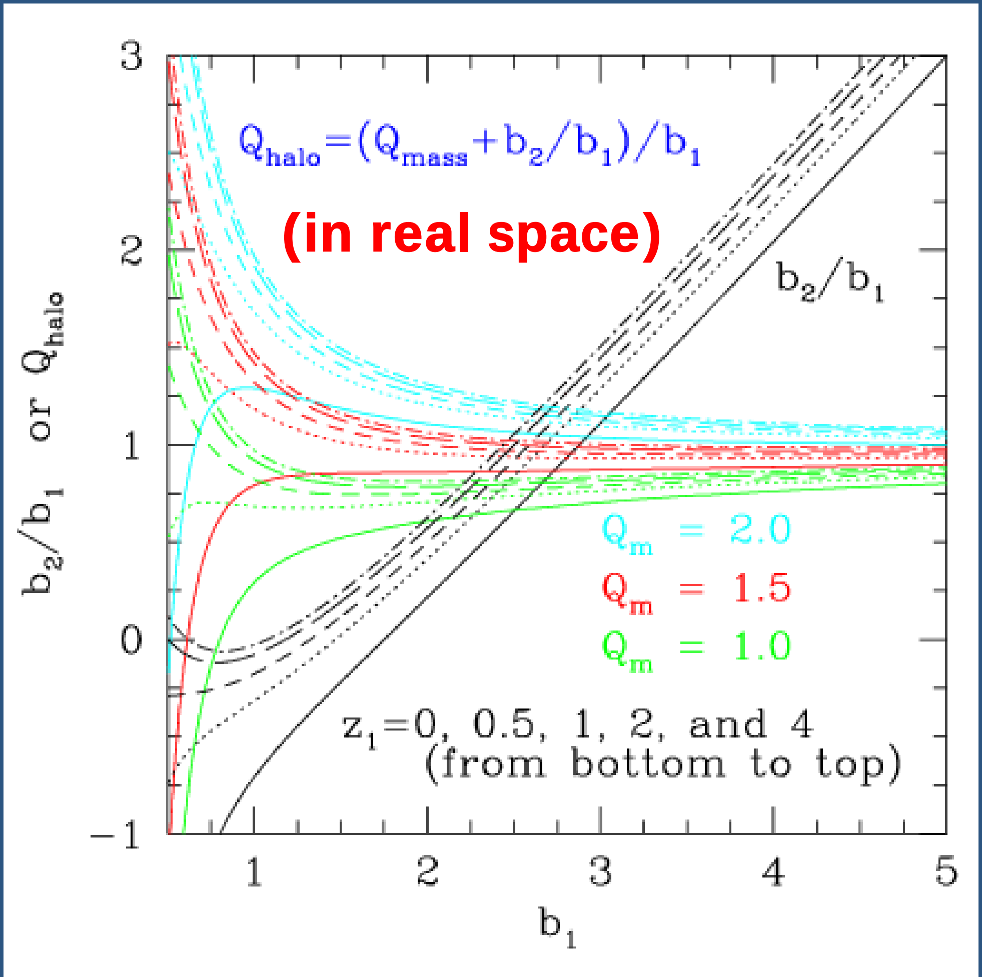




Clear luminosity, morphology and color dependences of (2pt) bias disappear in 3pt amplitude

Kayo, Suto, Nichol et al. PASJ 56(2004) 415

Halo biasing prediction for Q_{halo}



- Kayo et al.'s result implies a certain correlation between b_1 and b_2 ($\delta_g=b_1\delta_m+b_2\delta_m$)
- Indeed we found that this is the case in simple peak and halo biasing models (e.g., Mo, Jing & White 1997)
- maybe quite generic for galaxy biasing schemes mainly driven by gravity

Nishimichi, Suto & Jing, in preparation

Fourier phase correlation: phase-sum distribution function

- phase-sum distribution first derived by Matsubara (2003) in perturbation theory

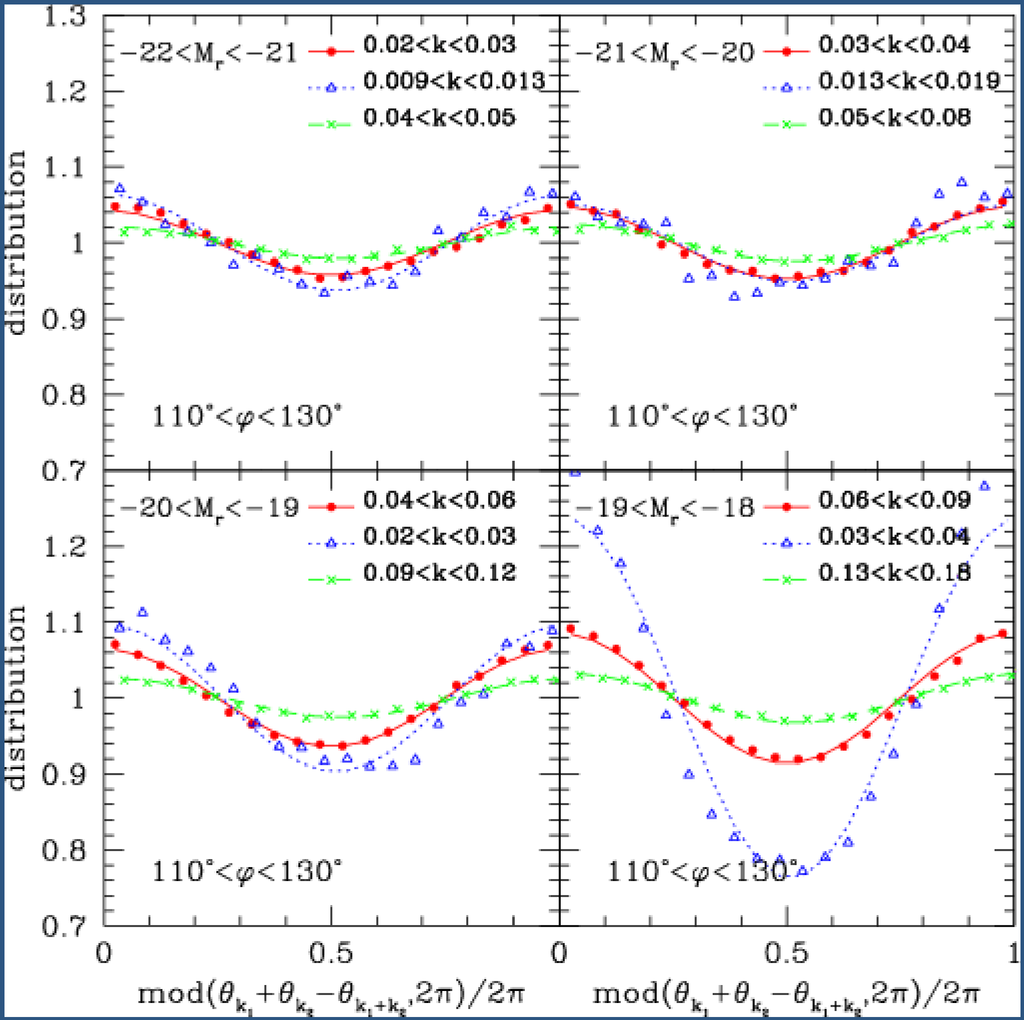
$$P(\theta_{\mathbf{k}_1} + \theta_{\mathbf{k}_2} - \theta_{\mathbf{k}_1+\mathbf{k}_2}) \propto 1 + \frac{\pi^{3/2}}{4} p^{(3)}(\mathbf{k}_1, \mathbf{k}_2) \cos\left(\theta_{\mathbf{k}_1} + \theta_{\mathbf{k}_2} - \theta_{\mathbf{k}_1+\mathbf{k}_2}\right) + \ldots$$

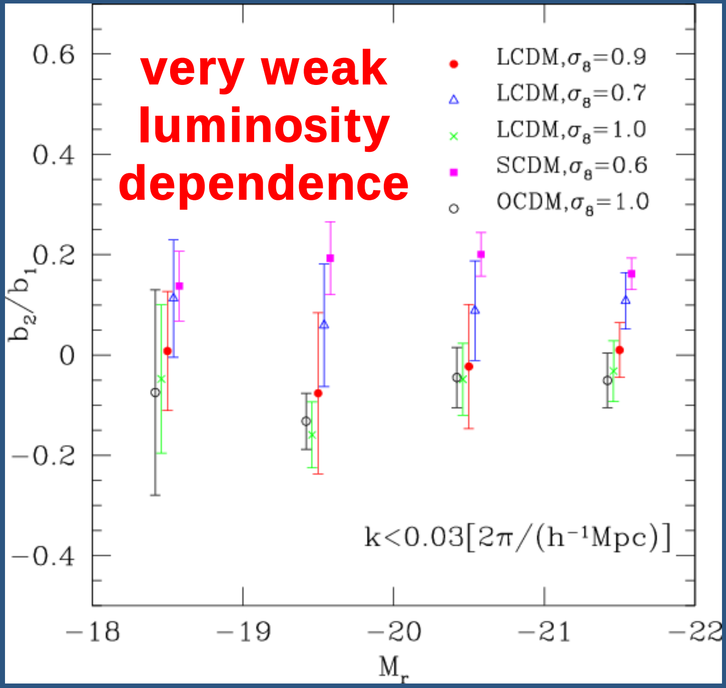
$$p^{(3)}(\mathbf{k}_1, \mathbf{k}_2) = \frac{B(\mathbf{k}_1, \mathbf{k}_2)}{\sqrt{V_{\mathrm{samp}} P(k_1) P(k_2) P(|\mathbf{k}_1 + \mathbf{k}_2|)}} \quad \left(\approx \sqrt{\frac{P(k)}{V_{\mathrm{samp}}}} \ll 1\right)$$

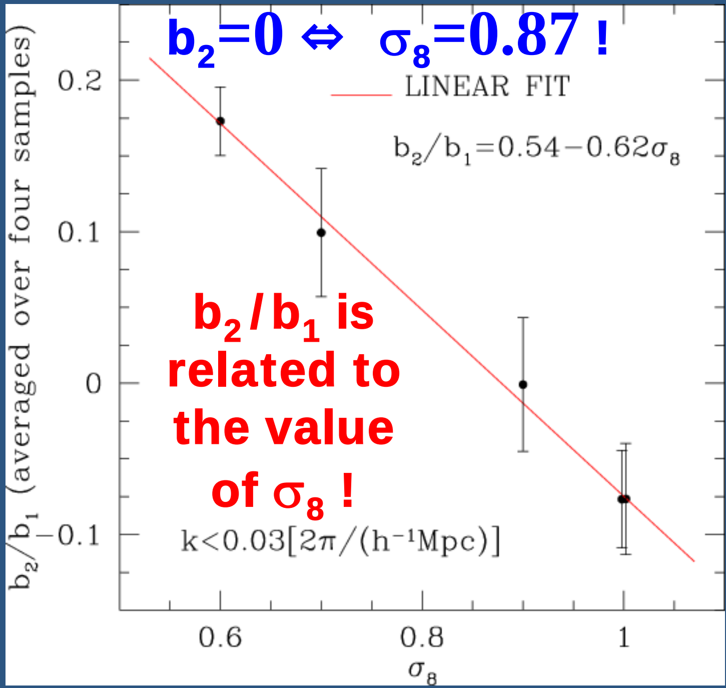
$B(k_1,k_2)$ bi-spectrum, $P(k)$ power spectrum, V_{samp} sampling volume

- wide validity confirmed by N-body simulation analysis
  - Hikage, Matsubara & Suto (2004)
- First application to SDSS galaxies
  - Hikage, Matsubara, Suto et al. PASJ (2005), submitted

Fourier phase analysis of SDSS galaxies







Hikage, Matsubara, Suto et al. PASJ (2005), submitted astro-ph/0506194