Pursuing Signatures of the Cosmological Light Cone Effect

or something else

Yasushi Suto

Department of Physics

The University of Tokyo

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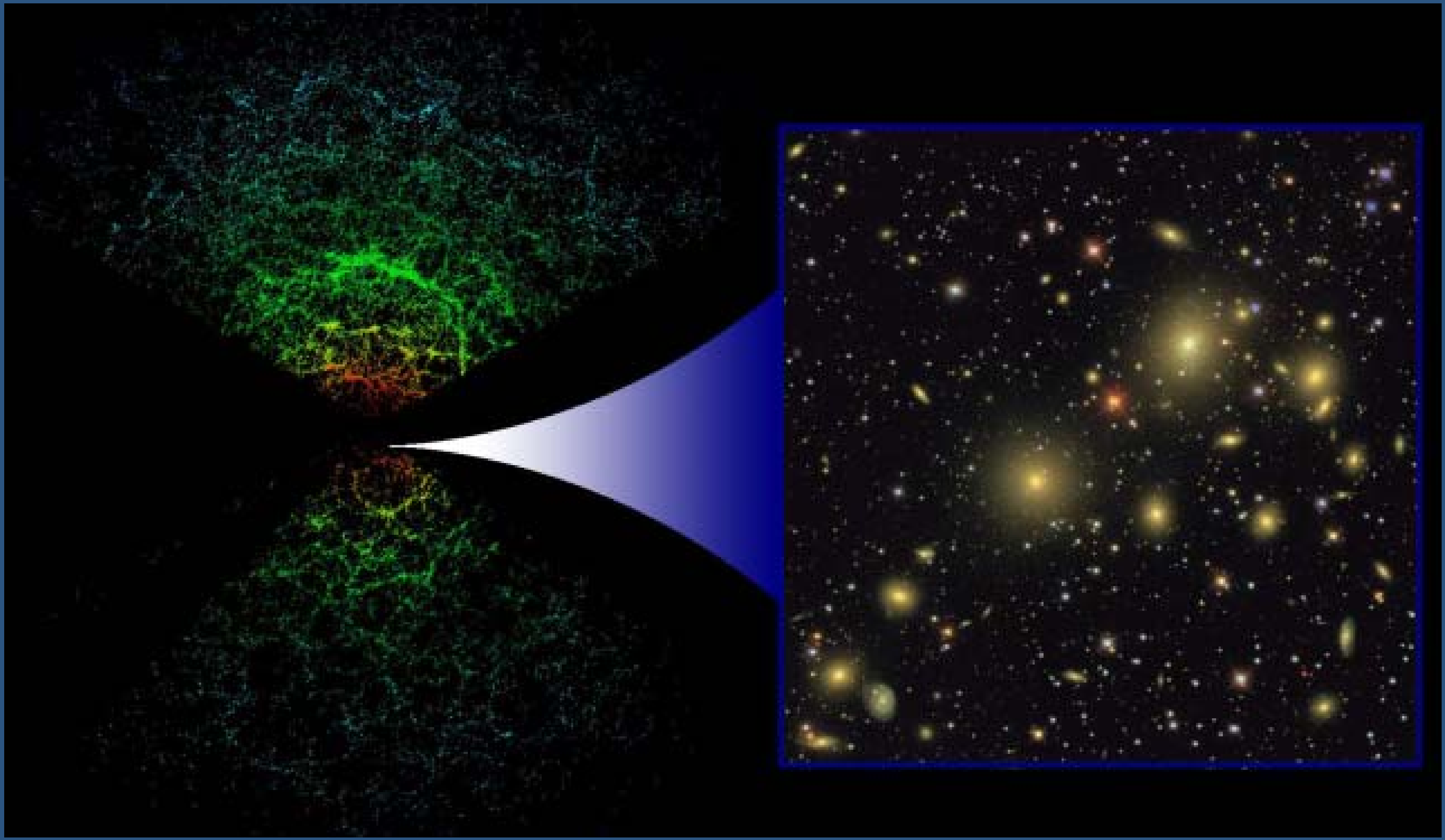
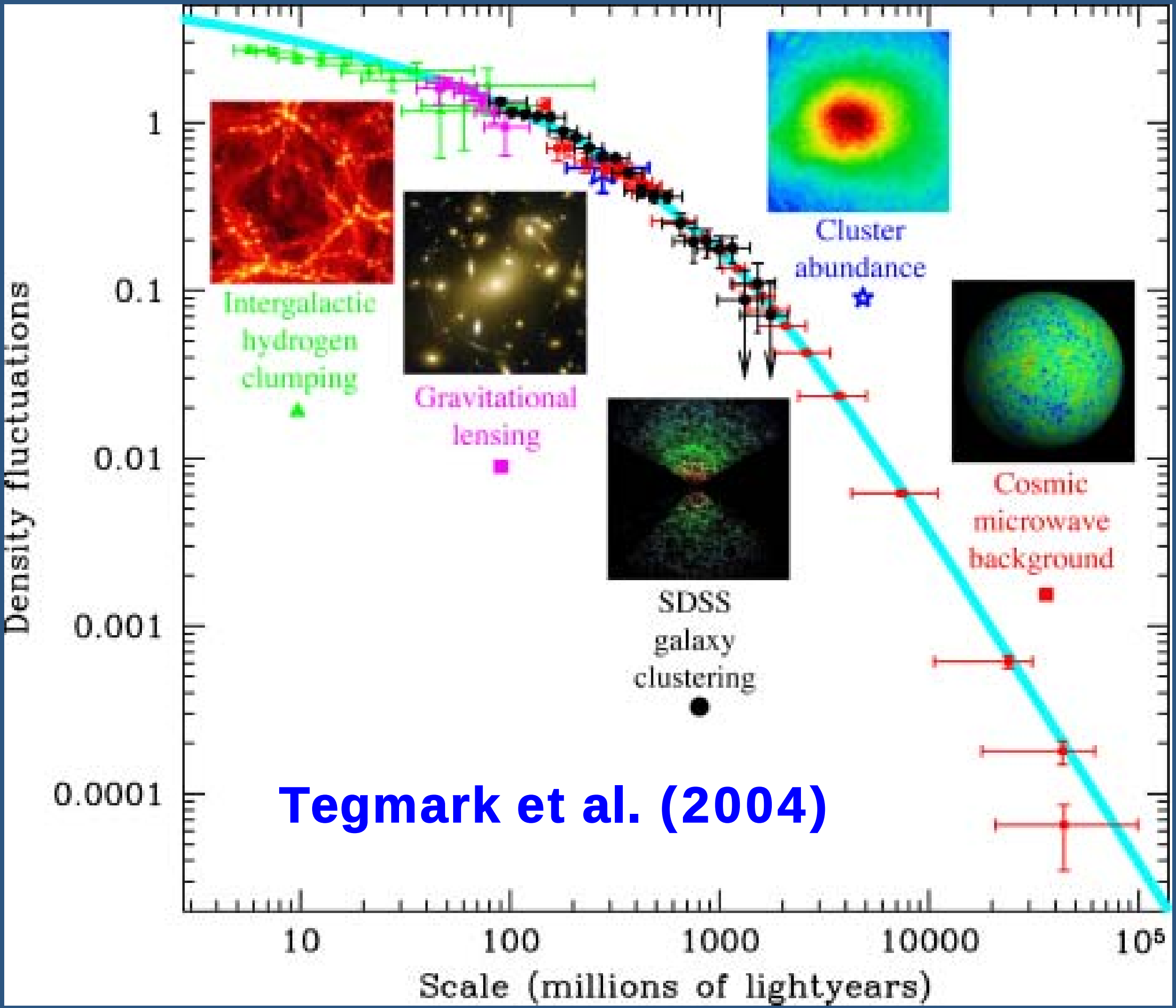
SDSS sample of galaxies



Non-trivial success of observational cosmology



So what's next ?

- Precision cosmology, not yet ?
  - We have to move on; determine all the cosmological parameters within 0.1% accuracy, for instance.
  - For what ? Really interesting ? Can convince taxpayers ?
- Beyond precision cosmology ?
  - Stop playing with the *values of parameters*, but try to understand *their meaning*, i.e., matter context in the universe
    - Nature of dark matter and dark energy
    - First objects in the universe
    - initial conditions (physical model of inflation)...
  - Revisit the cosmological observations in a more general framework
    - Equation of state of the universe
    - Validity of the cosmological principle
    - Validity of the general relativity on cosmological scales
- Or simply beyond cosmology itself !
  - Anthropic principle, Extrasolar planet, ...something else

Precise age and mass of a person

- Sometimes it is essential to know the critical values
  - Alcohol, driver’s license,
  - Olympic sports, some attraction in the Disney land
- Otherwise it is unlikely that we know our own weight within 1% precision, simply useless at all…
  - To be precise is not always appreciated, or even may be hated.
- Beyond some certain accuracy/precision, we need to convince ourselves why we need more ? Especially if it costs a lot.

Cosmological light-cone effect

- A conventional view (e.g., Matsubara & Suto 1996; Yamamoto & Suto 1998)
  - Clustering of cosmological objects is sensitive to yet unspecified many factors
    - Cosmological parameters
    - Evolution of objects and bias
  - In turn, a detailed comparison between predictions and observations constrains the values of such parameters (e.g., the next talk by Yahata)
- An alternative view
  - To check if quasars are really at cosmological distance
  - To check if general relativity applies at high redshifts

Physical law vs. matter content in the universe

- 1916： general relativity
- 1917： cosmological term

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

- 1980's～： vacuum energy

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G \left(T_{\mu\nu} - \frac{\Lambda}{8\pi G} g_{\mu\nu} \right)$$

- 1990's: decaying cosmological constant $\Lambda = \Lambda(t)$
- 2000's～: dark energy $p = w\rho$ or even $p = w(t)\rho$
- 2000's～: modification of gravity (physical law) instead of assuming dark energy (matter content): modify the left-hand-side again !

$$\tilde{G}_{\mu\nu} = 8\pi G T_{\mu\nu}$$

An example of attempts to look at the "old" observations in a new framework

"Constraining deviations
from the Newtonian gravity
on cosmological scales
using SDSS galaxy power spectrum"

Shirata, Shiromizu, Yoshida & Suto
to be submitted to Phys.Rev.D

Different attitudes in general relativistic cosmology

- **standard precision cosmology**

framework: general relativistic universe model

↓ cosmological observations

parameter estimation: Ω_b Ω_m Λ h …

- **amazingly successful, but too conventional !**
- **It is time to ask something beyond that.**
- **inversely, let us assume that we know the correct set of cosmological parameters, and then ask**

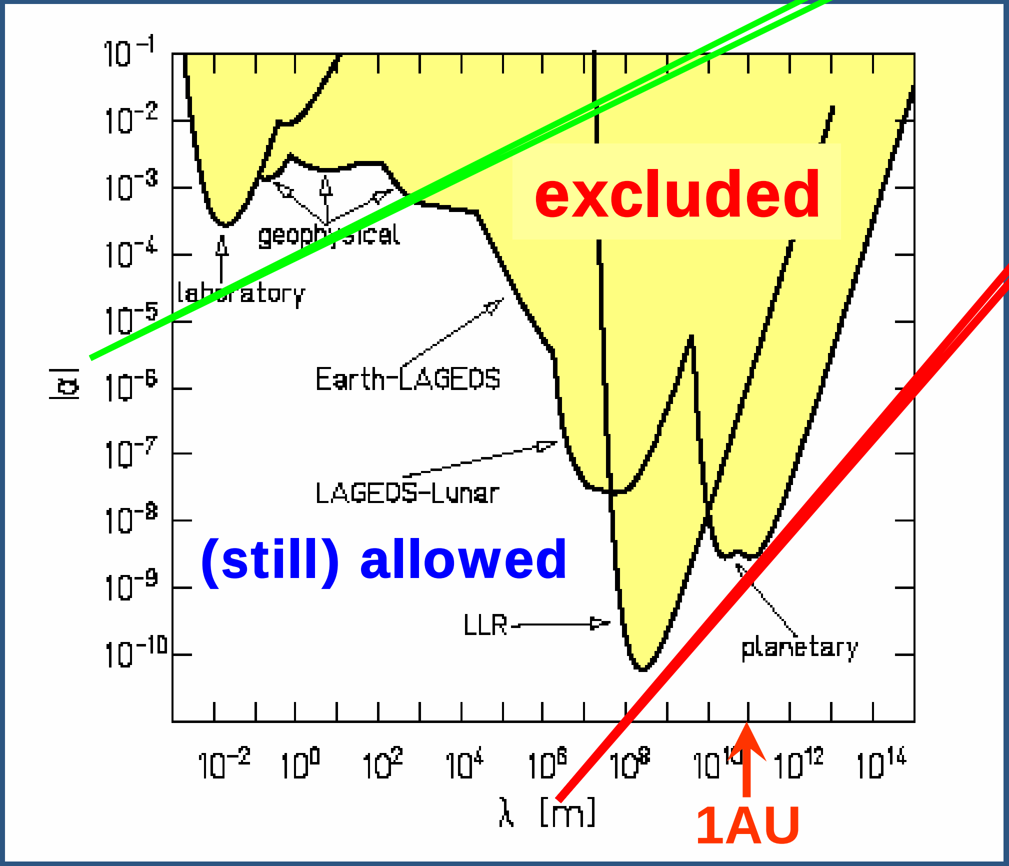
how accurate is the Newtonian gravity ?

- or more generally, attempt **the accurate test of general relativistic predictions on cosmological scales**.

Current constraints on deviations from Newton's law

Consider 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

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

recent inspirations from brane world scenario

cosmic acceleration induced by dark energy
or by extra-dimension ?
material content in the universe vs. law of physics ?

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

“modified” Friedmann equation

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

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

“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

in reality, barely indistiguishable from dark energy model...

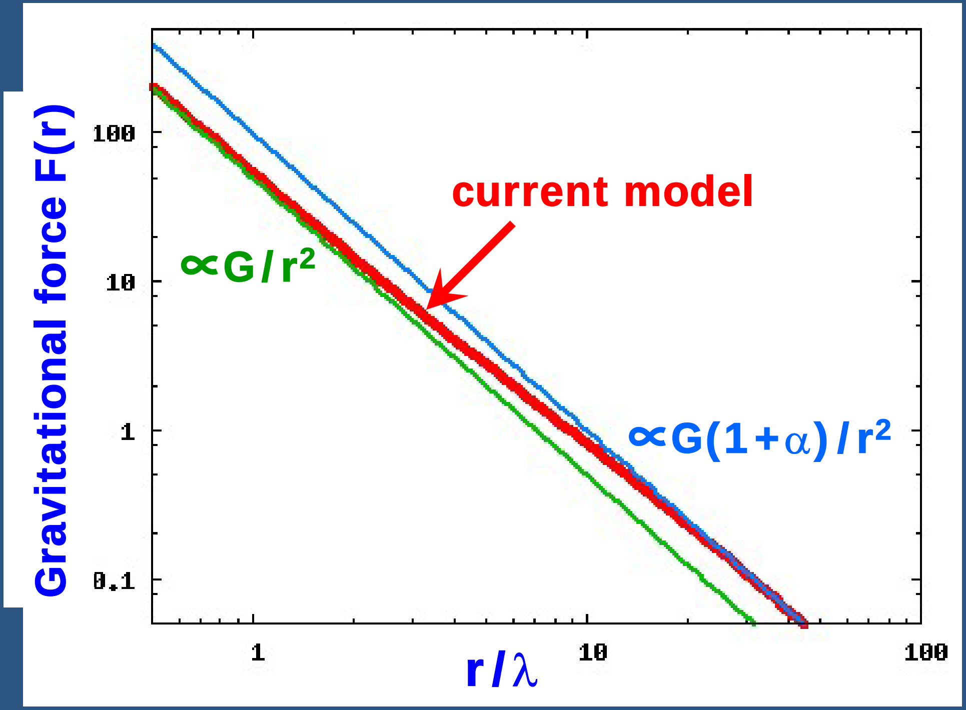
empirical constraints on deviations from Newton's law of gravitation using power spectrum of SDSS galaxies

- there is no established relativistic theory to predict the non-Newtonian gravity
- an empirical modeling (Sealfon et al. astro-ph/0404111)
  - adopt the standard Friedmann model with dark matter and cosmological constant
  - adopt the standard interpretation of CMB anisotropy as the initial condition for the primordial fluctuations
  - assume ***scale-independent bias of SDSS galaxies***
- different from Dvali et al.'s model. fairly empirical rather specific. we are currently repeating the analysis on the basis of Dvali et al.'s model

Yukawa-type additional gravitational potential

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

Note that this is a bit different parameterization



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)

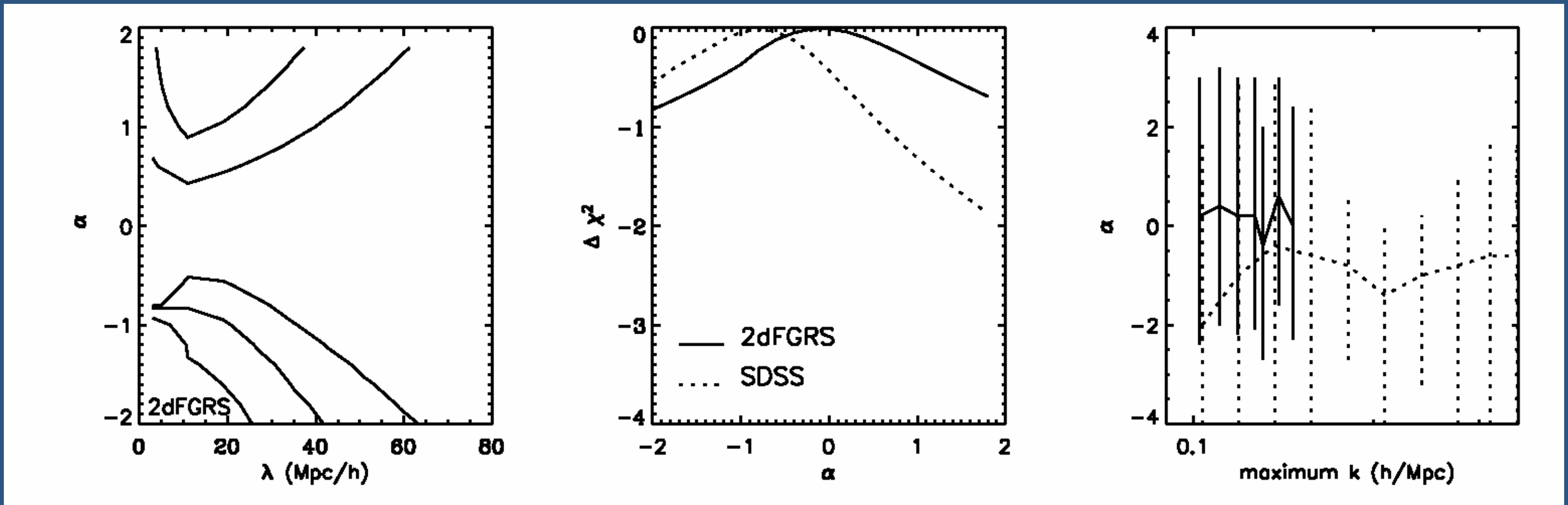
$r \gg \lambda$:

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

stronger (weaker) gravity on large scales
if $\alpha>0$ ($\alpha<0$)

Conclusion by Sealfon et al. astro-ph/0404111

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



for the range of 5 h^{-1}Mpc $<\lambda<$ 150 h^{-1}Mpc

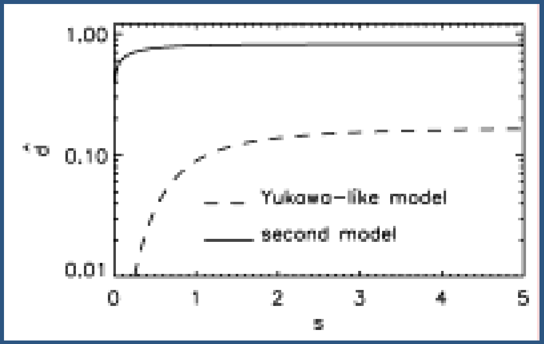
2dFGRS: $\alpha = 0.0^{+2.3}_{-2.3}$

SDSS: $\alpha = -0.8^{+1.4}_{-1.8}$

linear perturbation analysis

- Sealfon, Verde & Jimenez, astro-ph/0404111 attempted exactly what we had planned to do, but unfortunately their analysis is not satisfactory in the following two respects
  - they consider only the 1st-order term in α, although their final constraints extend even beyond $|\alpha|>1$!
  - they incorrectly assumed that the perturbation solution is a function of the scaling variable $s=a(t)/k\lambda$, but this is not the case...

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



$$\delta_k(t) = \delta_{\Lambda CDM}(t)\left[1+\alpha\,\hat{d}(s)\right] \quad \left(s=\frac{a(t)}{k\lambda}\right)$$

our method (Shirata et al. 2004)

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-Dodd formula

Still preliminary results !

exact solution in the Einstein-de Sitter model

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

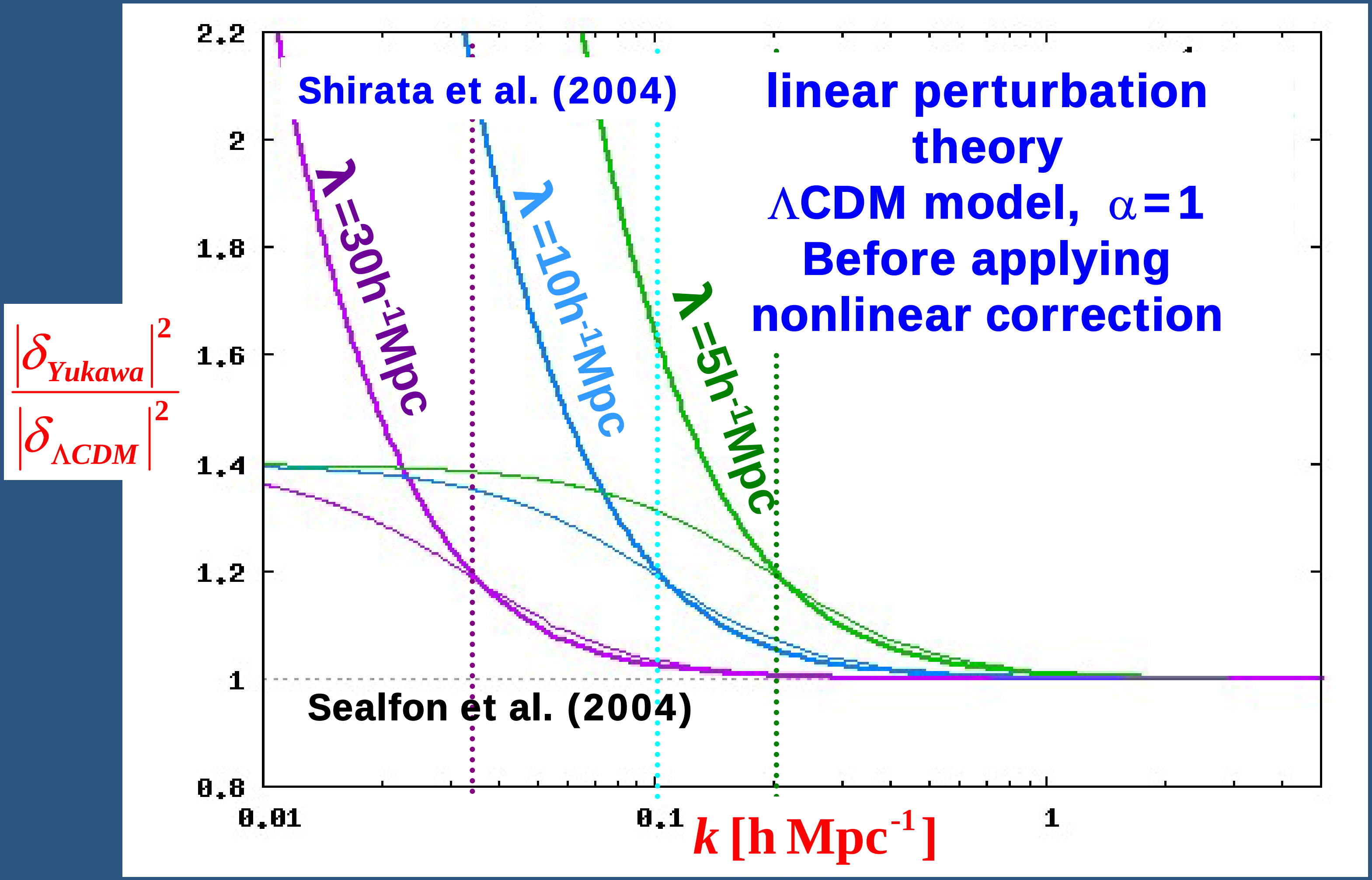
$$\lambda = 0 \qquad \Rightarrow \quad \delta_k \propto a^{-\frac{1}{4}\pm\frac{\sqrt{1+24(1+\alpha)}}{4}}$$

$$\lambda \neq 0$$

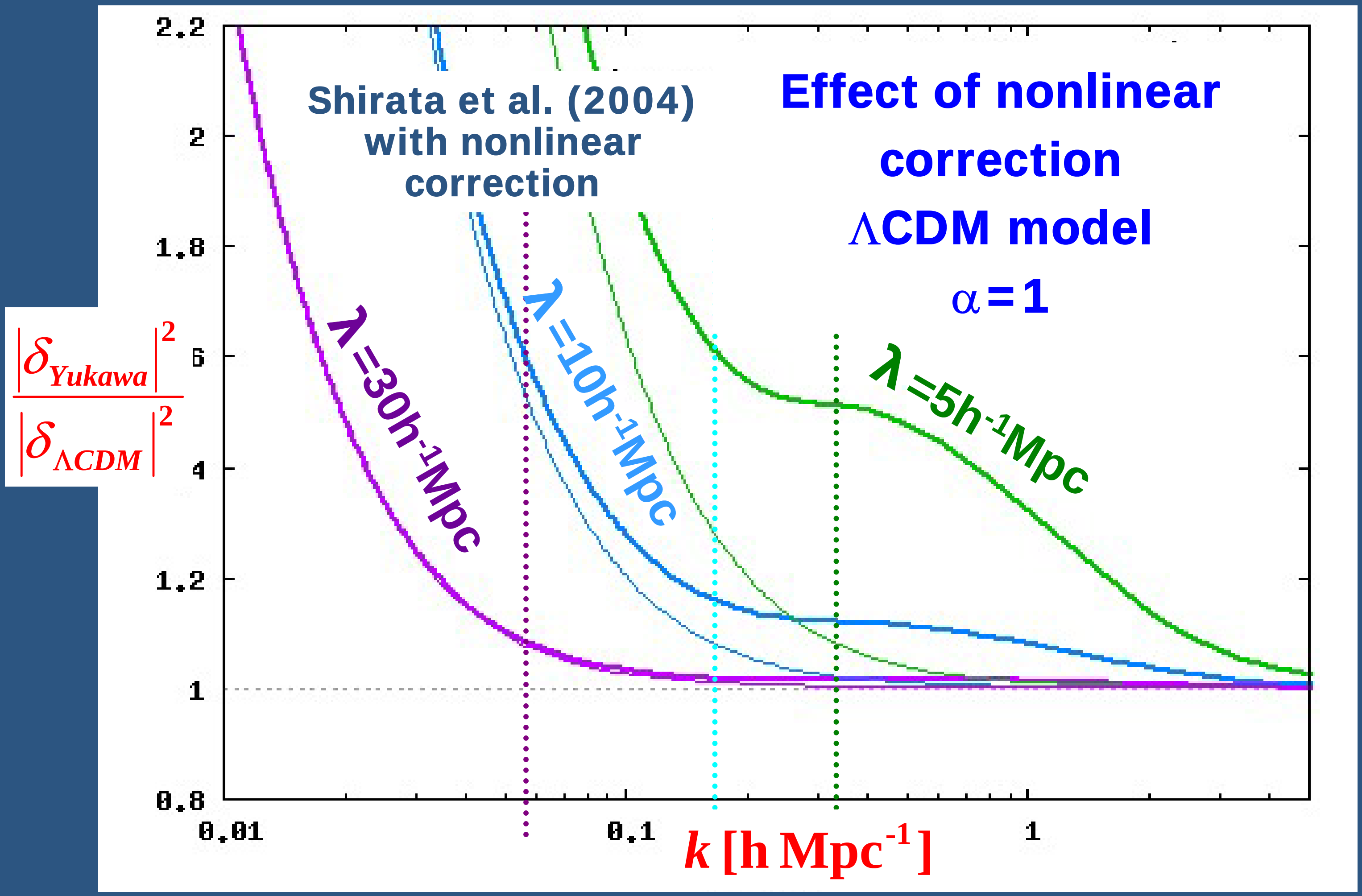
$$\Rightarrow \delta_k = \frac{C_1}{a^{3/2}}\ {}_2F_1\left(-\frac{5}{8}-\frac{1}{8}\sqrt{25+24\alpha}, -\frac{5}{8}+\frac{1}{8}\sqrt{25+24\alpha}, -\frac{1}{4}, -a^2\right)$$

$$+C_2 a\ {}_2F_1\left(\frac{5}{8}-\frac{1}{8}\sqrt{25+24\alpha}, \frac{5}{8}+\frac{1}{8}\sqrt{25+24\alpha}, \frac{9}{4}, -a^2\right)$$

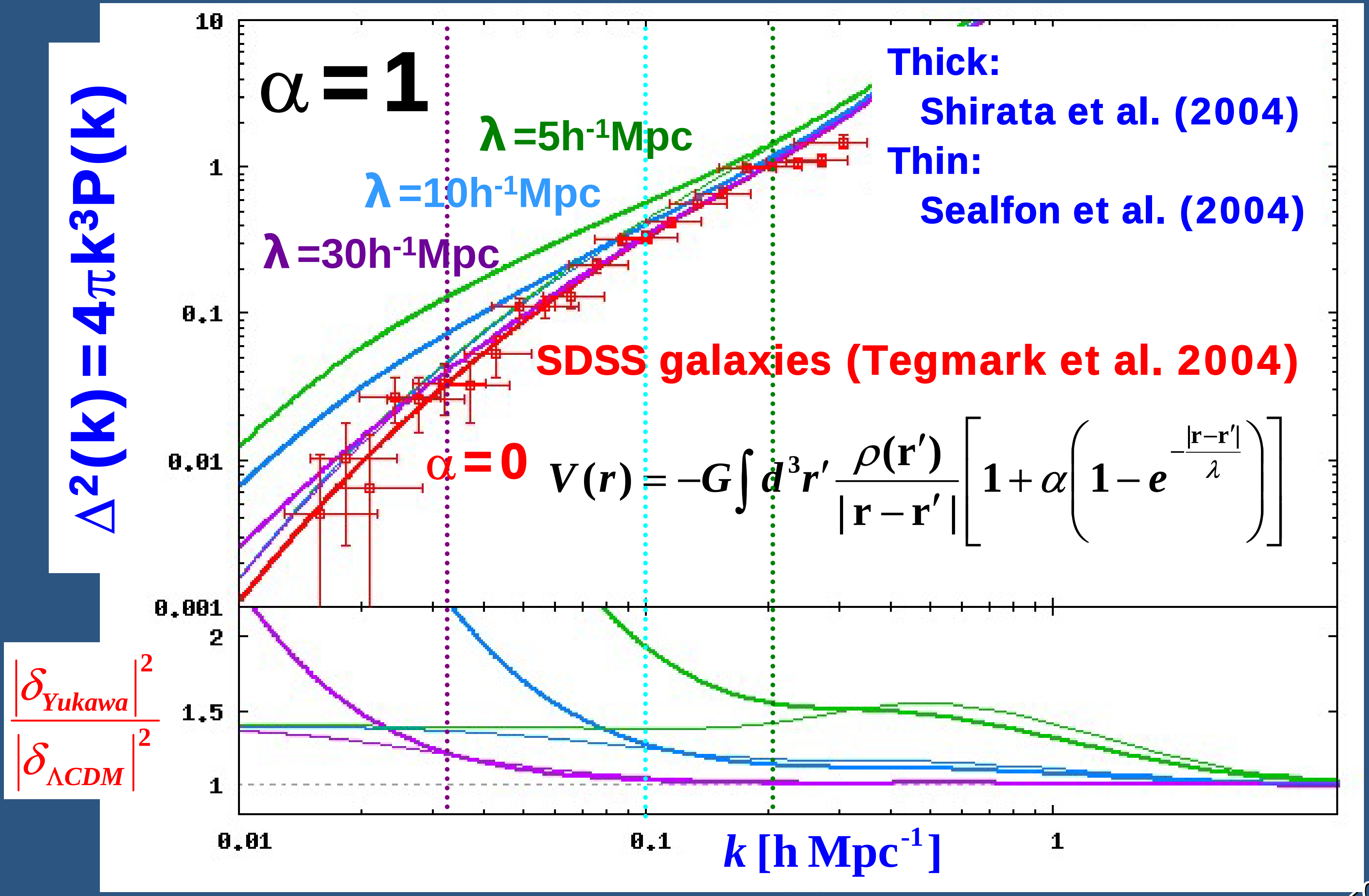
Linear theory prediction: comparison with Sealfon et al. (2004)



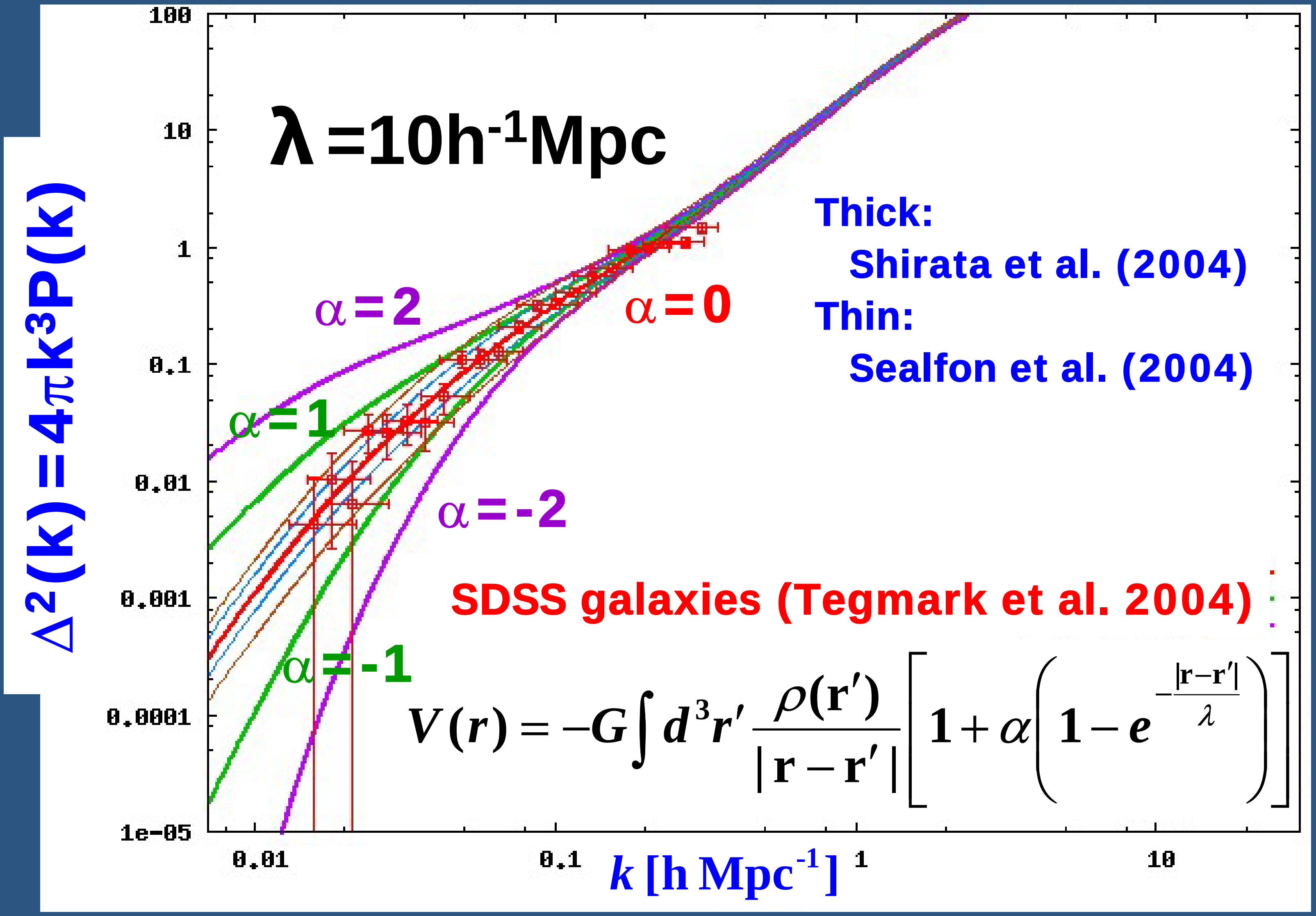
Nonlinear correction using the Peacock-Dodds fit



Power spectrum: λ dependence (α=1)

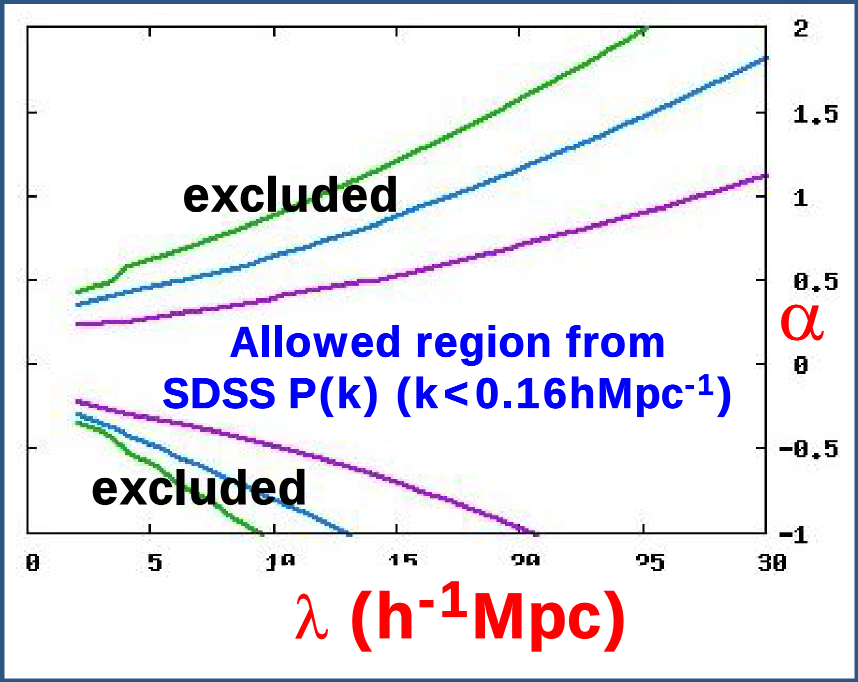


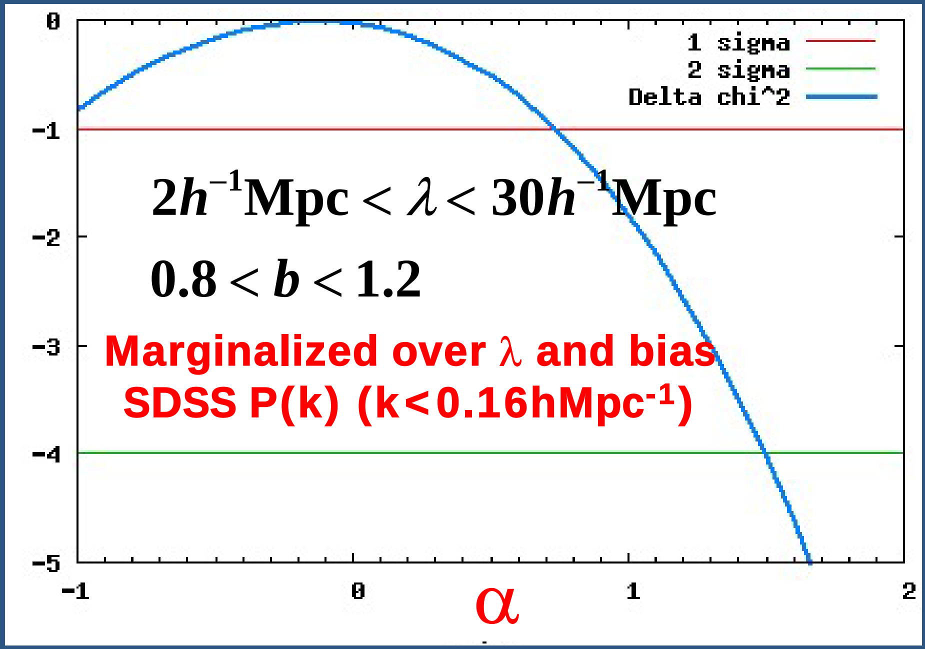
Power spectrum: α dependence ($\lambda = 10h^{-1}$Mpc)



(Preliminary) constraints on α and λ from SDSS galaxy P(k)

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





Still preliminary !

$$\alpha = -0.2^{+0.9}_{-0.8}$$

Shirata, Shiromizu, Yoshida and Suto (2004), in preparation

Summary and outlook

- The SDSS galaxy clustering can be used to constrain the possible deviations from the Newtonian gravity
- The current constraint may not yet be too restrictive to rule out a class of interesting possibilities
  - Include fully nonlinear effect using N-body simulation to tighten the constraints
  - Validity of hierarchical clustering ansatz in higher-order statistics
- We plan to repeat the analysis using a self-consistent (?) model of cosmic expansion and local gravity law (e.g., Dvali et al. 2000) as a specific example