Large Scale Structures in Kinetic Gravity Braiding Model and Observational Implication

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Based on R. Kimura and K. Yamamoto JCAP 04 (2011) 025

R. Kimura, T. Kobayashi and K. Yamamoto, in preparation

Today's talk

- ✤ Introduction
- ✤ Kinetic Gravity Braiding Model
- ✤ Large Scale Structures
- ✤ Observational Constraints
- ✤ Summary

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

Kinetic Gravity Braiding Model

<u>*KGB model*</u> (Deffayet et al. 2010, Kobayashi 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

- ✓ Second order differential equation
- ✓ No ghost instability
- ✓ Self-accelerating solution
- ✓ GR at small scale (Vainshtein effect)

Kinetic Gravity Braiding Model

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 ($n > 1/2$)

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

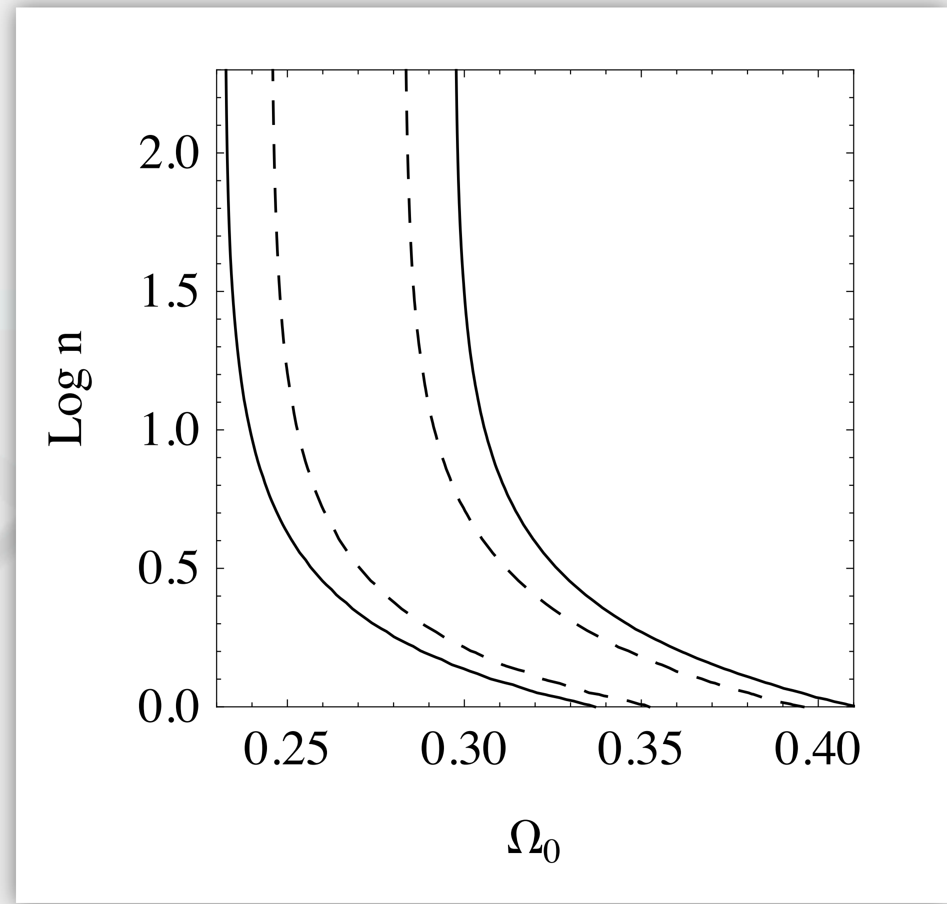
Dvali-Turner's Model (2003)

→ For n=1 Original galileon model (minimally coupled)

For large n ($n \gtrsim 100$) Cosmological constant model

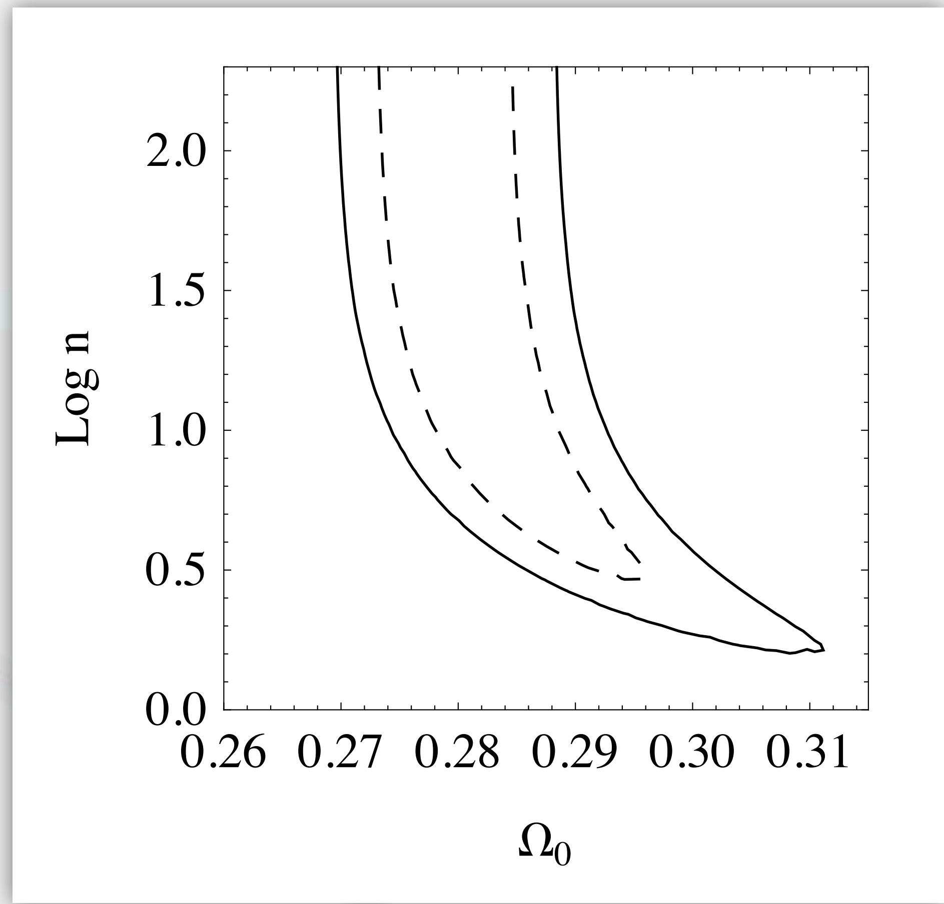
Observational Constraints

Type Ia supernovae



(SCP Union 2)

CMB shift parameter



(WMAP 7year)

$n \gtrsim 3$ *(95% C.L.)*

Kinetic Gravity Braiding Model

How about large scale structures ?

Kinetic Gravity Braiding Model

Newtonian gauge

$$ds^2 = -(1+2\Psi)dt^2 + a^2(t)(1+2\Phi)\delta_{ij}dx^i dx^j$$

Perturbed Einstein equations

$$2M_{\rm Pl}^2\left[-3H(\dot\Phi - H\Psi) + \frac{1}{a^2}\nabla^2\Phi\right] = -\delta\rho - \delta\rho_\phi$$

$$2M_{\rm Pl}^2\left(\dot\Phi - H\Psi\right) = \delta q + \delta q_\phi$$

$$2M_{\rm Pl}^2\left[(3H^2+2\dot H)\Psi + H\dot\Psi - \ddot\Phi - 3H\dot\Phi\right] = \delta p_\phi$$

$$\Psi + \Phi = 0$$

where

$$\delta\rho_\phi = K_X\delta X + G_X\left(3\dot\phi^3\dot\Phi - 12H\dot\phi^3\Psi + 9H\dot\phi^2\dot{\delta\phi} - \frac{\dot\phi^2}{a^2}\nabla^2\delta\phi\right) + 3G_{XX}H\dot\phi^3\delta X$$

$$\delta q_\phi = -K_X\dot\phi\delta\phi - G_X\dot\phi^2\left(\dot\phi\Psi - \dot{\delta\phi} + 3H\delta\phi\right)$$

$$\delta p_\phi = K_X\delta X + G_X\left(\dot\phi^3\dot\Psi - \dot\phi^2\ddot{\delta\phi} + 4\dot\phi^2\ddot\phi\Psi - 2\dot\phi\ddot\phi\dot{\delta\phi}\right) - G_{XX}\dot\phi^2\ddot\phi\delta X$$

Kinetic Gravity Braiding Model

Perturbed scalar field equations

$$
\begin{aligned}
&- K_X \left[3\dot{\phi}\dot{\Phi} - \dot{\phi}\dot{\Psi} - 2(\ddot{\phi} + 3H\dot{\phi})\Psi + \ddot{\delta\phi} + 3H\dot{\delta\phi} - \frac{1}{a^2}\nabla^2\delta\phi \right] \\
&- 3G_{XXX}H\dot{\phi}^3\ddot{\phi}\delta X - G_X \Bigg[3\dot{\phi}^2\ddot{\Phi} + 6(\ddot{\phi} + 3H\dot{\phi})\dot{\phi}\dot{\Phi} - 9H\dot{\phi}^2\dot{\Psi} \\
&- 12\left\{ (\dot{H} + 3H^2)\dot{\phi}^2 + 2H\dot{\phi}\ddot{\phi} \right\}\Psi - \frac{\dot{\phi}^2}{a^2}\nabla^2\Psi + 6H\dot{\phi}\ddot{\delta\phi} \\
&+ 6\left\{ H\ddot{\phi} + (\dot{H} + 3H^2)\dot{\phi} \right\}\dot{\delta\phi} - \frac{2}{a^2}(\ddot{\phi} + 2H\dot{\phi})\nabla^2\delta\phi \Bigg] \\
&- G_{XX} \Bigg[3\dot{\phi}^3\ddot{\phi}\dot{\Phi} - 3H\dot{\phi}^4\dot{\Psi} - 3\left\{ 8H\dot{\phi}^3\ddot{\phi} + (\dot{H} + 3H^2)\dot{\phi}^4 \right\}\Psi \\
&+ 3H\dot{\phi}^3\ddot{\delta\phi} + 3\left\{ 5H\dot{\phi}^2\ddot{\phi} + (\dot{H} + 3H^2)\dot{\phi}^3 \right\}\dot{\delta\phi} - \frac{\dot{\phi}^2\ddot{\phi}}{a^2}\nabla^2\delta\phi \Bigg] = 0
\end{aligned}
$$

Large Scale Structures

- **Large n solution**

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

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

$$\delta X = \mathrm{Const}/a^3 \to 0$$

$$c_s^2 \simeq 0$$

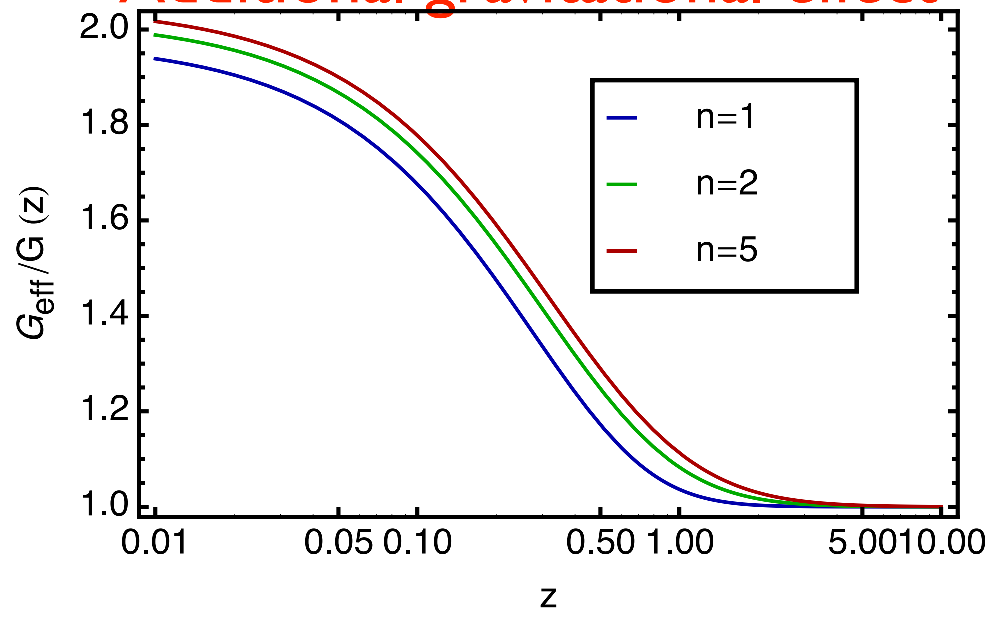
NO effects caused by the scalar field at linear order (=ΛCDM model)

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

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

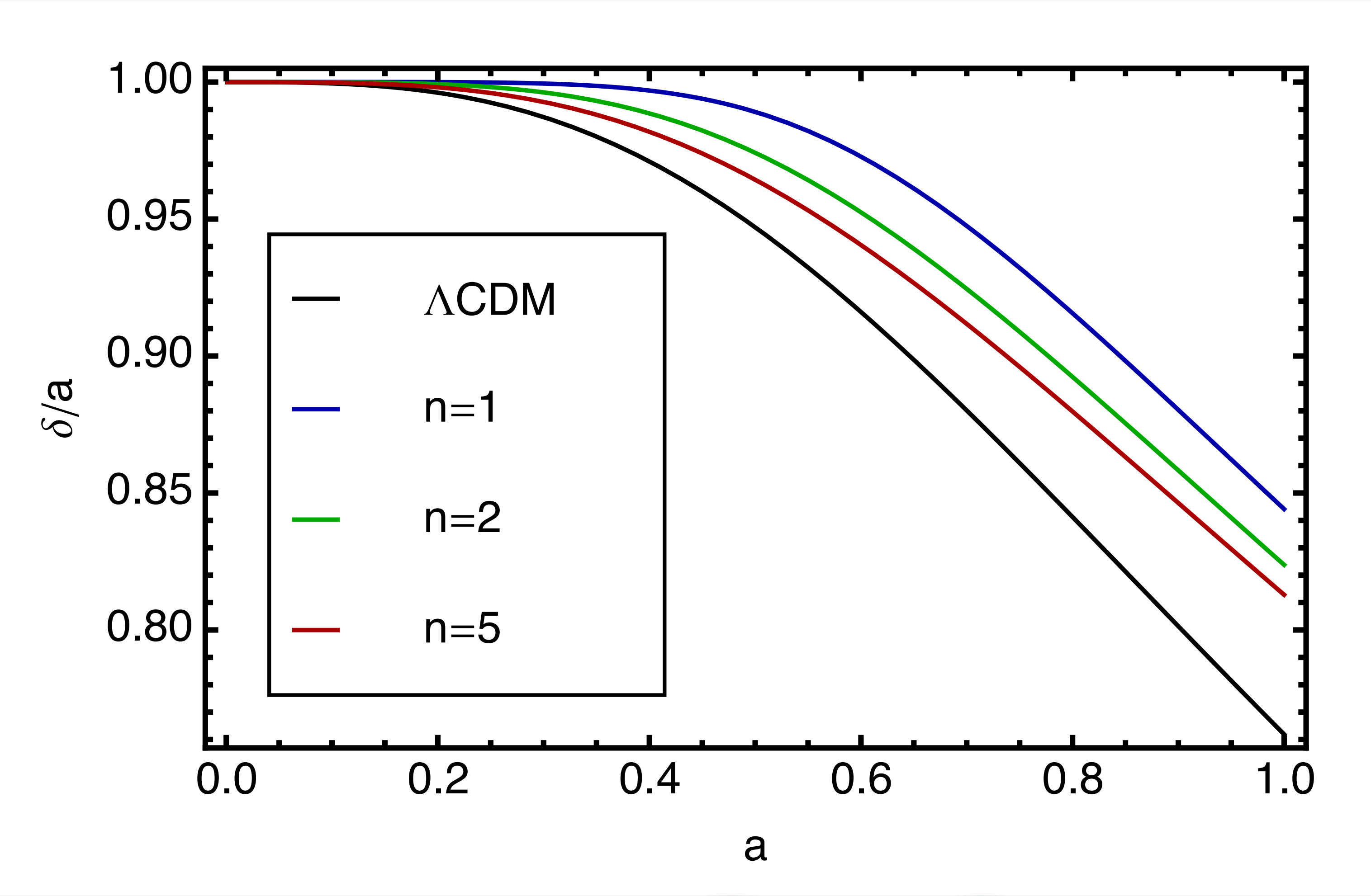
$$G_{\mathrm{eff}} = G\left[1 + 4\pi G \frac{G_X^2 \dot{\phi}^4}{\beta(a)}\right]$$

Additional gravitational effect



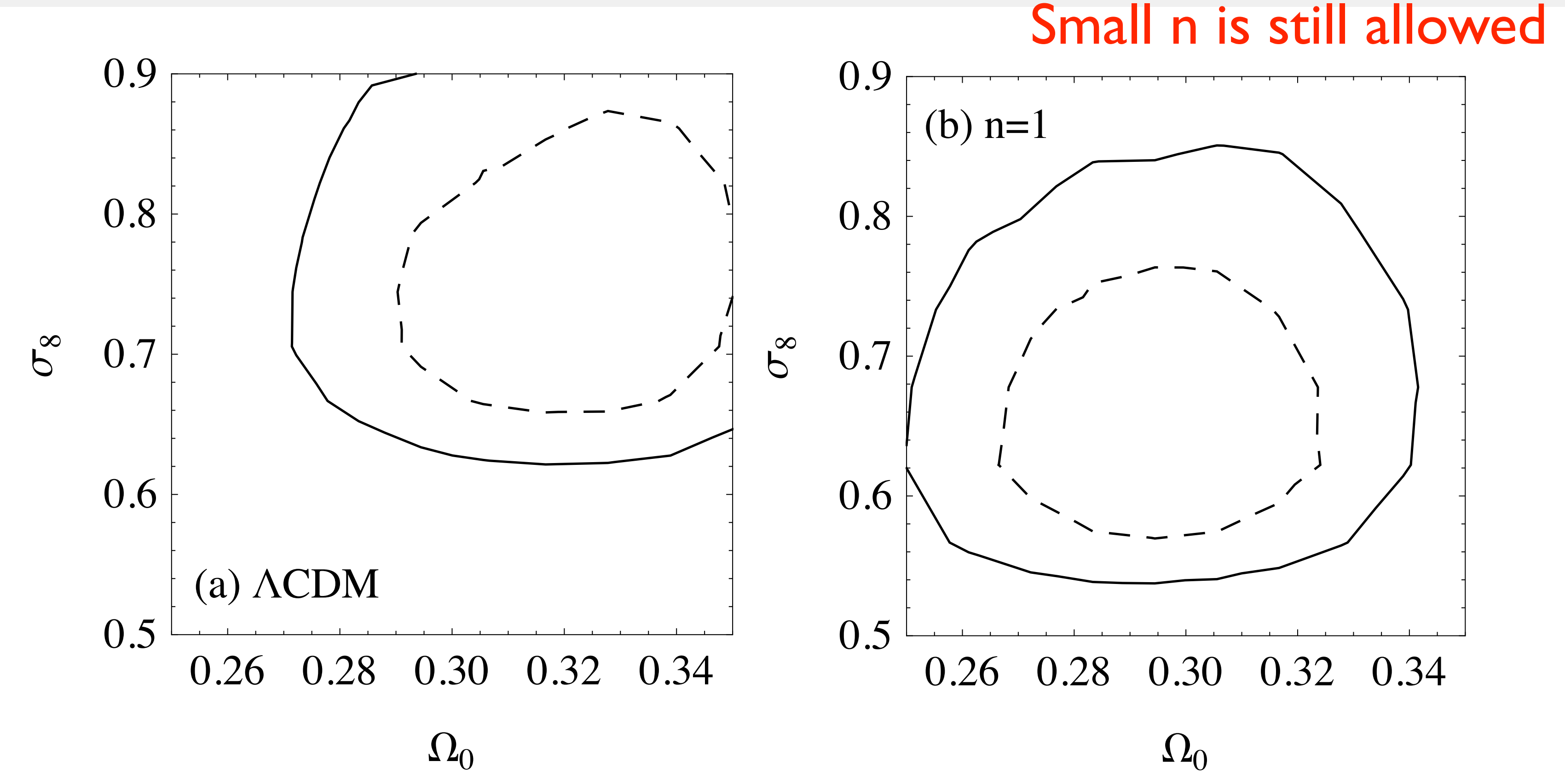
The growth of density perturbations should be different from the ΛCDM model !!

Growth Rate



Constraints from the matter power spectrum

Small n is still allowed ....



(SDSS LRG sample DR7)

This constraints are still weak !!!

Kinetic Gravity Braiding Model

What could be a powerful tool to constrain on the KGB model ?

Galaxy-ISW Cross-correlation

ISW term in CMB anisotropy

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

Modified Poisson equation

$$\frac{\nabla^2}{a^2}\Psi = 4\pi G_{\rm eff}\rho\delta$$

Galaxy-ISW Cross-correlation

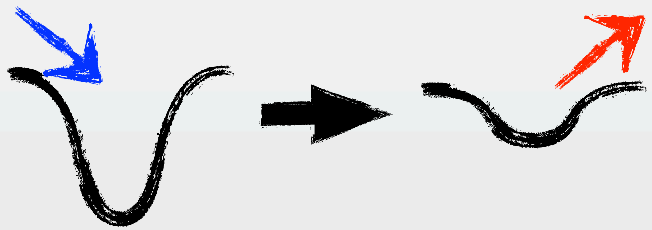
$$\left\langle \frac{\Delta T(\vec{\gamma})}{T} \frac{\Delta N_g(\vec{\gamma}')}{N} \right\rangle$$

$$\propto -\frac{d}{d\eta}\left(\frac{G_{\rm eff}}{G}\frac{\delta(\eta)}{a}\right)$$

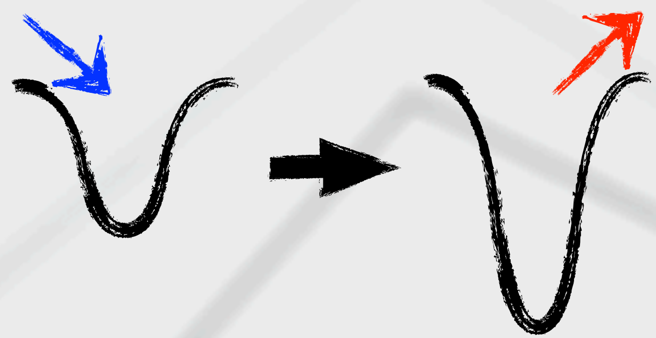
determine the sign of CCF

Galaxy distribution

ΛCDM model

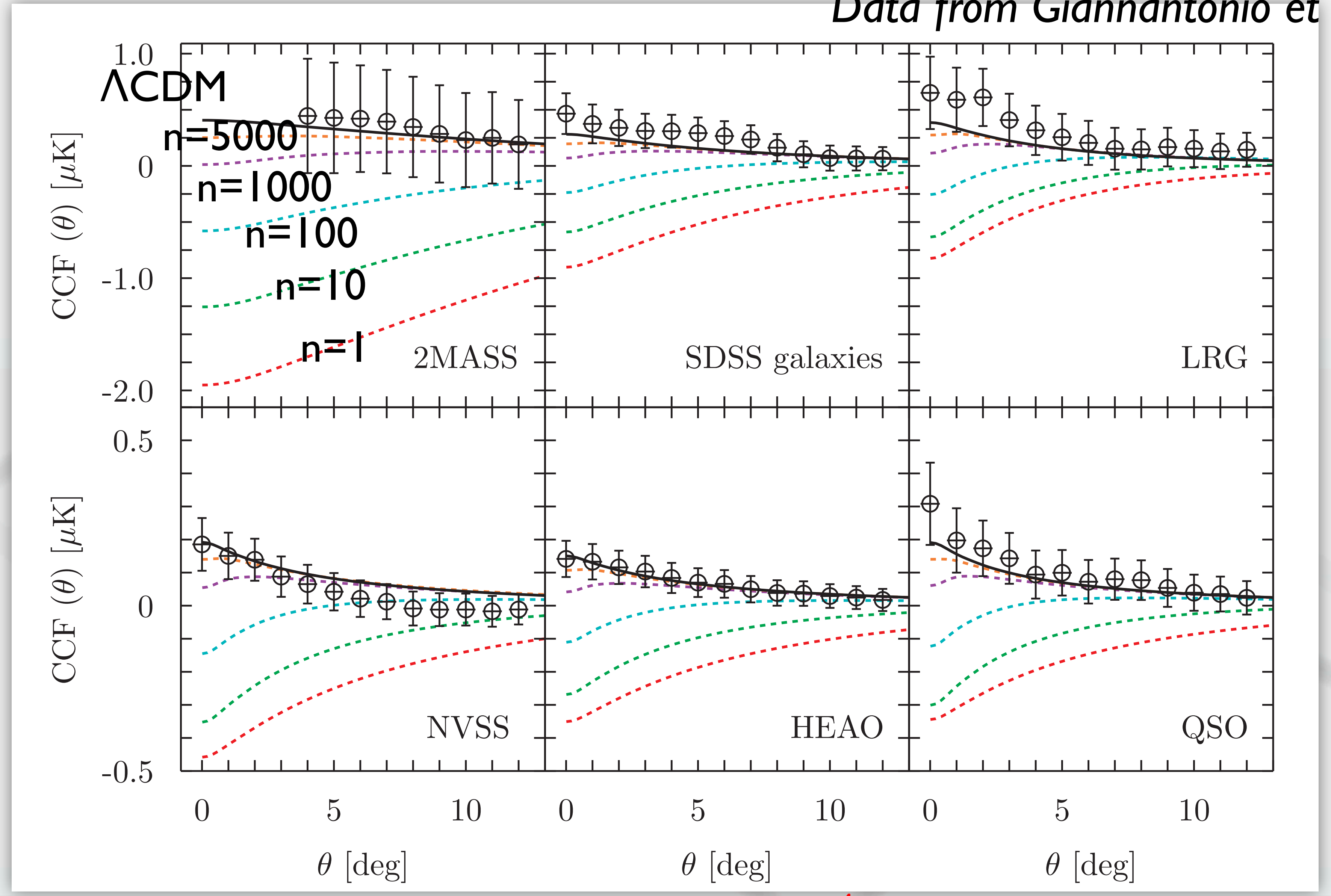


Kinetic gravity braiding (small n)



Galaxy-LSS Cross-correlation

Data from Giannantonio et al. '08



$n \gtrsim 10^4$ *(95% C.L.)*

Summary

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

✓ The background evolution can mimic the ΛCDM model. However, the growth of LSS in KGB model has different signatures from the ΛCDM model

✓ISW-LSS cross-correlation is a powerful tool to constrain on modified gravity

✓ Small n value in the KGB model (correspond to the galileon model) is disfavored by Galaxy-ISW cross-correlation

Thank you !!