# Kinetic Gravity Braidingモデルにおける大規模構造の進化と観測的制限

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# Modified Gravity

**What causes an accelerated expansion of the universe ??**

- Cosmological constant ??
- Dark energy ??
- Modification of gravity ??

**Modified gravity theory must satisfy ...**

✓ Modification at large distance

✓ Recovery of GR at small scale

✓ Accelerated expansion of the universe at present

✓ Consistency with cosmological observations

# Galileon Theory

Lagrangian

$$\mathcal{L} = c_1(\nabla\phi)^2 + c_2\underline{(\Box\phi)}(\nabla\phi)^2 + \cdots$$

second derivative of the scalar field

- The field equation remains second order differential equation !

**Modification of gravitational force**

$$\frac{F_\phi}{F_{\rm grav}} = \frac{\vec{\nabla}\phi}{M_{\rm Pl}\vec{\nabla}\Phi} = \left(\frac{r}{r_*}\right)^{3/2} \ll 1$$

at small distance

Vainshtein mechanism

$$\frac{F_\phi}{F_{\rm grav}} \sim \mathcal{O}(1)$$

at large distance

# Kinetic Gravity Braiding Model

*KGB model* (Deffayet et al. 2010)

$$S = \int d^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R + K(X) - G(X)\Box\phi + \mathcal{L}_{\rm m}\right]$$

$X = -g^{\mu\nu}\nabla_\mu\phi\nabla_\nu\phi/2$

$\Box\phi = g^{\mu\nu}\nabla_\mu\nabla_\nu\phi$

$K(X),\ G(X)$ : arbitrary functions of the kinetic term

**Example** (Kimura and Yamamoto. 2011)

$$K(X) = -X$$

$$G(X) = M_{\rm Pl}\left(\frac{r_c^2}{M_{\rm Pl}^2}X\right)^n$$

$r_c$ : crossover scale $(\sim H_0^{-1})$

$n$ : model parameter $(n > 1/2)$

# Kinetic Gravity Braiding Model

Choosing the attractor solution, $\dot{\phi} = K_X / 3G_X H$

$$\left(\frac{H}{H_0}\right)^2 = (1-\Omega_0)\left(\frac{H}{H_0}\right)^{-\frac{2}{2n-1}} + \Omega_0 a^{-3}$$

behave like dark energy

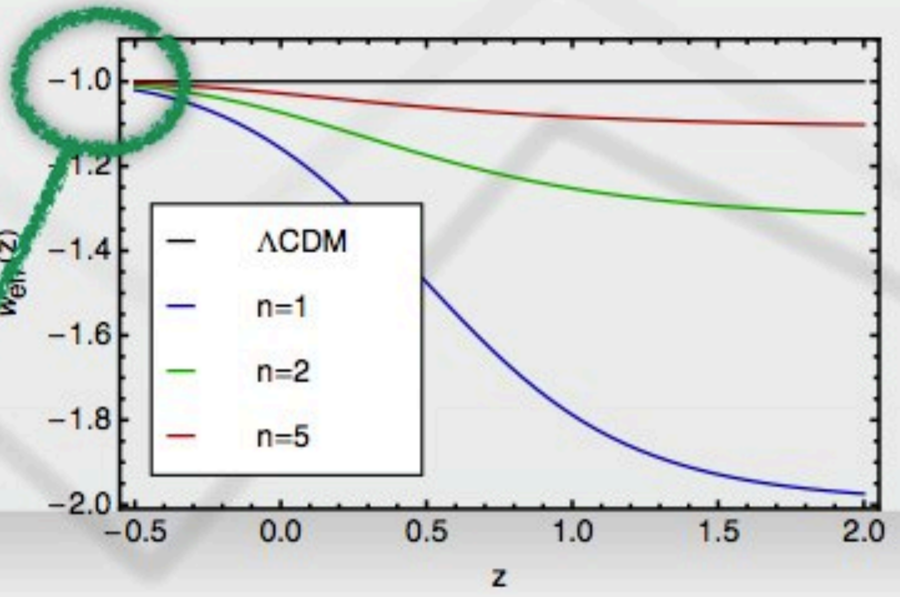
$$\longrightarrow \quad \left(\frac{H}{H_0}\right)^2 \simeq 1 - \Omega_0 + \Omega_0 a^{-3}$$

Large n limit

Friedmann eq. in the ΛCDM model

Effective equation of state

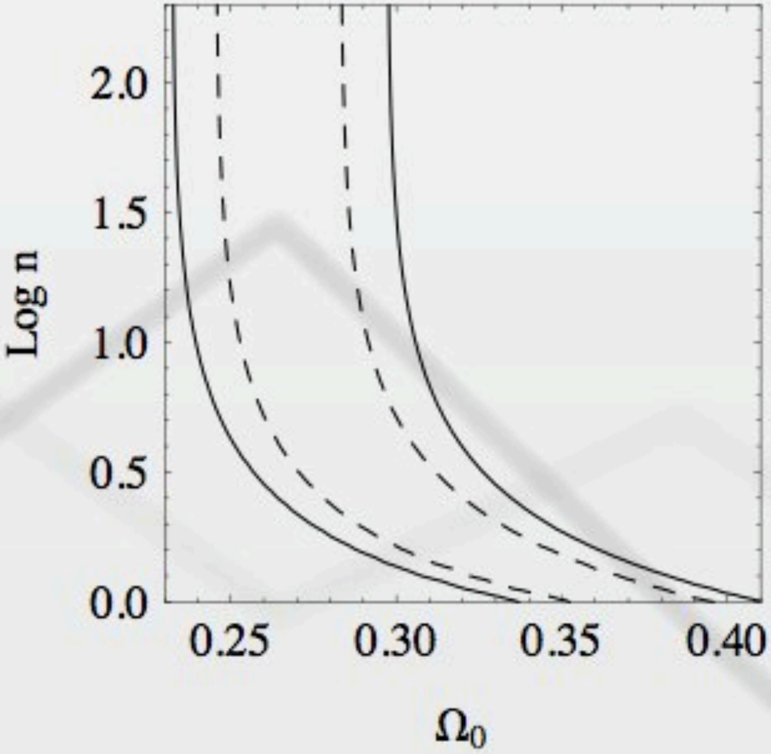
$$w_{\text{eff}} \equiv p_\phi / \rho_\phi$$



de-Sitter expansion !

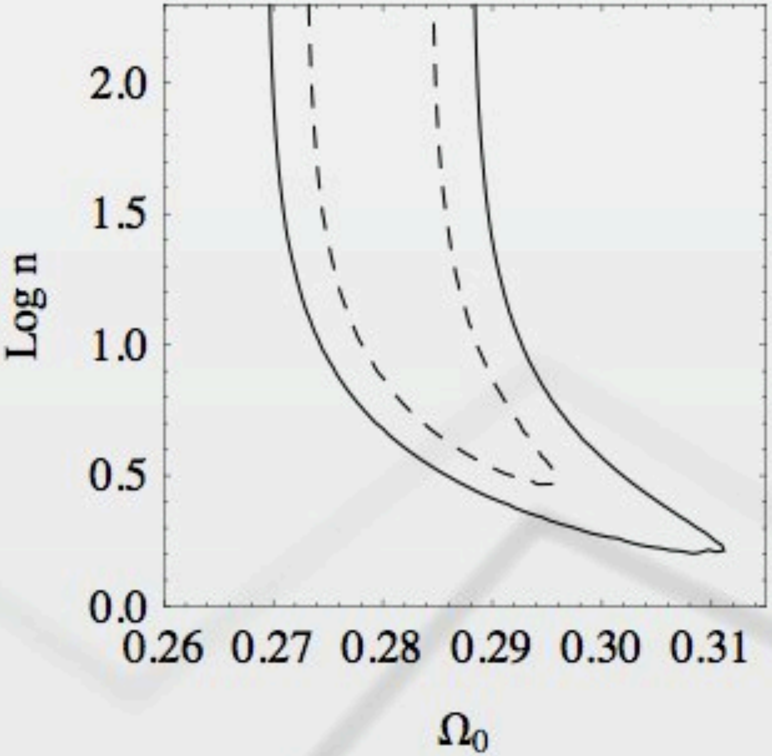
# Observational Results

Type 1a supernovae



(SCP Union 2)

CMB shift parameter



(WMAP 7year)

$n > 3$

# Stability Analysis

$$\phi(t,\mathbf{x}) \to \phi(t) + \delta\phi(t,\mathbf{x})$$

Quadratic action for the perturbed scalar field

$$\delta S^{(2)} = \frac{1}{2}\int d^4x\sqrt{-g}\kappa(a)\left[\dot{\delta\phi}^2 - \frac{c_s^2(a)}{a^2}(\partial_i\delta\phi)^2\right]$$

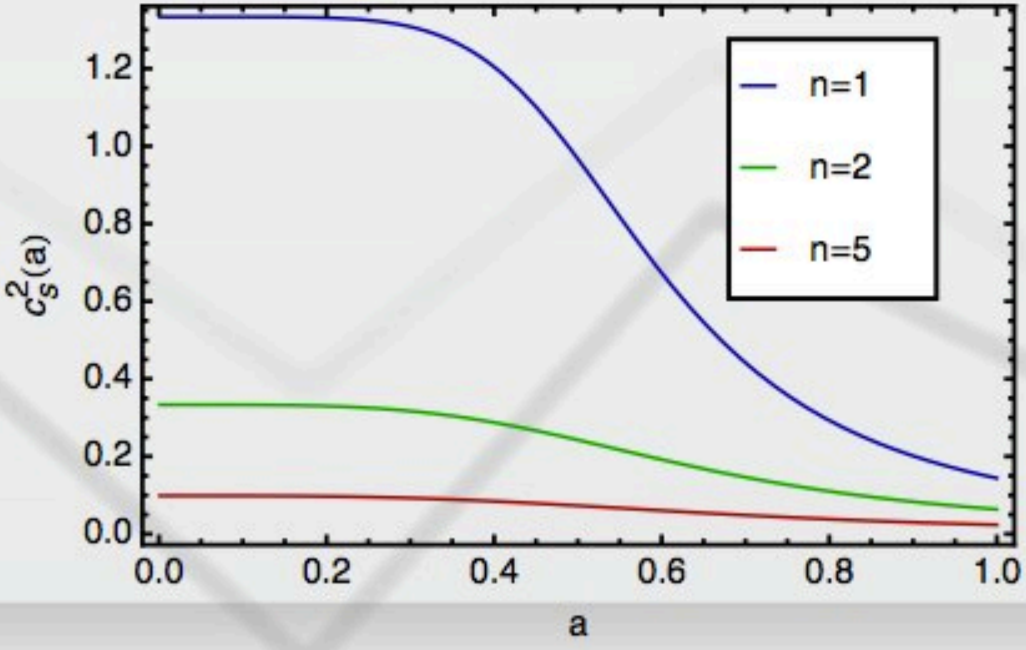
$\kappa(a) > 0$ (No ghostlike behavior)

$c_s^2(a) > 0$ (Stable)

The sound speed

$$c_s^2 \propto 1/n$$

The sound speed of the perturbed scalar field becomes zero if n=∞ !



# Large Scale Structures

- **Large n solution**

$$\delta\dot{X} + 3H\delta X = 0$$

$$\delta X = \dot{\phi}\delta\dot{\phi} - \dot{\phi}^2\Psi$$

$$\delta X = \mathrm{Const}/a^3$$

$$c_s^2 \simeq 0$$

NO effects caused by the scalar field

- **Small n solution (+sub-horizon)** $\mathcal{O}(k^2c_s^2/a^2) \gg \mathcal{O}(H^2)$

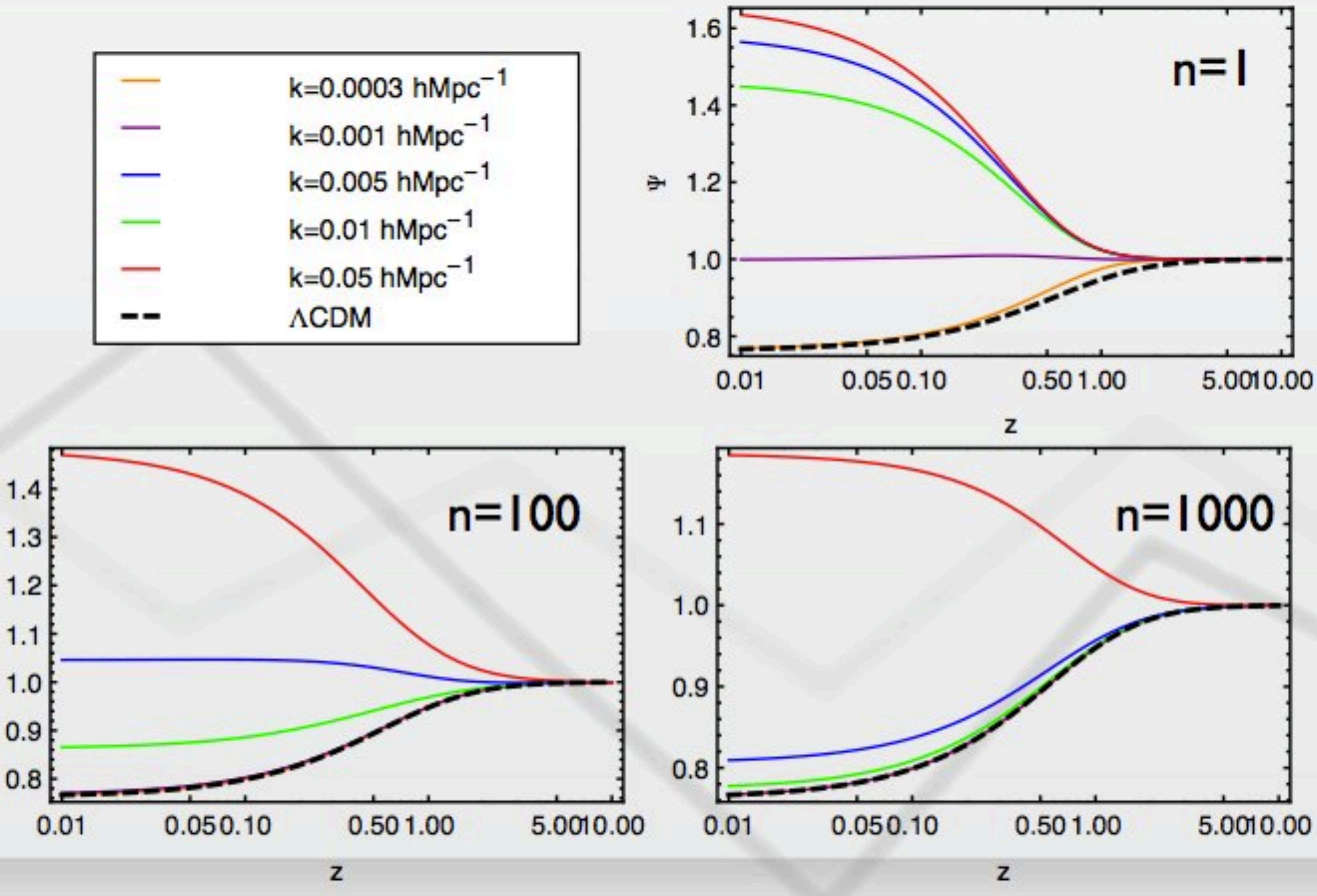
$$\ddot{\delta} + 2H\dot{\delta} \simeq 4\pi G_{\mathrm{eff}}\rho\delta$$

$$G_{\mathrm{eff}} = G\left[1 + 4\pi G\frac{G_X^2\dot{\phi}^4}{\beta(a)}\right]$$

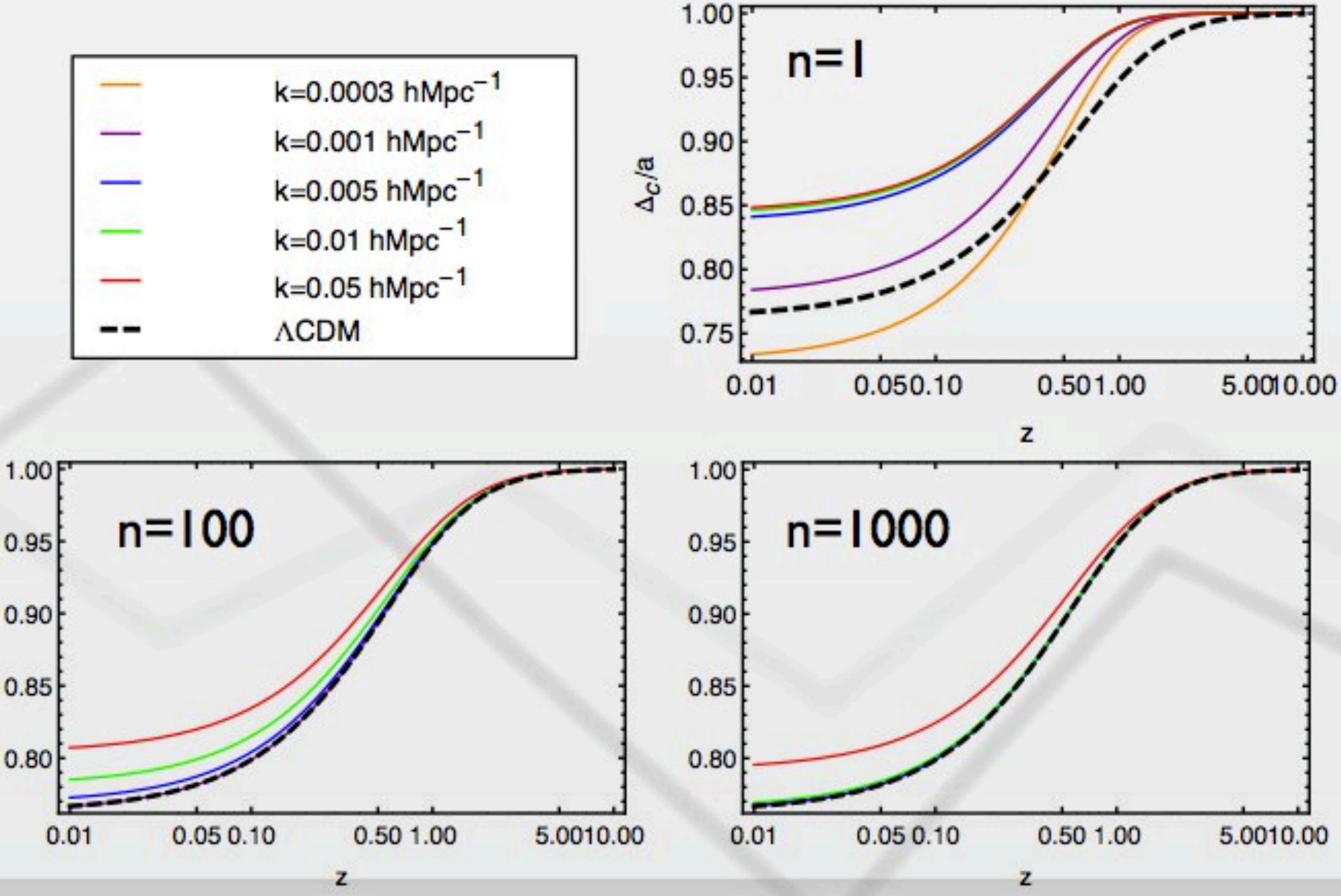
Additional gravitational effect

The growth of density perturbations should be different from the ΛCDM model !!

# Gravitational Potential



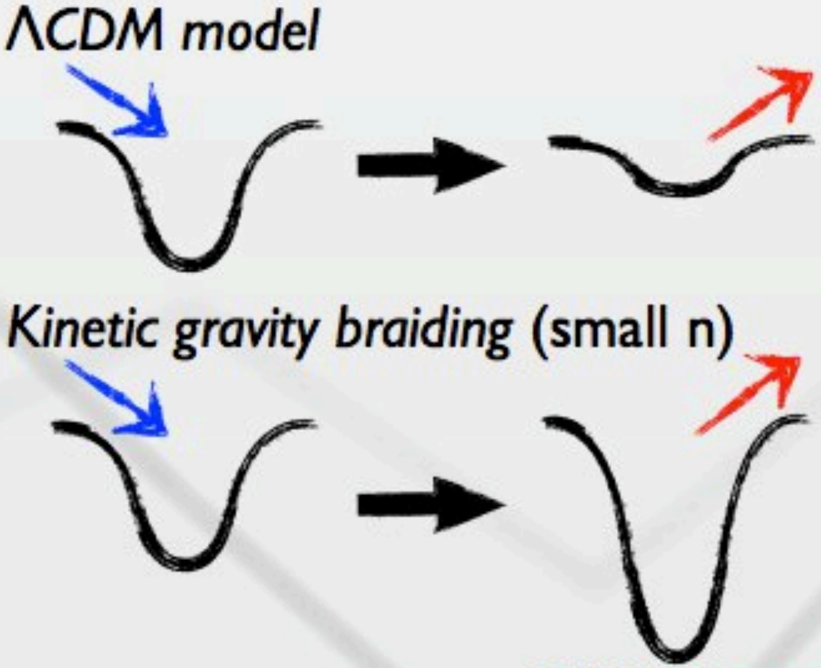
# Density Perturbations



# ISW-LSS Cross-correlation

ISW term in CMB anisotropy

$$\left(\frac{\Delta T(\vec{\gamma})}{T}\right)_{\mathrm{ISW}} = \int_{\eta_d}^{\eta_0} d\eta[\Psi'(\eta,\mathbf{x}) - \Phi'(\eta,\mathbf{x})]$$



*ΛCDM model*

*Kinetic gravity braiding* (small n)

*ISW in CMB power spectrum is dominated by cosmic variance !*

→

*ISW-LSS cross-correlation can extract information of ISW effect ! (Crittenden & Turok '95 )*

# ISW-LSS Cross-correlation

Cross-correlation

$$\left\langle \frac{\Delta T(\vec{\gamma})}{T}\,\frac{\Delta N_g(\vec{\gamma}')}{N} \right\rangle = \frac{1}{4\pi}\sum_{\ell}(2\ell+1)C_\ell P_\ell(\mu),$$

*Temperature anisotropy*

*Galaxy distribution*

*Selection function*

*Growth factor*

*Bias*

*Power spectrum*

*where*

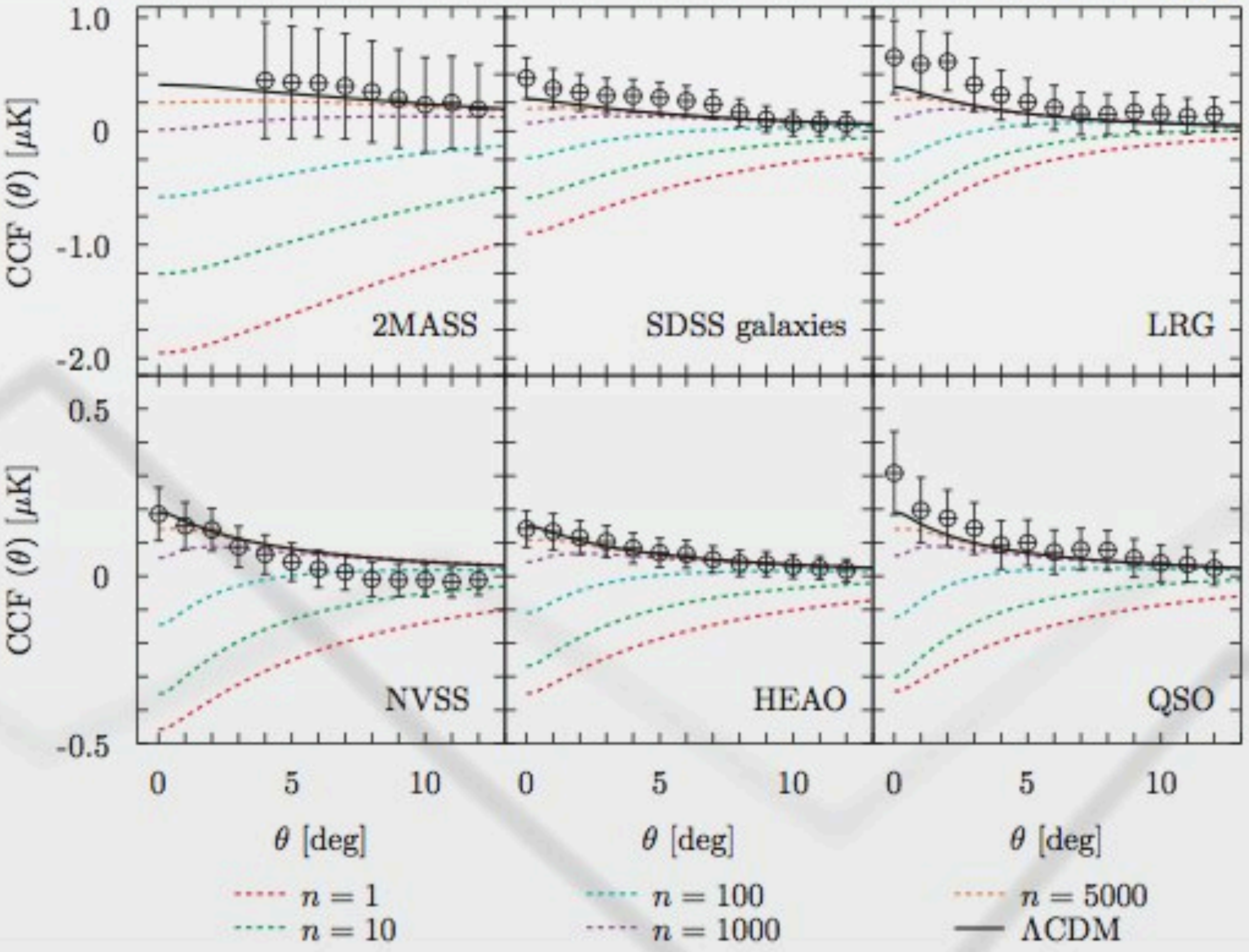
$$C_\ell = \frac{3\Omega_0 H_0^2}{(\ell+1/2)^2}\int dz H(z)\mathcal{W}(z)\frac{D_1(z)}{D_1(z=0)}\underline{\frac{dU_k(\eta)}{dz}}b(z,k)P(k)\bigg|_{k=(\ell+1/2)/\chi}$$

determine the sign of CCF

$$U_k(a) = \frac{G_{\mathrm{eff}}(a)}{G}\frac{D_1(a)}{a}$$

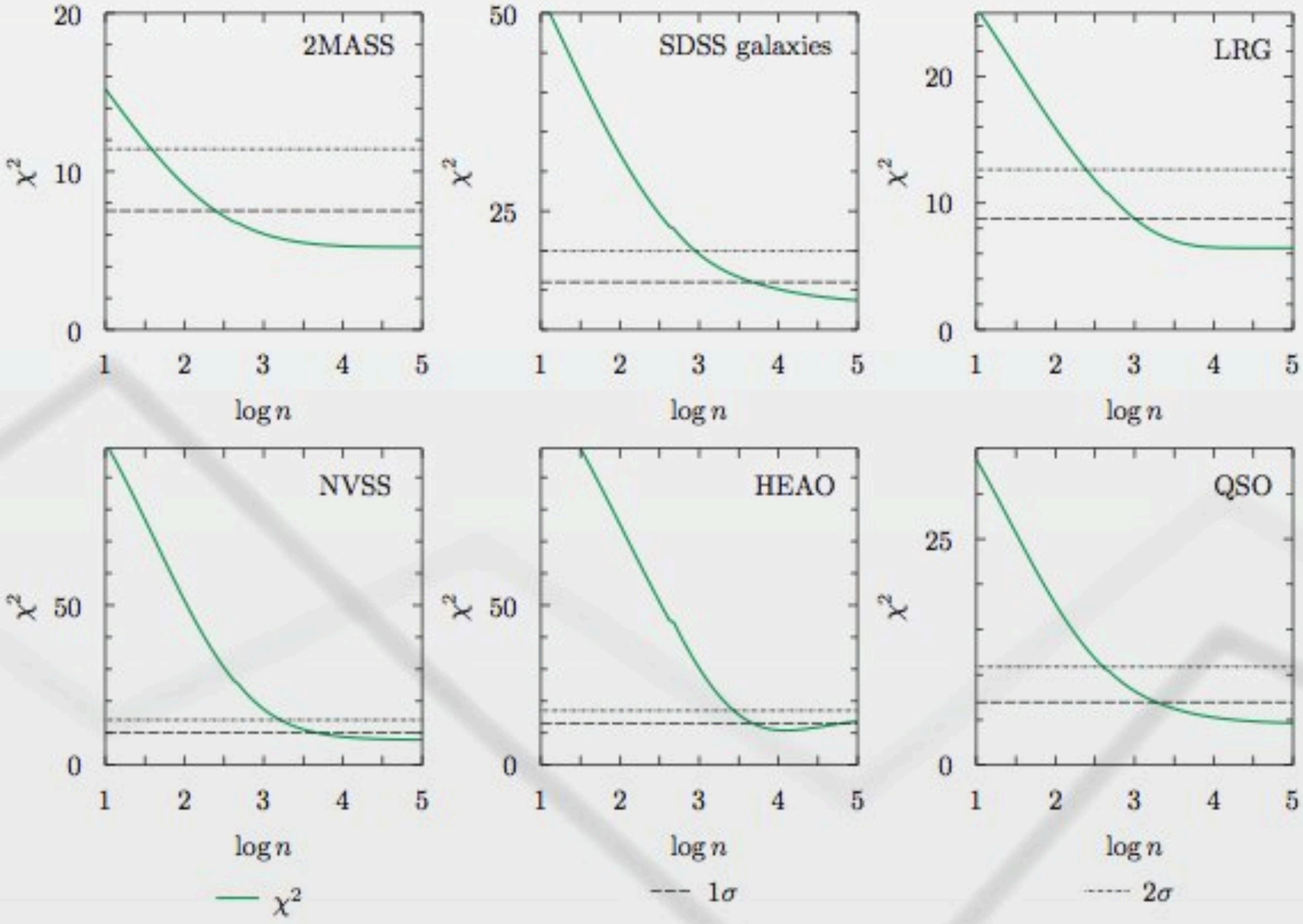
# ISW-LSS Cross-correlation

*Data from Giannantonio et al. '08*



$$n \gtrsim 10^4$$

# Observational Results



Large n is favored by ISW-LSS cross-correlation !!

# Summary

✓ KGB model has a self-accelerating solution and passes solar system constraints

✓ The background evolution can mimic the $\Lambda$CDM model

✓ Growth of LSS in KGB model has different signatures from the $\Lambda$CDM model

✓ Small n value in the KGB model is disfavored by observations such as SNIa, CMB and ISW-LSS cross-correlation.