Distinguishing modified gravity from ΛCDM with cosmic growth rate

平野 耕一 （都留文科大学）

TSURU UNIVERSITY

arXiv:1512.09077 [astro-ph.CO]

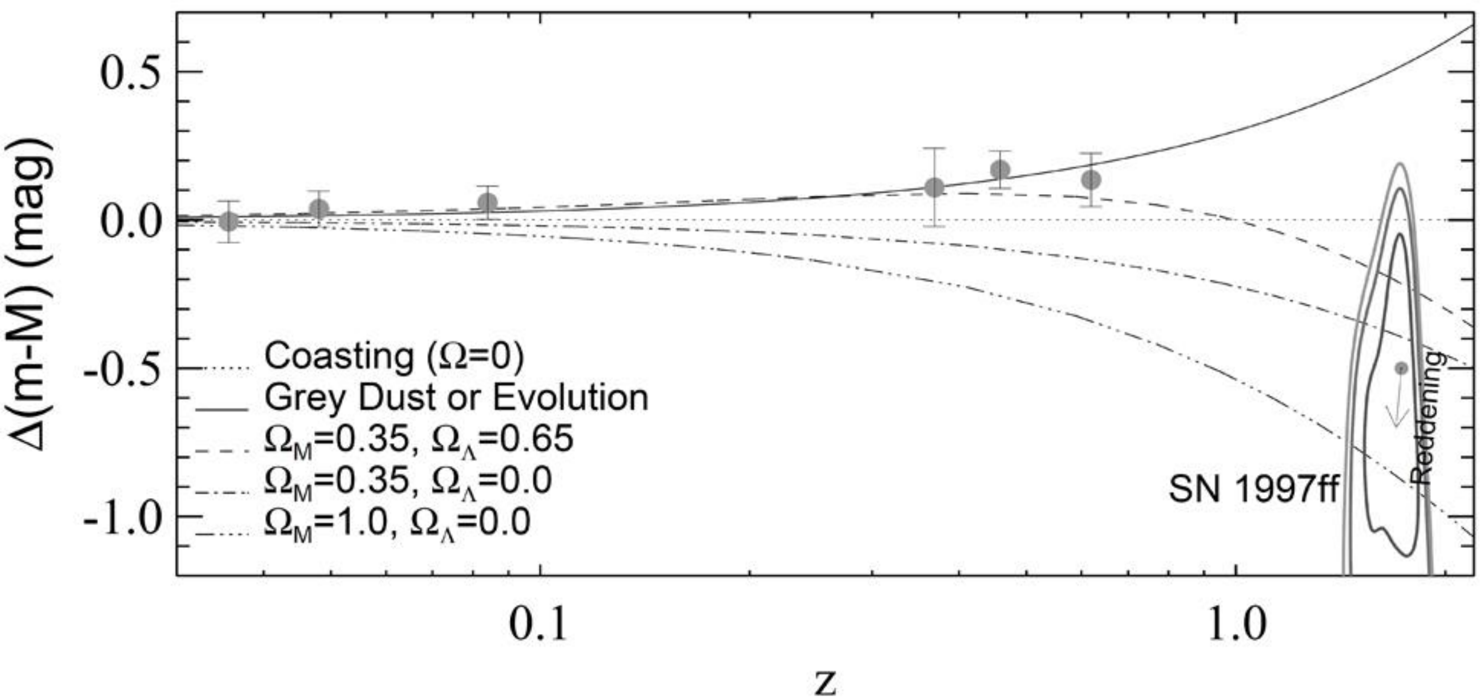
松江素粒子物理学研究会
2016/03/25 於：島根大学

目次

1. Motivation

Ｉa型超新星や宇宙背景放射（CMB）等の観測により、現在の宇宙の加速膨張が示されている。

A.G.Riess et al, ApJ. (2001)



宇宙の現在の加速膨張を説明する手段

1. ダークエネルギー

・宇宙項　　等

2. 修正重力理論

・DGP

・f(R)

・K-essence

・Kinetic Gravity Braiding

・Galileon　　等

１と２のどちらが本当かを知りたい。

2. Modified Gravity Models

Horndeski Theories

G. W. Horndeski, Int. J. Theor. Phys. (1974)

$$\mathcal{L} = \sum_{i=2}^{5} \mathcal{L}_i \,, \qquad X = -g^{\mu\nu}\nabla_\mu\phi\nabla_\nu\phi/2.$$

$$\begin{aligned}
\mathcal{L}_2 &= K(\phi, X), \\
\mathcal{L}_3 &= -G_3(\phi, X)\Box\phi, \\
\mathcal{L}_4 &= G_4(\phi, X)\, R + G_{4,X}\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)\,(\nabla^\mu\nabla^\nu\phi)\right], \\
\mathcal{L}_5 &= G_5(\phi, X)\, G_{\mu\nu}\,(\nabla^\mu\nabla^\nu\phi) \\
&\quad - \frac{1}{6}\, G_{5,X}\left[(\Box\phi)^3 - 3(\Box\phi)\,(\nabla_\mu\nabla_\nu\phi)\,(\nabla^\mu\nabla^\nu\phi) + 2(\nabla^\mu\nabla_\alpha\phi)\,(\nabla^\alpha\nabla_\beta\phi)\,(\nabla^\beta\nabla_\mu\phi)\right].
\end{aligned}$$

運動方程式が2階となるような単一スカラー・テンソル理論で最も一般的な形

Quintessence,　*f*(R),　DGP,　Brans-Dicke
K-essence,　Kinetic Gravity Braiding,　Galileon
等の多くのモデルが含まれる。

Beyond Horndeski

GLPV theories (J. Gleyzes, D. Langlois, F. Piazza and F. Vernizzi, PRL. (2015))

$$\mathcal{L} = \sum_{i=2}^{5} \mathcal{L}_i \,,$$

$$L_2^\phi \equiv G_2(\phi, X) \,,$$

$$L_3^\phi \equiv G_3(\phi, X) \Box\phi \,,$$

$$L_4^\phi \equiv G_4(\phi, X)\, {}^{(4)}\!R - 2G_{4,X}(\phi, X)(\Box\phi^2 - \phi^{\mu\nu}\phi_{\mu\nu}) + F_4(\phi, X)\epsilon^{\mu\nu\rho}{}_{\sigma}\, \epsilon^{\mu'\nu'\rho'\sigma}\phi_\mu\phi_{\mu'}\phi_{\nu\nu'}\phi_{\rho\rho'} \,,$$

$$L_5^\phi \equiv G_5(\phi, X)\, {}^{(4)}\!G_{\mu\nu}\phi^{\mu\nu} + \frac{1}{3}G_{5,X}(\phi, X)(\Box\phi^3 - 3\,\Box\phi\,\phi_{\mu\nu}\phi^{\mu\nu} + 2\,\phi_{\mu\nu}\phi^{\mu\sigma}\phi^{\nu}{}_{\sigma}) + F_5(\phi, X)\epsilon^{\mu\nu\rho\sigma}\epsilon^{\mu'\nu'\rho'\sigma'}\phi_\mu\phi_{\mu'}\phi_{\nu\nu'}\phi_{\rho\rho'}$$

・運動方程式に3階微分項があり得るが、Ostrogradski ゴーストが現れないヘルシーな理論

・$F_4(\phi, X) = 0\,,\ F_5(\phi, X) = 0\,,$ とすると、Horndeski に帰着。

XG3（eXtended Galileon with 3 space covariance）(X. Gao, Phys.Rev. (2014))

・GLPV をさらに拡張

・運動方程式に3階微分項があり得るが、Ostrogradski ゴーストが現れないヘルシーな理論

3. Cosmic Growth Rate

ΛCDMと修正重力モデルとで、
バックグラウンドの宇宙膨張の進化がほぼ同じであっても
物質密度揺らぎの進化は一般に大きく異なる。

ΛCDMと修正重力モデルとの違い等を調べるとき、
物質密度揺らぎの成長率を用いるのが有効

the Growth Rate of cosmic structure

サブホライズンスケールでの準静的近似のもとでの
物質密度揺らぎδの発展方程式

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G_{\rm eff}\rho\delta \simeq 0,$$

物質密度揺らぎ

$$\delta \equiv \delta\rho_m/\rho_m$$

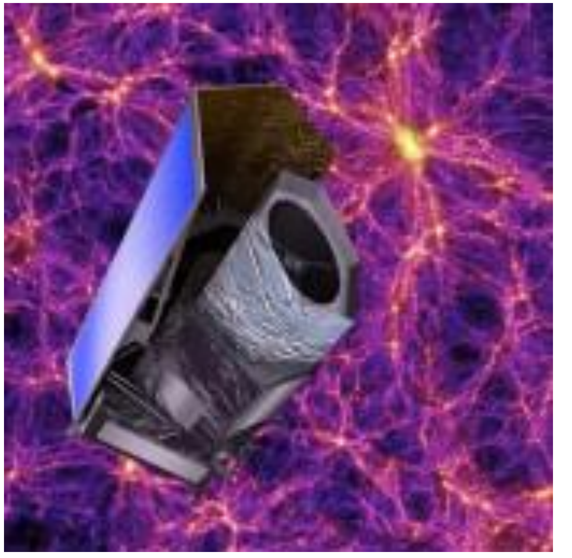
$G_{\rm eff}$:実効重力定数

物質密度揺らぎの成長率
（Growth Rate）

$$f = \frac{\mathrm{d}\ln\delta}{\mathrm{d}\ln a}.$$

4. Euclid

Euclid



広視野銀河サーベイ
2019年打ち上げ予定

目的
・宇宙加速膨張の起源の解明
・宇宙の構造形成の進化の解明

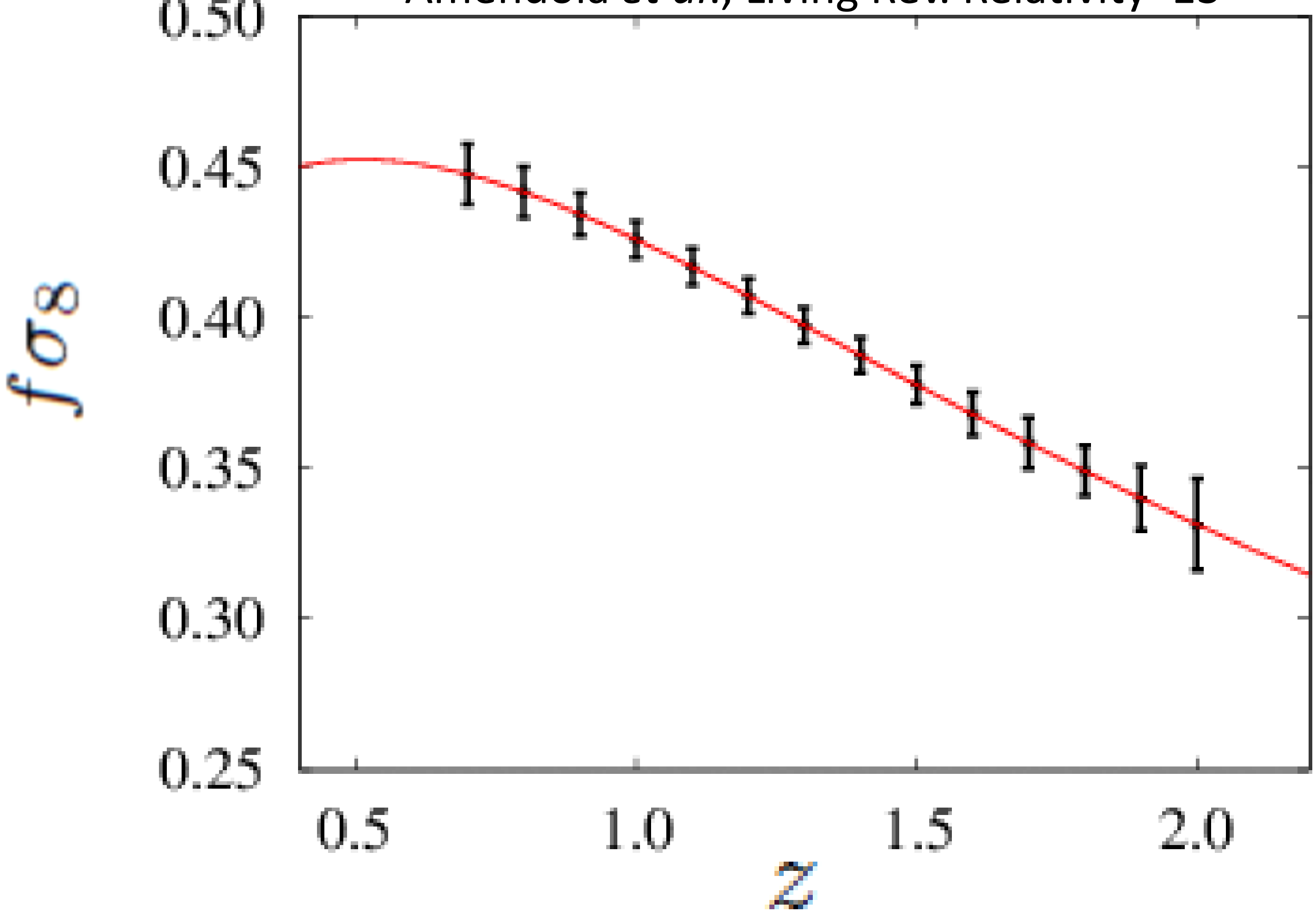
Euclid is a European Space Agency medium-class mission.

The Euclid system shall perform a wide survey of at least 15,000 deg2 of the extragalactic sky - goal 20,000 deg2;

The Euclid system shall perform a deep survey of at least 40 deg2;

Euclid （Euclid Collaboration）

Amendola *et al.*, Living Rev. Relativity ‘13



Mock Data

5. Comparison with Euclid Data

DGP (Dvali, Gabadadze, Porrati, PLB 2000)

4D Newtonian gravity on a Brane in 5D Minkowski bulk

Action
$$S = \frac{1}{16\pi} M_{(5)}^3 \int_{bulk} d^5x \sqrt{-g_{(5)}} R_{(5)} + \frac{1}{16\pi} M_{(4)}^2 \int_{brane} d^4x \sqrt{-g_{(4)}} (R_{(4)} + L_m),$$

観測と適合しない。(Xia, PRD 2009)

Friedmann-like equation

$$H^2 = \frac{8\pi G}{3}\rho + \epsilon \frac{H}{r_c},$$

ϵ = +1 : self-accelerating branch

ϵ = −1 : normal branch

r_c :crossover scale

Extended DGP (Dvali & Turner, 2003)

Friedmann-like equation

$$H^2 = \frac{8\pi G}{3}\rho + \frac{H^\alpha}{{r_c}^{2-\alpha}}.$$

α = 1 → DGP

α = 0 → ΛCDM

Crossover scale $r_c = H_0^{-1}/(1-\Omega_{m0})^{\alpha-2}$.

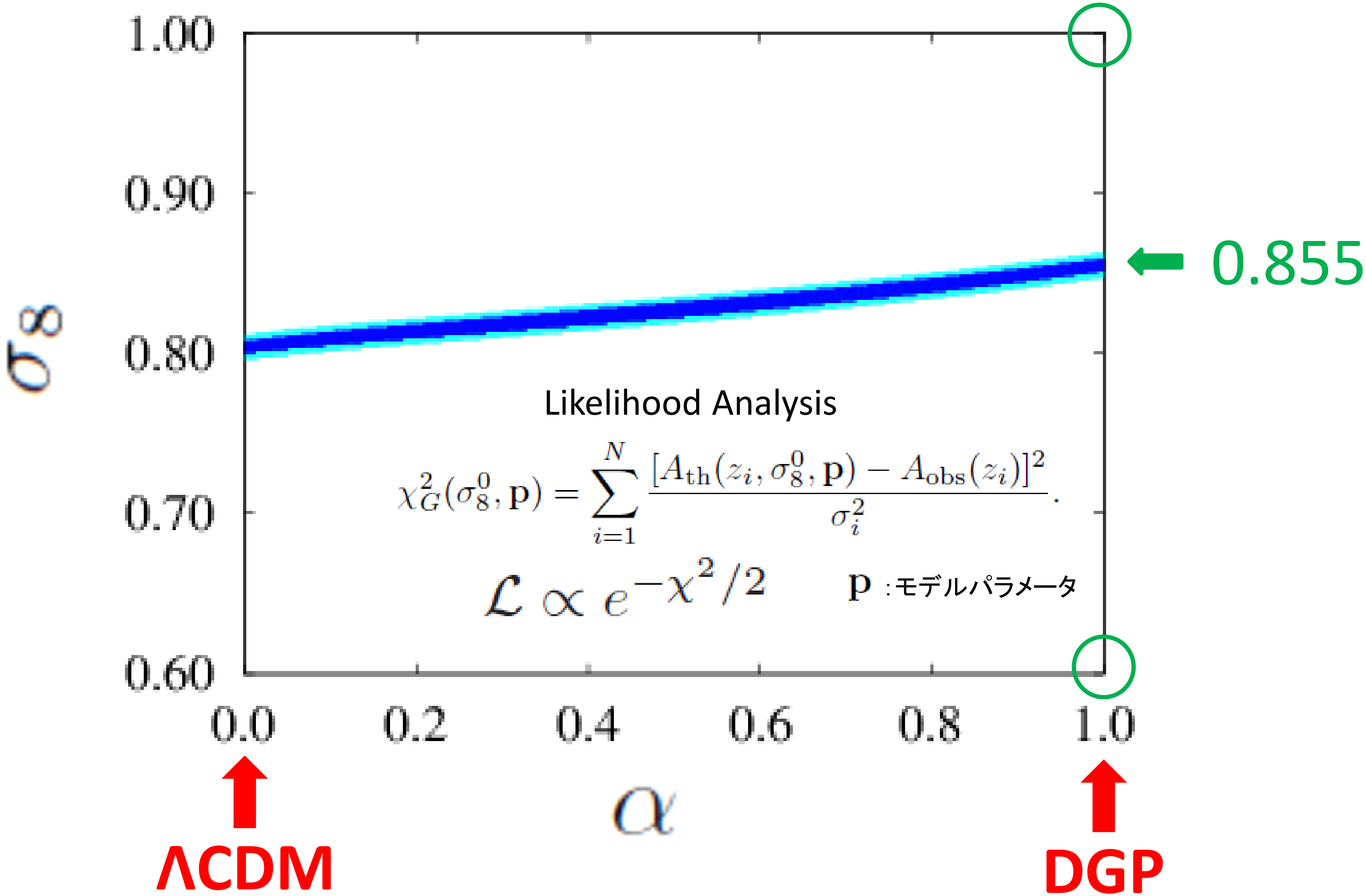
独立なパラメータ

Ω_{m0}, α

Effective gravitational constant $\frac{G_{\rm eff}}{G} = 1 + \frac{1}{3\beta}$

$$\beta := 1 - \frac{2\,(r_c H)^{2-\alpha}}{\alpha}\left[1 + \frac{1}{3}\frac{(2-\alpha)\dot{H}}{H^2}\right].$$

Extended DGP



Likelihood Analysis

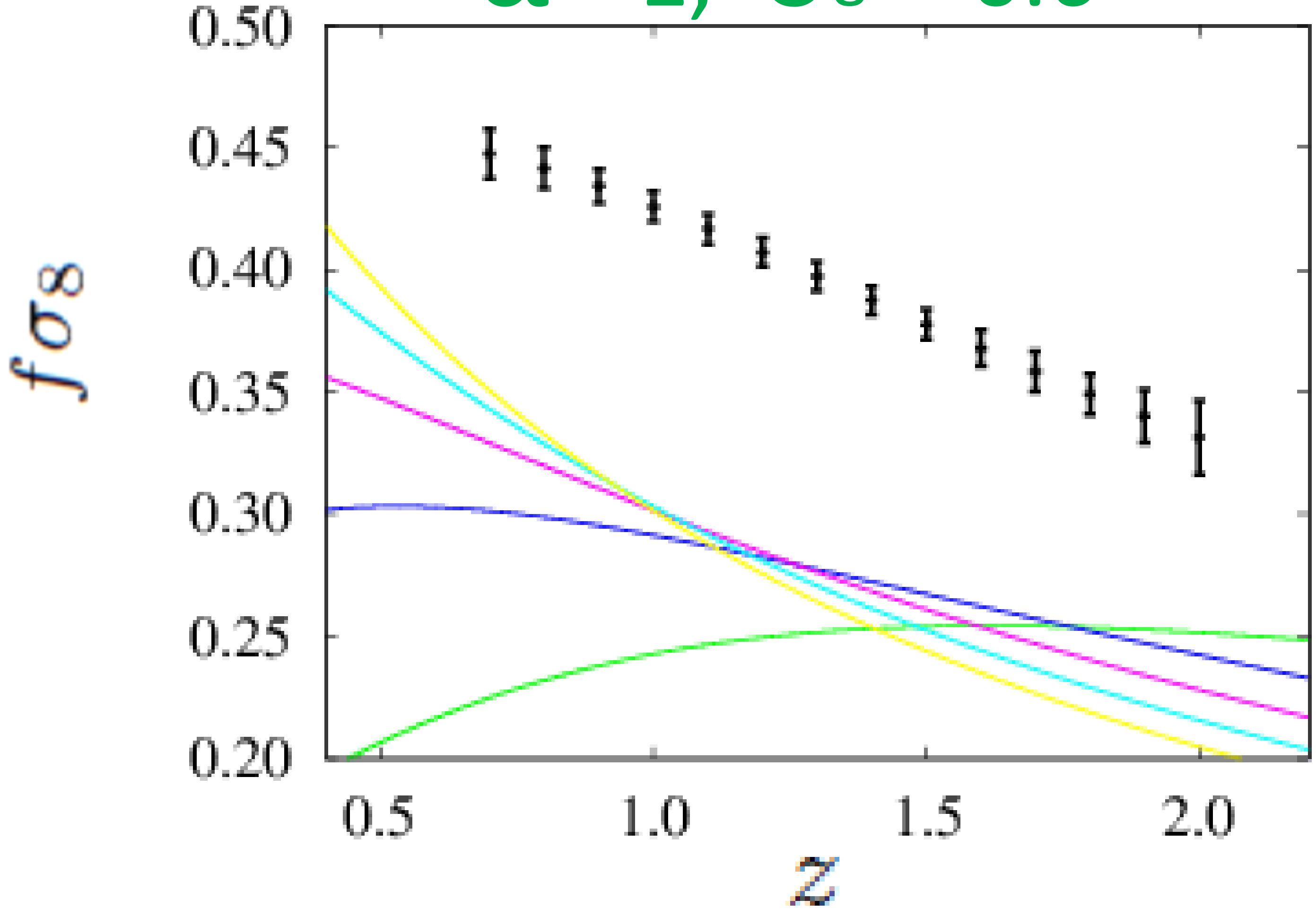
$$\chi_G^2(\sigma_8^0, \mathrm{p}) = \sum_{i=1}^{N} \frac{[A_{\mathrm{th}}(z_i, \sigma_8^0, \mathrm{p}) - A_{\mathrm{obs}}(z_i)]^2}{\sigma_i^2}.$$

$$\mathcal{L} \propto e^{-\chi^2/2}$$

p :モデルパラメータ

Extended DGP

$\alpha = 1, \ \sigma_8 = 0.6$



$\Omega_{m0} =$

0.1

0.3

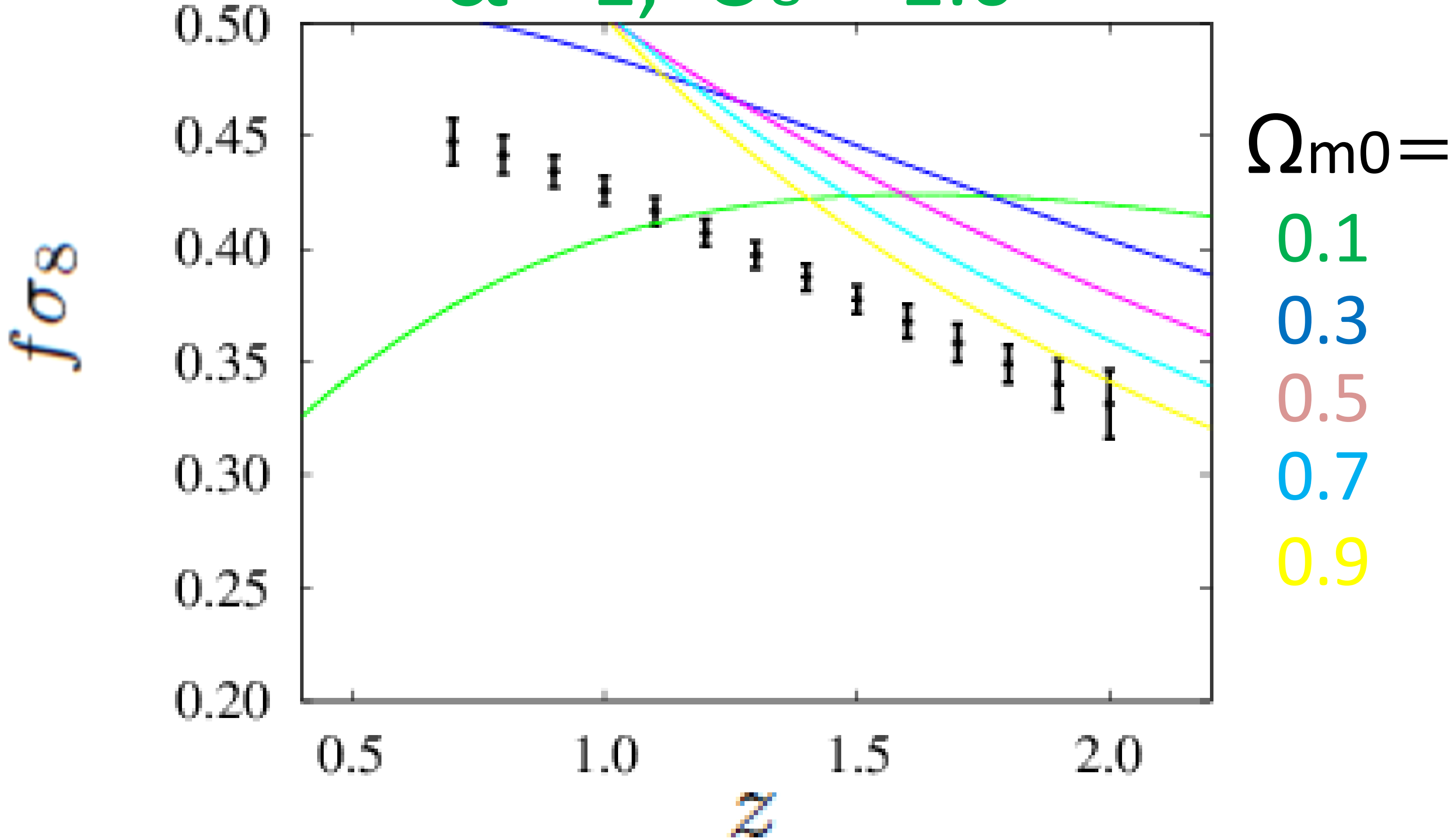
0.5

0.7

0.9

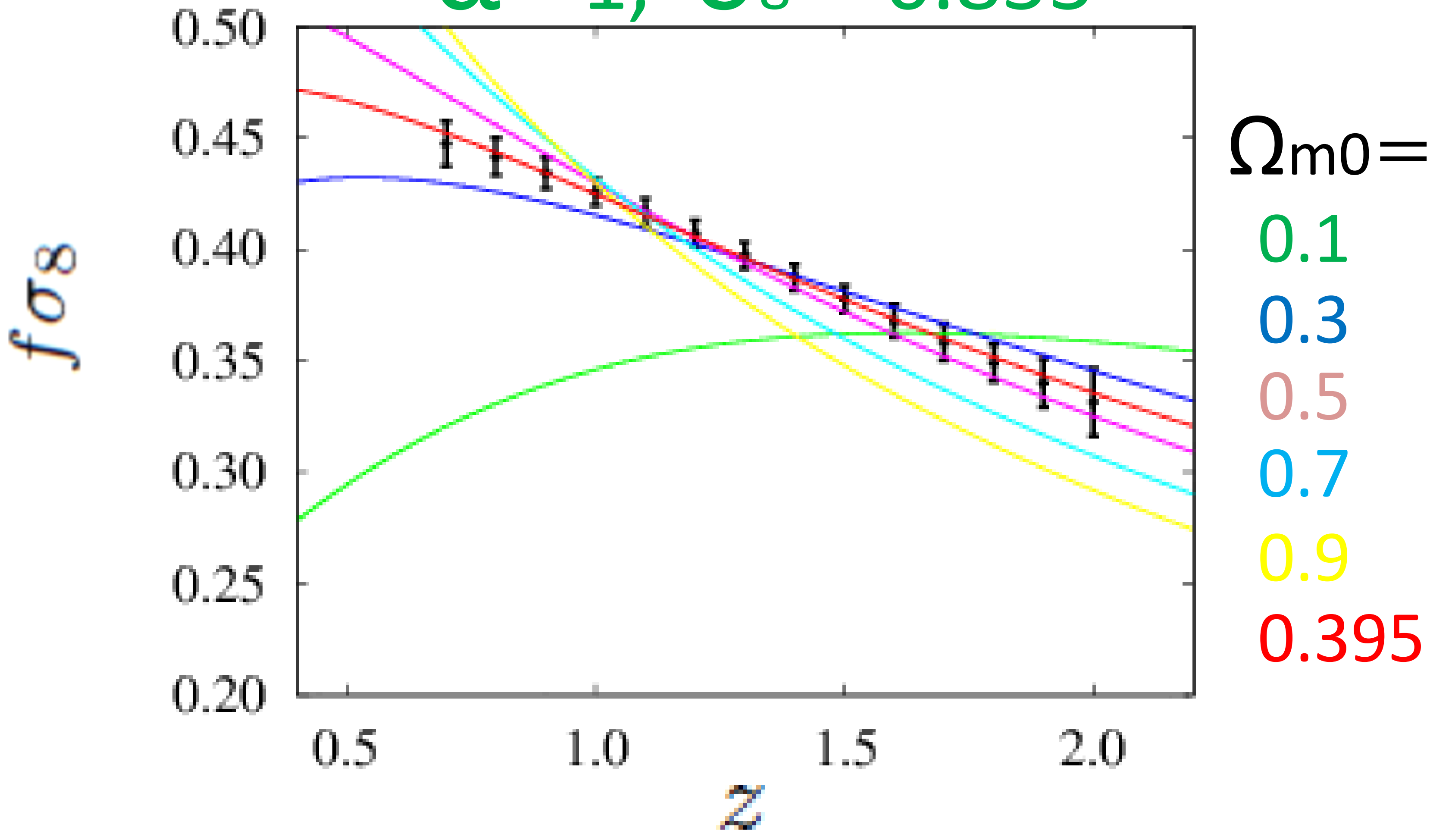
Extended DGP

$\alpha = 1, \ \sigma_8 = 1.0$

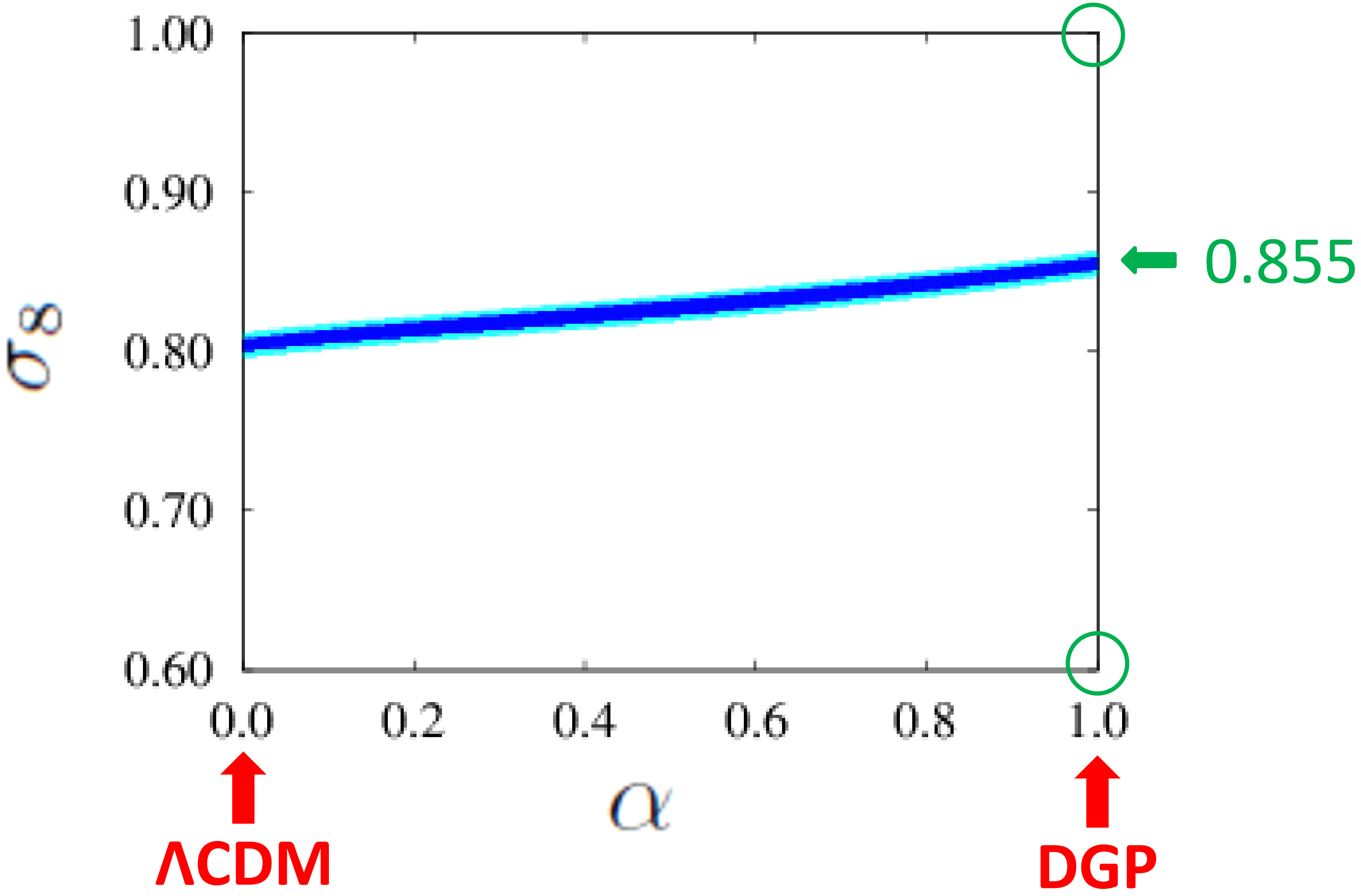


Extended DGP

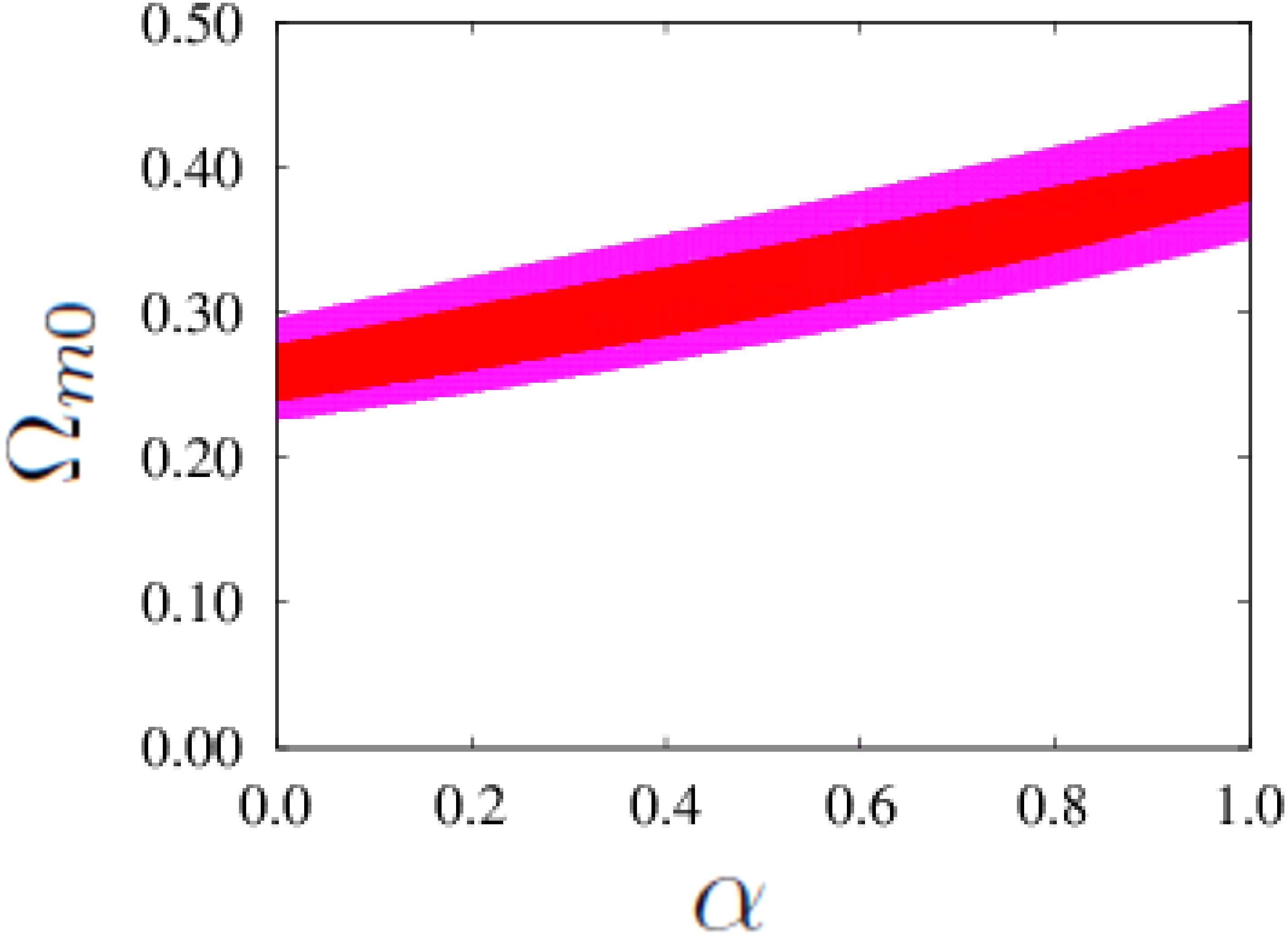
$\alpha = 1, \ \sigma_8 = 0.855$



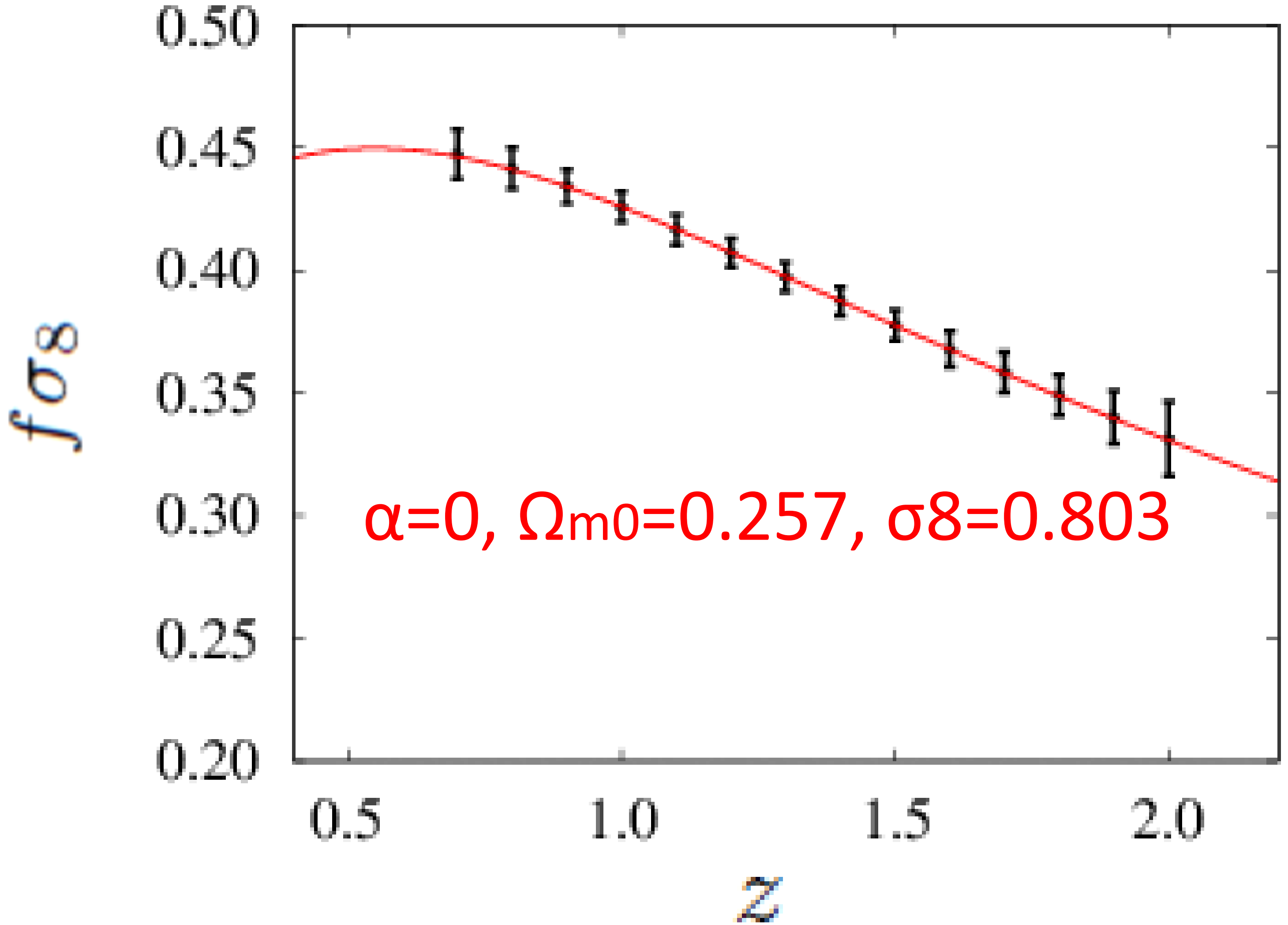
Extended DGP



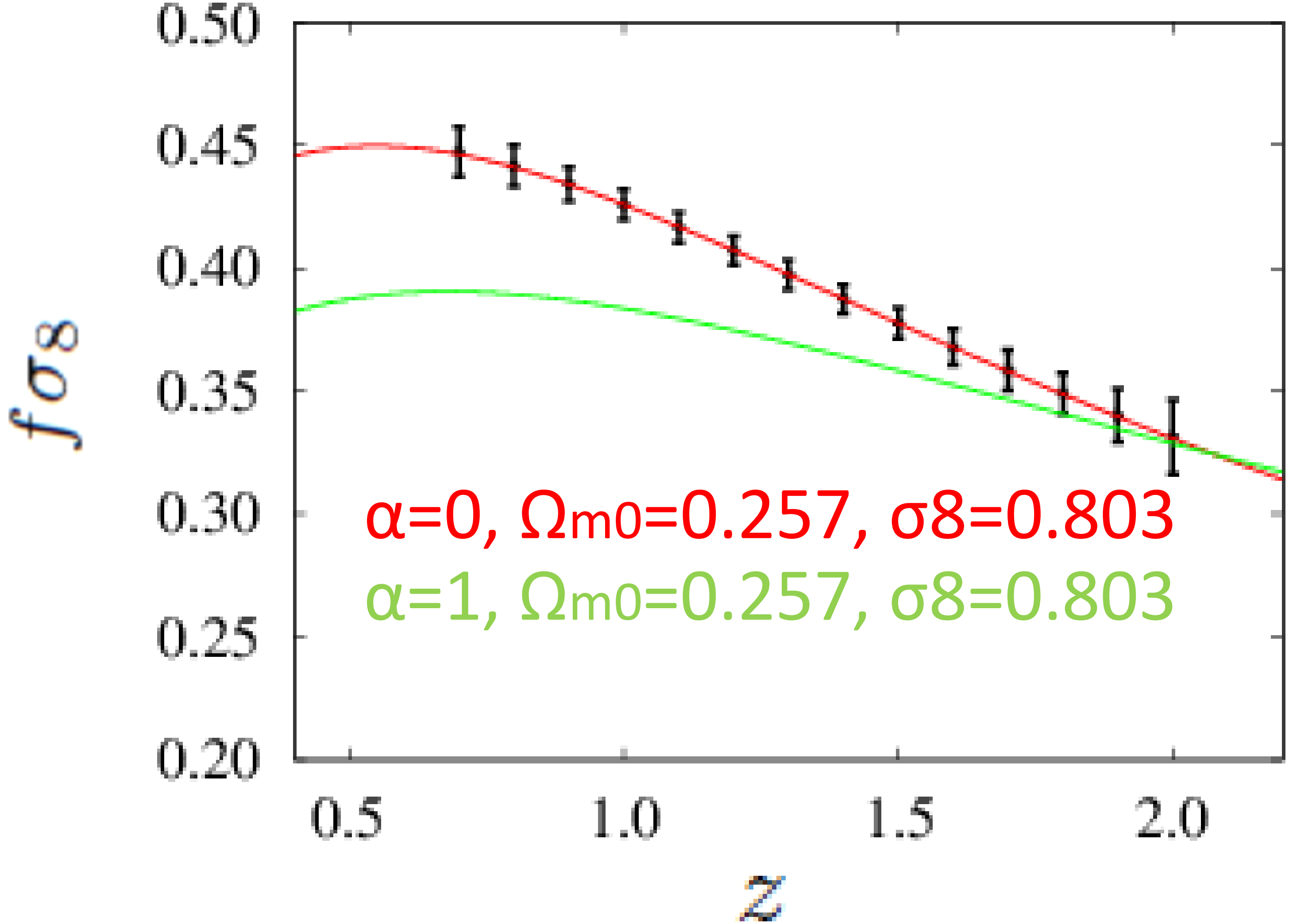
Extended DGP



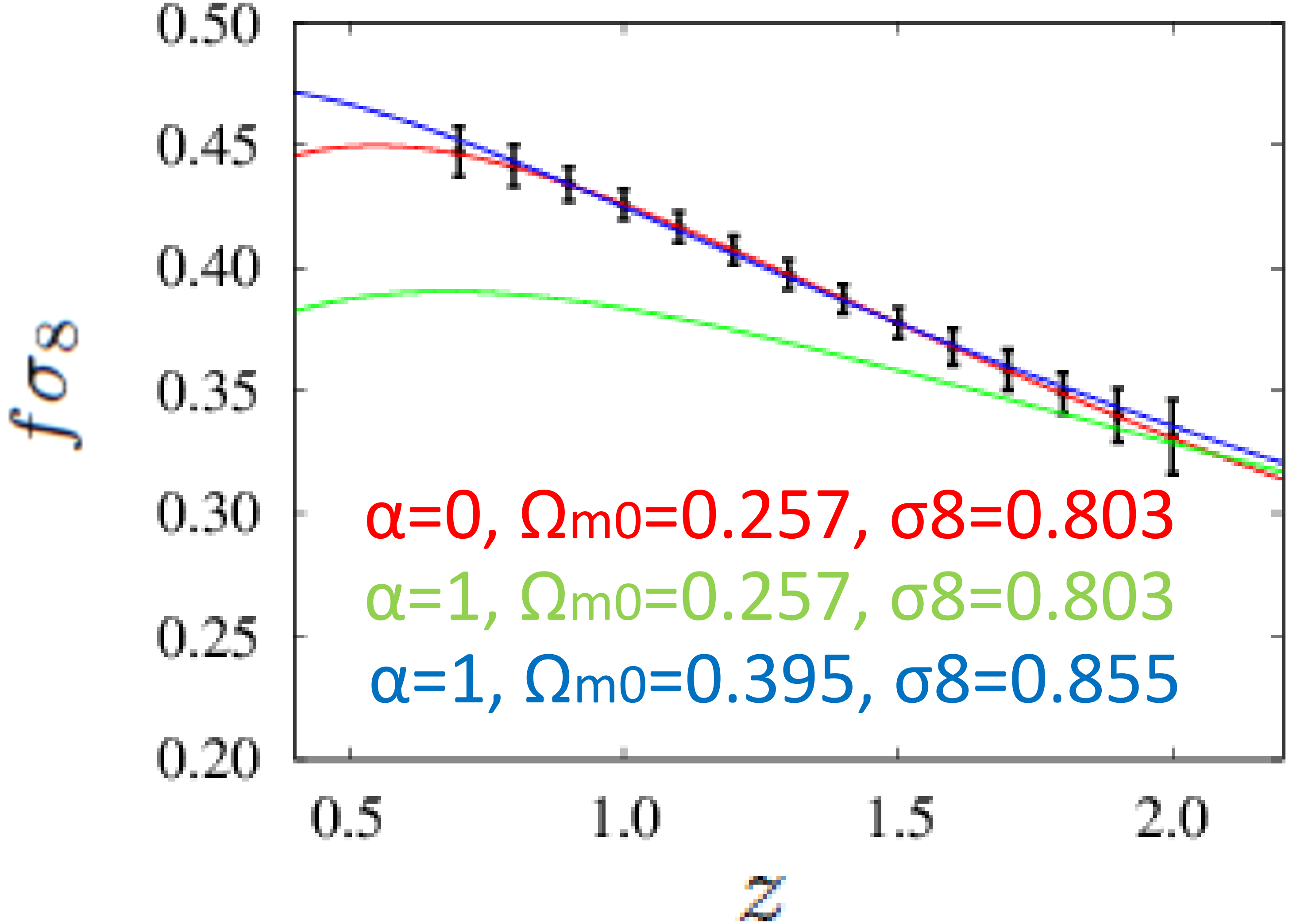
Extended DGP



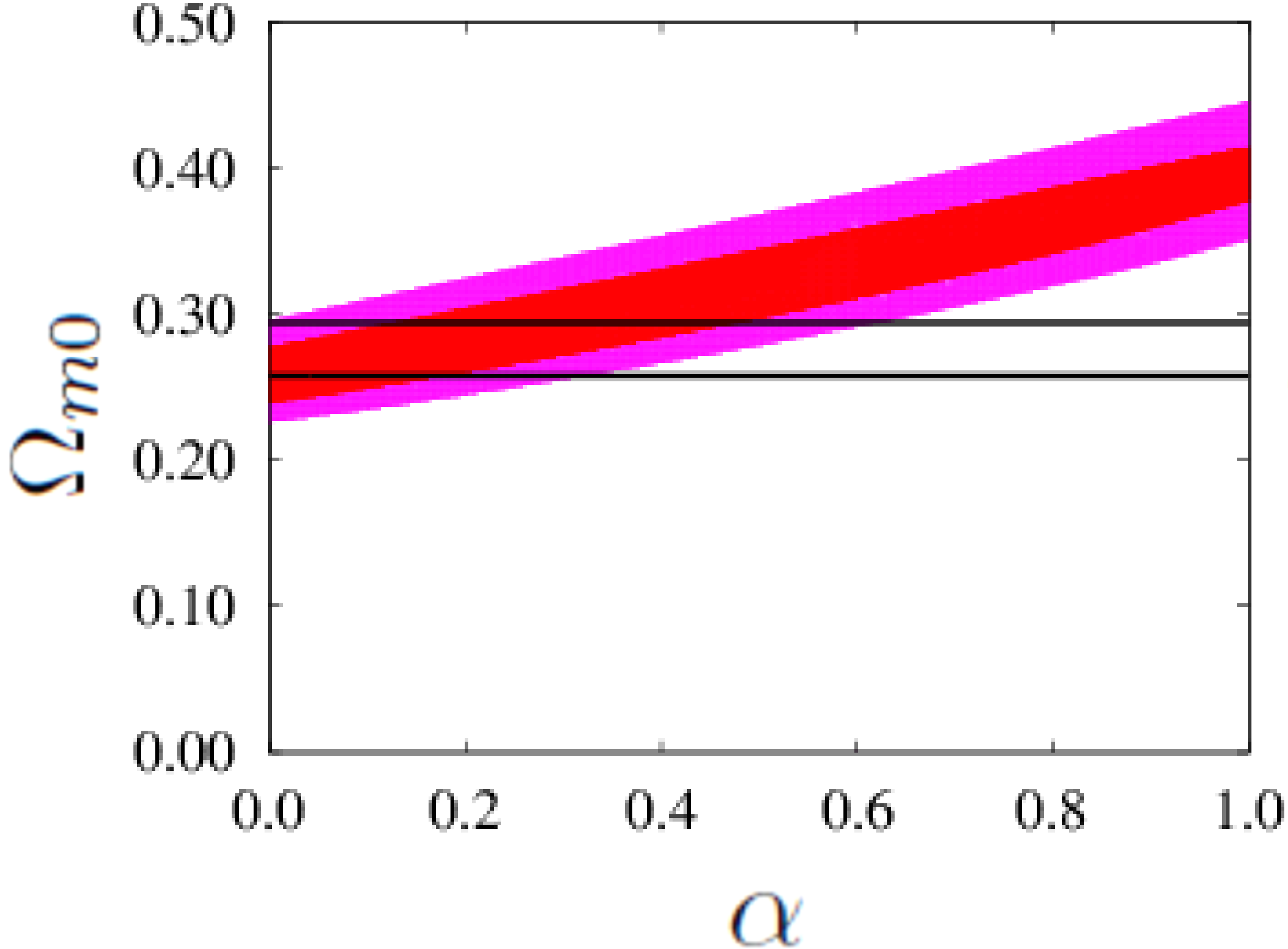
Extended DGP



Extended DGP



Extended DGP



Ω_{m0}= (1σ)

0.276 ± 0.018

CMB+BAO+SN

（Xia, PRD 2009）

Kinetic Gravity Braiding Model

(Kimura & Yamamoto, JCAP 2011)

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

$$K(X) = -X, \qquad X = -g^{\mu\nu} \nabla_\mu \phi \nabla_\nu \phi / 2.$$

$$G(X) = M_{\rm Pl} \left(\frac{r_c^2}{M_{\rm Pl}^2} X \right)^n, \quad n = 1$$ → Deffayet+, JCAP '10

$$\mathcal{L} = \sum_{i=2}^{5} \mathcal{L}_i \,,$$

$$\begin{aligned}
\mathcal{L}_2 &= K(\phi, X), \\
\mathcal{L}_3 &= -G_3(\phi, X) \Box \phi, \\
\mathcal{L}_4 &= G_4(\phi, X)\, R + G_{4,X} \left[(\Box \phi)^2 - (\nabla_\mu \nabla_\nu \phi)\, (\nabla^\mu \nabla^\nu \phi) \right], \\
\mathcal{L}_5 &= G_5(\phi, X)\, G_{\mu\nu}\, (\nabla^\mu \nabla^\nu \phi) - \frac{1}{6} G_{5,X} \left[(\Box \phi)^3 - 3(\Box \phi)\, (\nabla_\mu \nabla_\nu \phi)\, (\nabla^\mu \nabla^\nu \phi) + 2(\nabla^\mu \nabla_\alpha \phi)\, (\nabla^\alpha \nabla_\beta \phi)\, (\nabla^\beta \nabla_\mu \phi) \right].
\end{aligned}$$

$$K(\phi, X) = -X, \qquad G_3(\phi, X) = M_{\rm Pl} \left(\frac{r_c^2}{M_{\rm Pl}^2} X \right)^n, \qquad G_4(\phi, X) = 0, \quad G_5(\phi, X) = 0$$

Kinetic Gravity Braiding Model

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

Friedmann-like equation

$$3M_{\rm Pl}^2 H^2 = \rho_\phi + \rho_m + \rho_r,$$

$$-M_{\rm Pl}^2\left(2\dot{H} + 3H^2\right) = p_\phi + p_r,$$

$$\rho_\phi = -K + K_X\dot{\phi}^2 - G_\phi\dot{\phi}^2 + 3G_X H\dot{\phi}^3,$$

$$p_\phi = K - G_\phi\dot{\phi}^2 - G_X\dot{\phi}^2\ddot{\phi},$$

Field equation

$$K_\phi - (K_X - 2G_\phi)(\ddot{\phi} + 3H\dot{\phi}) - K_{\phi X}\dot{\phi}^2 - K_{XX}\ddot{\phi}\dot{\phi}^2 + G_{\phi\phi}\dot{\phi}^2$$
$$+ G_{X\phi}\dot{\phi}^2(\ddot{\phi} - 3H\dot{\phi}) - 3G_X(2H\dot{\phi}\ddot{\phi} + 3H^2\dot{\phi}^2 + \dot{H}\dot{\phi}^2) - 3G_{XX}H\dot{\phi}^3\ddot{\phi} = 0.$$

Kinetic Gravity Braiding Model

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

Crossover scale

$$r_c = \left(\frac{2^{n-1}}{3n}\right)^{1/2n}\left[\frac{1}{6(1-\Omega_0-\Omega_{r0})}\right]^{(2n-1)/4n} H_0^{-1},$$

独立なモデルパラメータ

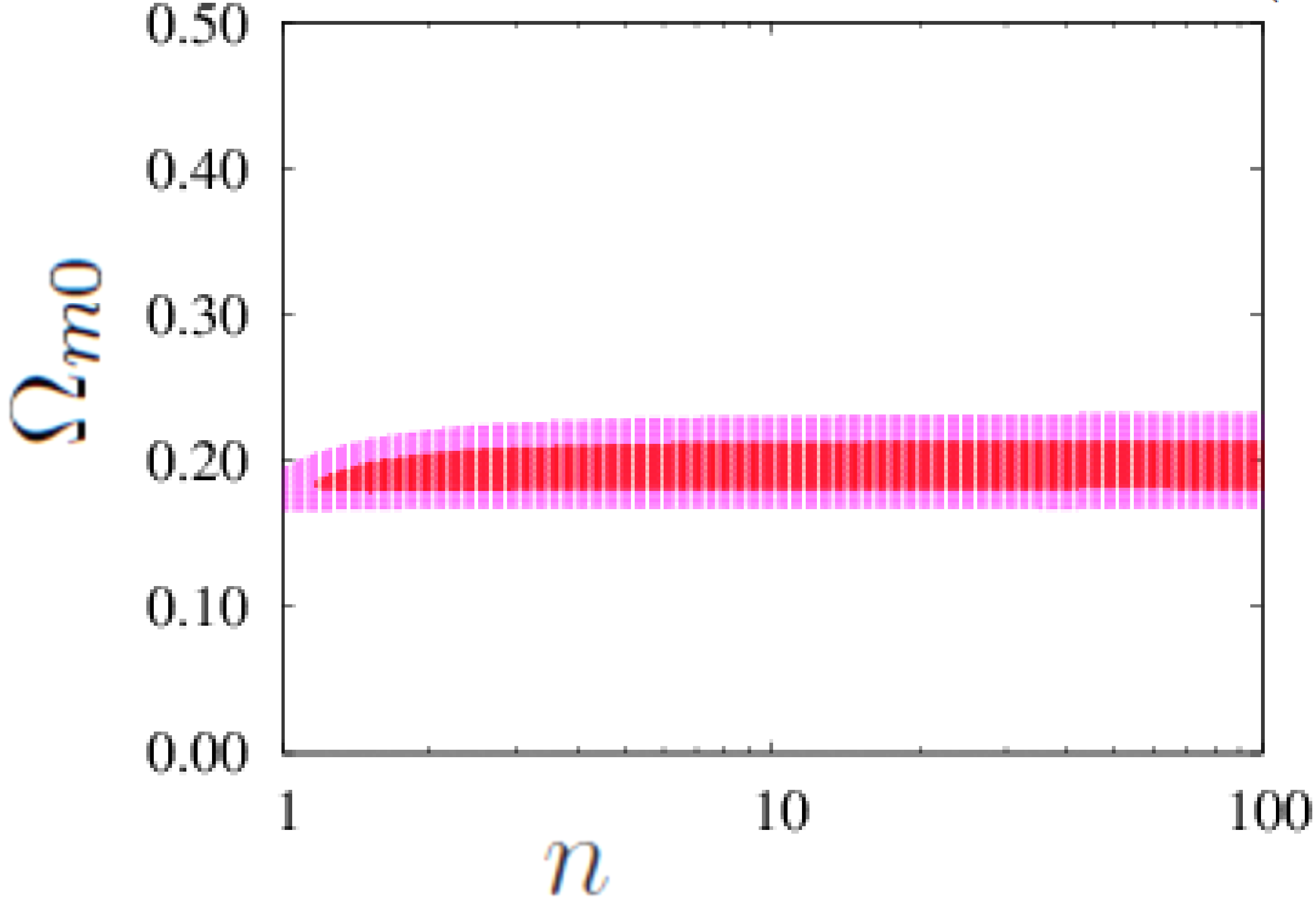
$\Omega_{m0},\ n$

Effective gravitational constant

$$G_{\rm eff} = G\left[1+4\pi G\frac{G_X^2\dot{\phi}^4}{\beta(a)}\right]$$
$$= G\frac{2n+3n\Omega_{\rm m}(a)-\Omega_{\rm m}(a)}{\Omega_{\rm m}(a)(5n-\Omega_{\rm m}(a))}.$$

Kinetic Gravity Braiding Model

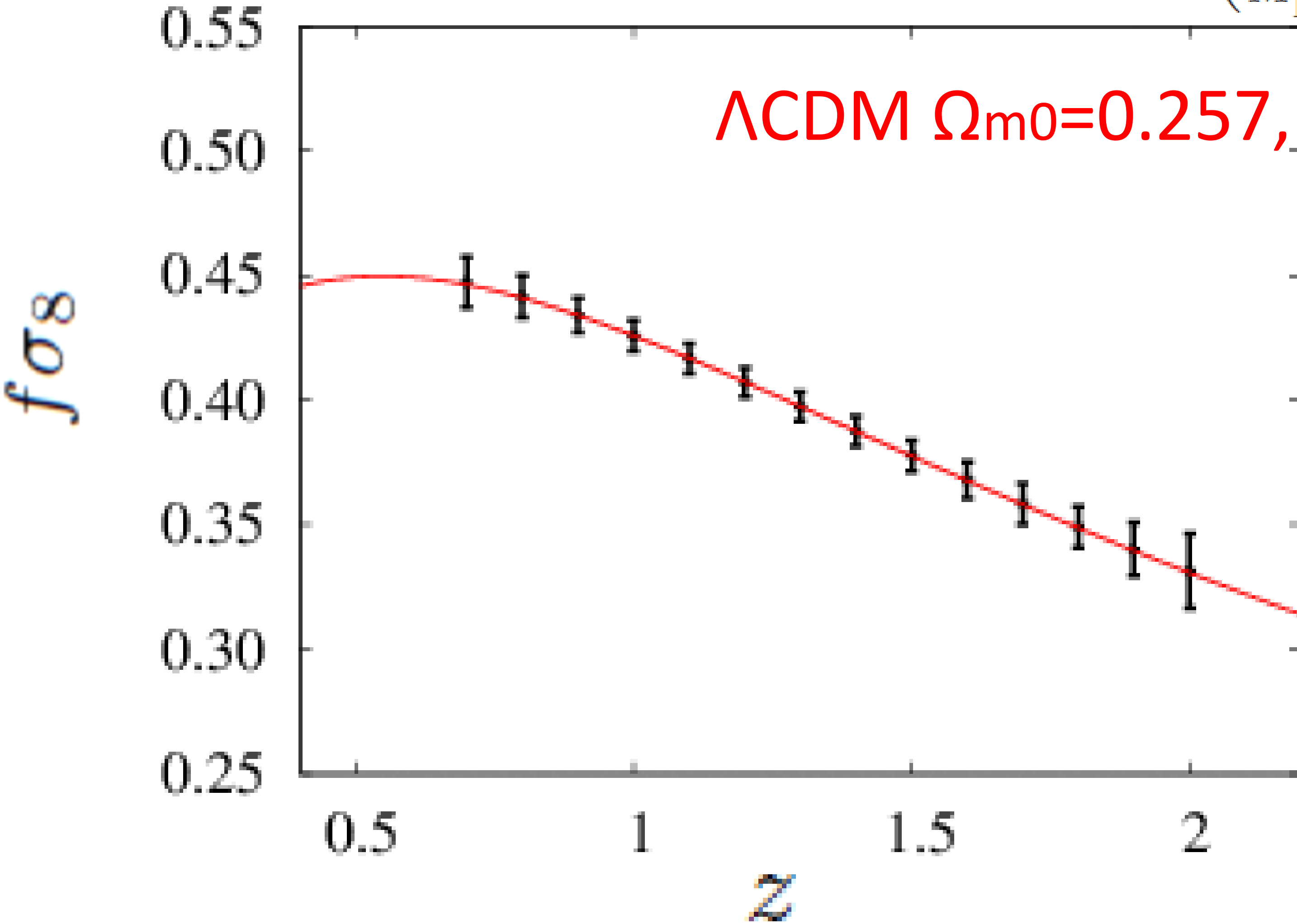
$$K(X) = -X, \quad G(X) = M_{\rm Pl}\left(\frac{r_c^2}{M_{\rm Pl}^2}X\right)^n,$$



Kinetic Gravity Braiding Model

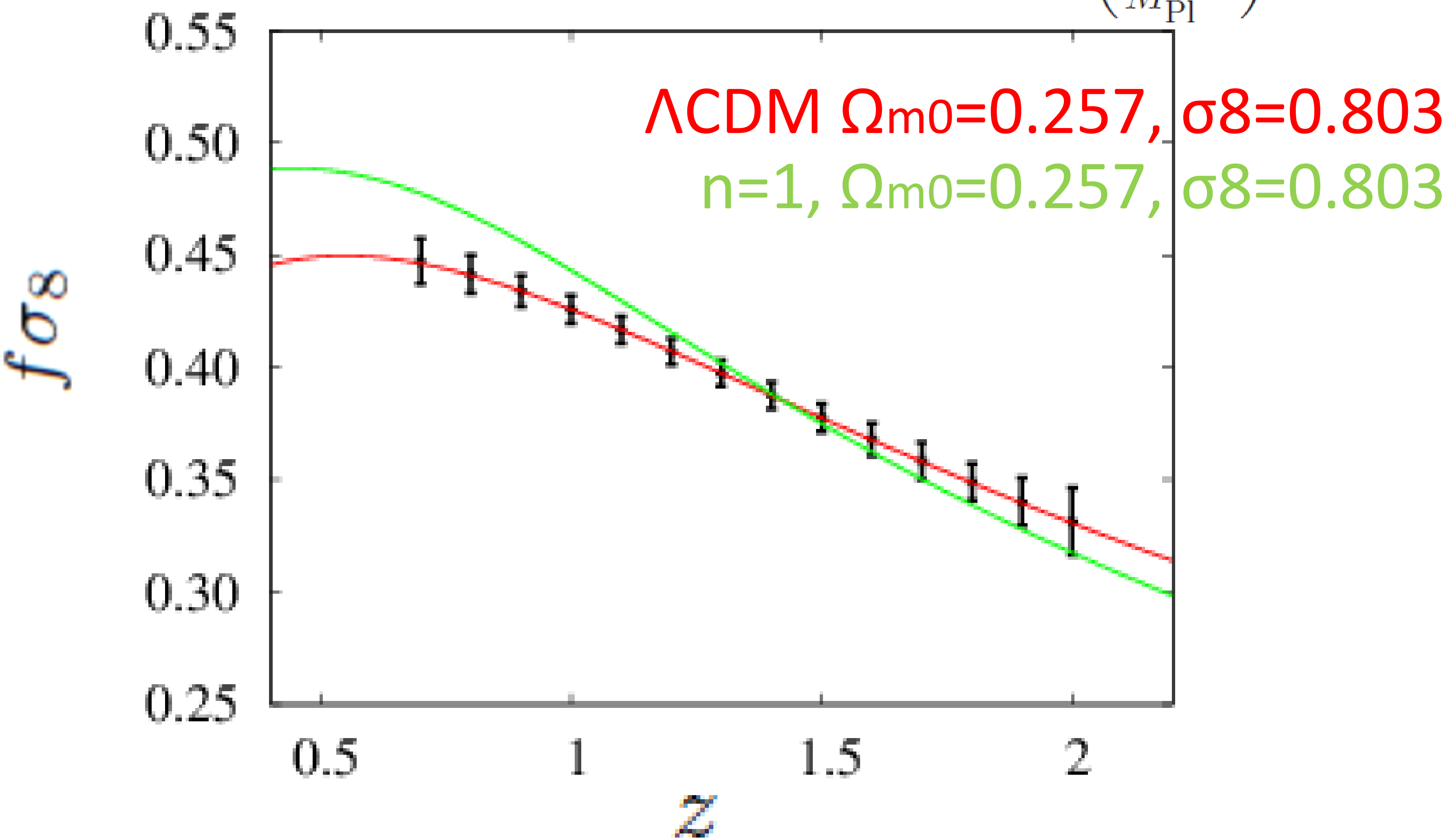
$$K(X) = -X, \quad G(X) = M_{\rm Pl}\left(\frac{r_c^2}{M_{\rm Pl}^2}X\right)^n,$$

ΛCDM Ω_{m0}=0.257, σ8=0.803



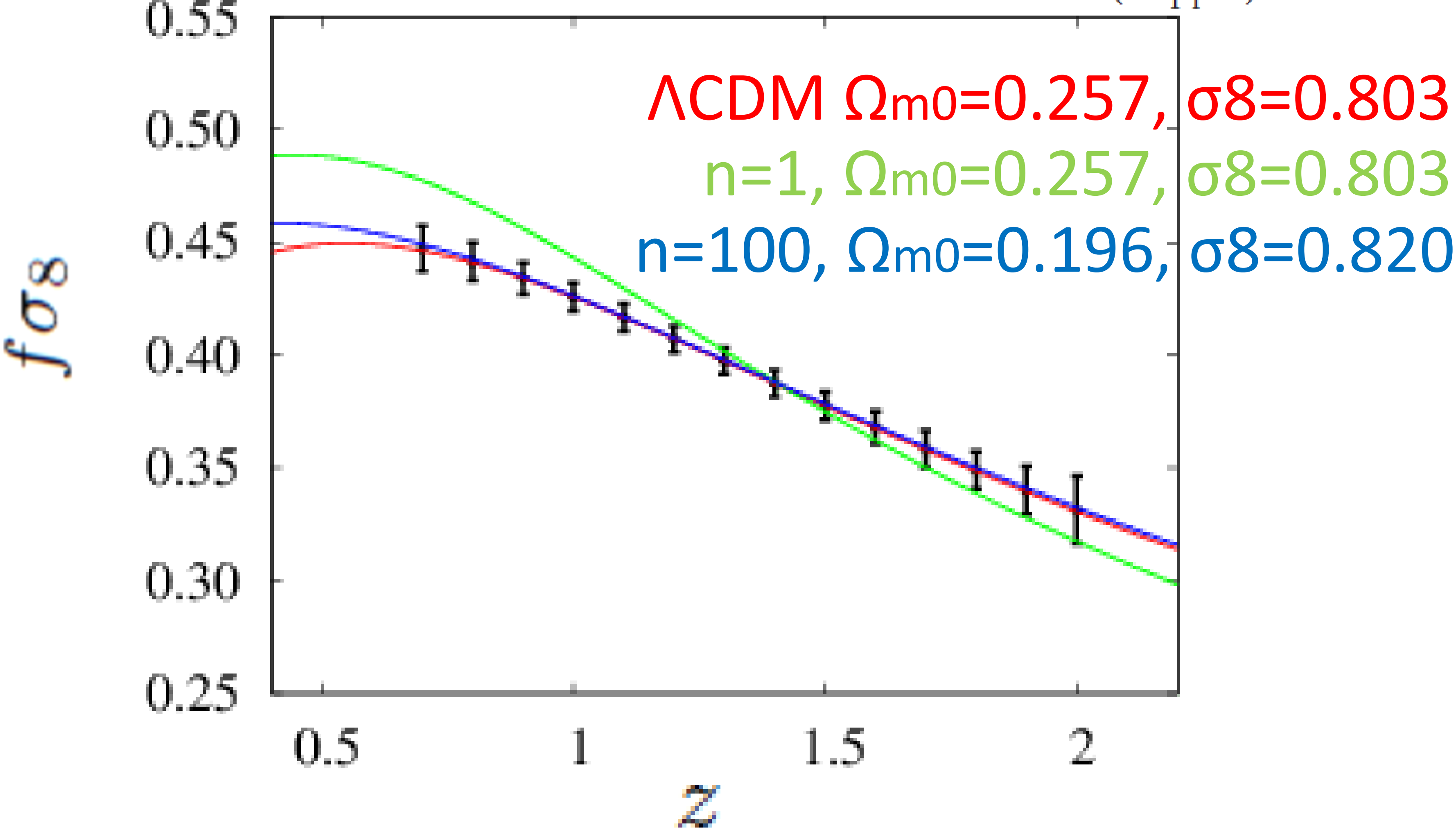
Kinetic Gravity Braiding Model

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



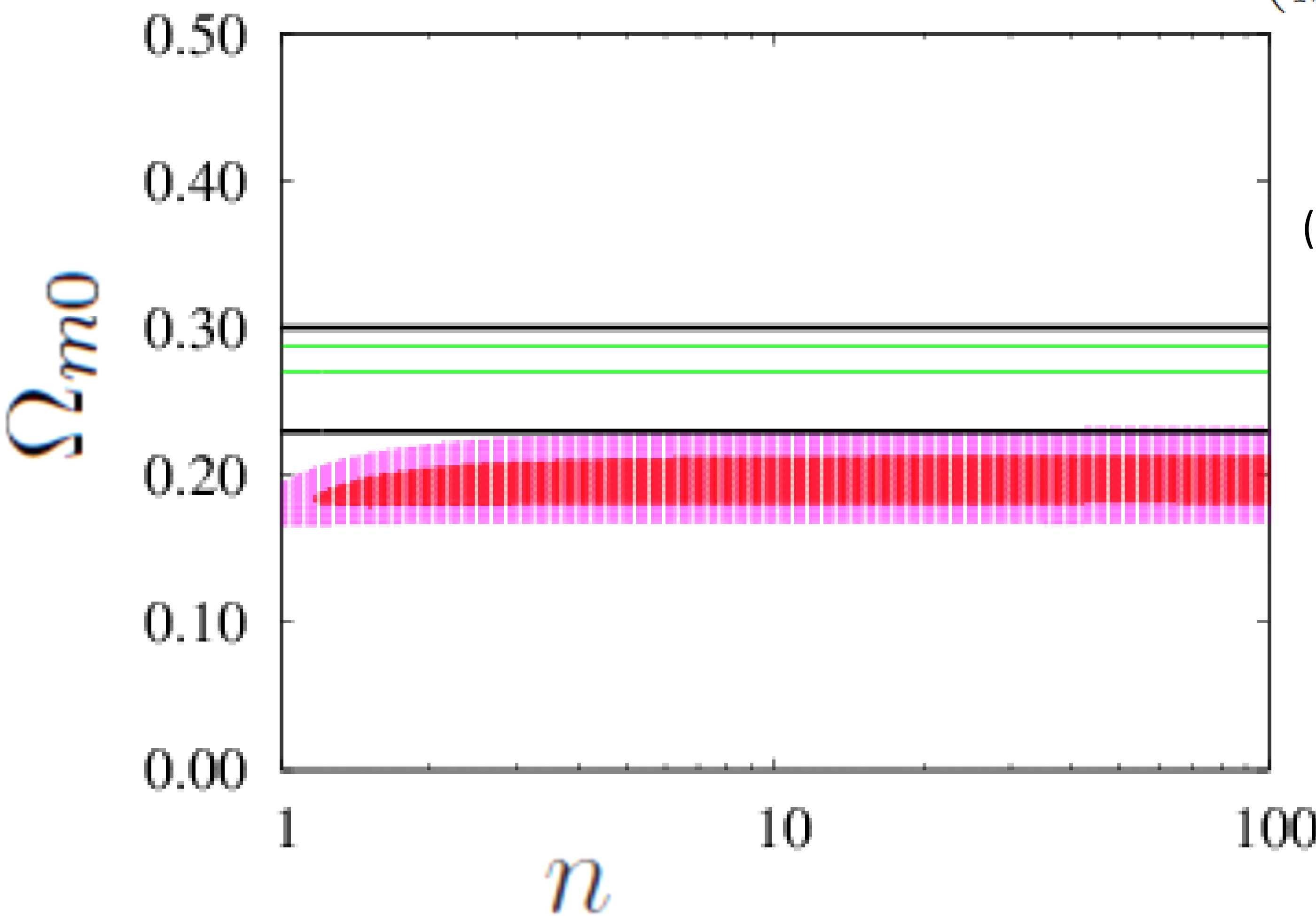
Kinetic Gravity Braiding Model

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



Kinetic Gravity Braiding Model

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



(Kimura & Yamamoto, JCAP ’11)

CMBからの制限

SNIaからの制限

Galileon

(Silva & Koyama, PRD 2009)
(Kobayashi+, PRD 2010)

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

Action $$S = \int d^4x\sqrt{-g}\left[\frac{M_{\rm pl}^2}{2}F(\phi)R + K(\phi,X) - G(\phi,X)\Box\phi + L_m\right],$$

$$F(\phi) = \frac{2}{M_{\rm pl}^2}\phi, \quad K(\phi,X) = 2\frac{\omega}{\phi}X, \quad G(\phi,X) = 2\xi(\phi)X,$$

$$\xi(\phi) = \frac{r_c^2}{\phi^2},$$

$$\mathcal{L} = \sum_{i=2}^{5}\mathcal{L}_i\,,$$

$$\begin{aligned}
\mathcal{L}_2 &= K(\phi,X),\\
\mathcal{L}_3 &= -G_3(\phi,X)\Box\phi,\\
\mathcal{L}_4 &= G_4(\phi,X)\,R + G_{4,X}\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)\,(\nabla^\mu\nabla^\nu\phi)\right],\\
\mathcal{L}_5 &= G_5(\phi,X)\,G_{\mu\nu}\,(\nabla^\mu\nabla^\nu\phi) - \frac{1}{6}G_{5,X}\left[(\Box\phi)^3 - 3(\Box\phi)\,(\nabla_\mu\nabla_\nu\phi)\,(\nabla^\mu\nabla^\nu\phi) + 2(\nabla^\mu\nabla_\alpha\phi)\,(\nabla^\alpha\nabla_\beta\phi)\,(\nabla^\beta\nabla_\mu\phi)\right].
\end{aligned}$$

$$K(\phi,X) = 2\frac{\omega}{\phi}X, \quad G_3(\phi,X) = 2\xi(\phi)X, \quad \xi(\phi) = \frac{r_c^2}{\phi^2},$$

$$G_4(\phi,X) = 0$$

$$G_5(\phi,X) = 0$$

Galileon

$$K(\phi, X) = 2\frac{\omega}{\phi}X, \quad G(\phi, X) = 2\xi(\phi)X, \quad \xi(\phi) = \frac{r_c^2}{\phi^2},$$

Friedmann-like equation

$$3H^2 = \frac{1}{M_{\rm pl}^2}(\rho_m + \rho_r + \rho_\phi), \quad -3H^2 - 2\dot{H} = \frac{1}{M_{\rm pl}^2}(p_r + p_\phi),$$

$$\rho_\phi = 2\phi\left[-3H\frac{\dot{\phi}}{\phi} + \frac{\omega}{2}\left(\frac{\dot{\phi}}{\phi}\right)^2 + \phi^2\xi(\phi)\left\{3H + \frac{\dot{\phi}}{\phi}\right\}\left(\frac{\dot{\phi}}{\phi}\right)^3\right] + 3H^2\left(M_{\rm pl}^2 - 2\phi\right),$$

$$p_\phi = 2\phi\left[\frac{\ddot{\phi}}{\phi} + 2H\frac{\dot{\phi}}{\phi} + \frac{\omega}{2}\left(\frac{\dot{\phi}}{\phi}\right)^2 - \phi^2\xi(\phi)\left\{\frac{\ddot{\phi}}{\phi} - \left(\frac{\dot{\phi}}{\phi}\right)^2\right\}\left(\frac{\dot{\phi}}{\phi}\right)^2\right] - (3H^2 + 2\dot{H})\left(M_{\rm pl}^2 - 2\phi\right).$$

Field equation

$$\begin{aligned}&(K_{,X} + 2XK_{,XX} + 6H\dot{\phi}G_{,X} + 6H\dot{\phi}XG_{,XX} - 2XG_{,\phi X} - 2G_{,\phi})\ddot{\phi}\\&+(3HK_{,X} + \dot{\phi}K_{,\phi X} + 9H^2\dot{\phi}G_{,X} + 3\dot{H}\dot{\phi}G_{,X} + 6HXG_{,\phi X} - 6HG_{,\phi} - G_{,\phi\phi}\dot{\phi})\dot{\phi}\\&-K_{,\phi} - 6M_{\rm pl}^2H^2F_{,\phi} - 3M_{\rm pl}^2\dot{H}F_{,\phi} = 0,\end{aligned}$$

Galileon

$$K(\phi, X) = 2\frac{\omega}{\phi}X, \quad G(\phi, X) = 2\xi(\phi)X, \quad \xi(\phi) = \frac{r_c^2}{\phi^2},$$

Ω_{m0} が決めた値になるまで Crossover scale を振ってイテレーションする。

独立なモデルパラメータ

$\Omega_{m0}, \ \omega$

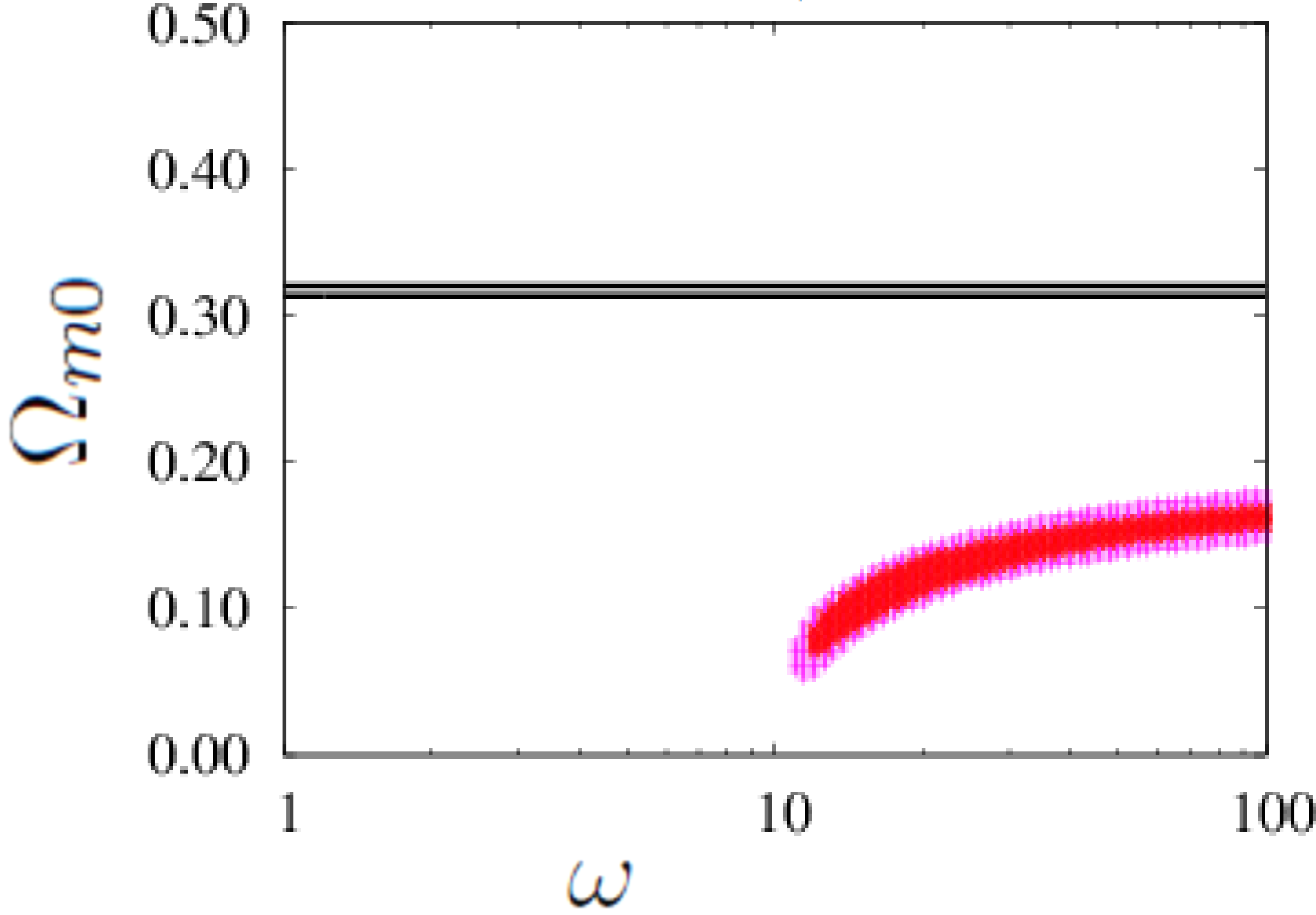
Effective gravitational constant

$$G_{\text{eff}} = \frac{1}{16\pi\phi}\left[1 + \frac{(1+\xi(\phi)\dot{\phi}^2)^2}{J}\right],$$

$$J = 3 + 2\omega + \phi^2\xi(\phi)\left[4\frac{\ddot{\phi}}{\phi} - 2\frac{\dot{\phi}^2}{\phi^2} + 8H\frac{\dot{\phi}}{\phi} - \phi^2\xi(\phi)\frac{\dot{\phi}^4}{\phi^4}\right].$$

Galileon

$$K(\phi, X) = 2\frac{\omega}{\phi}X, \quad G(\phi, X) = 2\xi(\phi)X, \quad \xi(\phi) = \frac{r_c^2}{\phi^2},$$

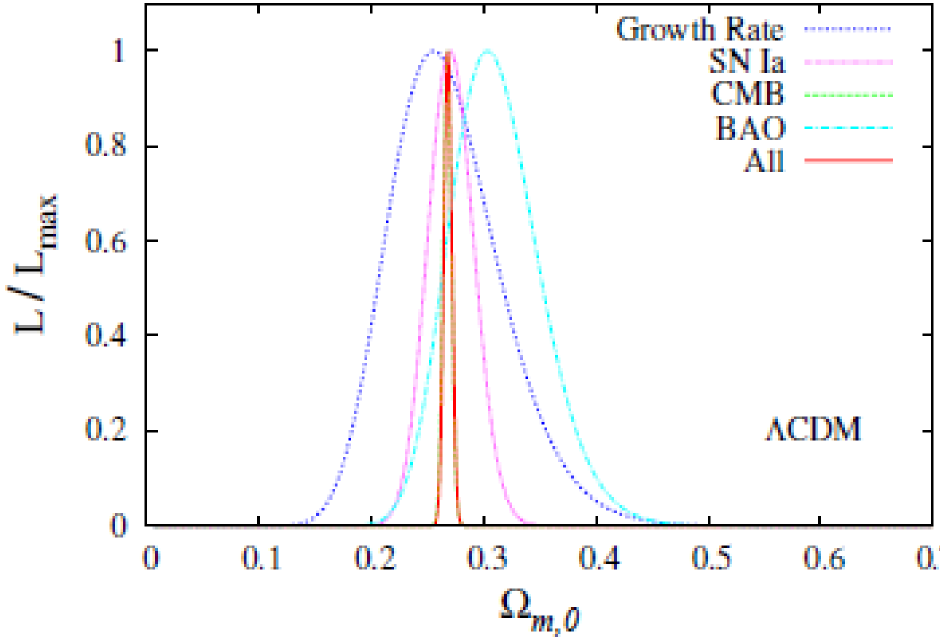


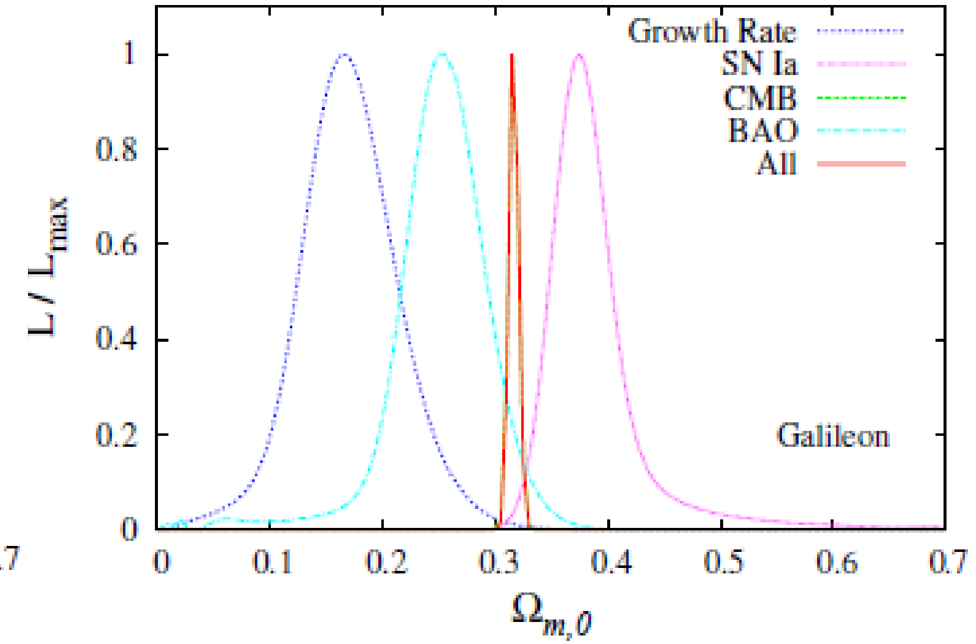
(KH+, PTP '12)

CMB+BAO+SN

既存の観測データとの比較1

(KH+, PTP 2012)

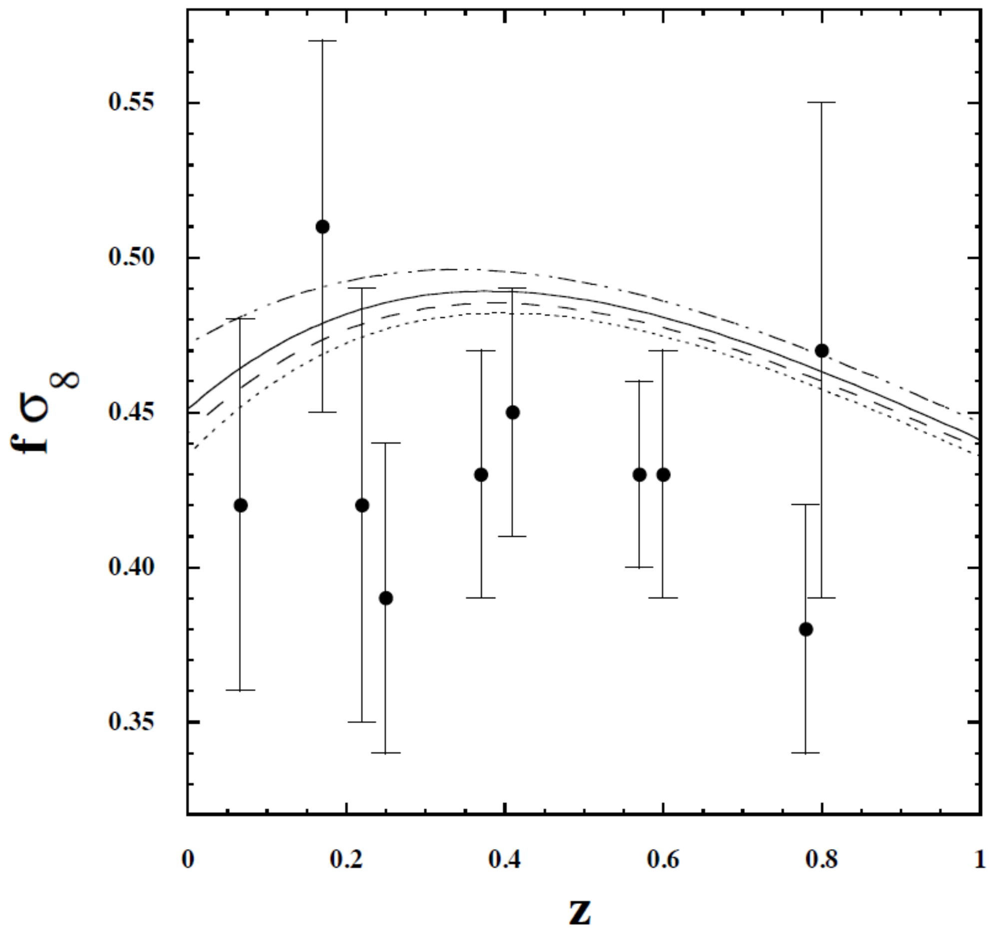




ΛCDM **Galileon**

既存の観測データとの比較2

R. Kase, S. Tsujikawa and A. De Felice, PRD, (2016)



GLPV theories
との比較

6. Summary

Euclid の 物質密度揺らぎの成長率 (Cosmic Growth Rate) により制限されるパラメータ領域と、

宇宙背景放射 (CMB) 等により制限されるパラメータ領域とが

重ならないモデルが多いため、

将来の Euclid の Cosmic Growth Rate の観測と、

CMB 等の精密観測を組み合わせることにより、

多くのモデルが棄却され、

多くのモデルの判別が可能となることが分かった。