Large Scale Structure in Degenerate Higher-order Scalar-Tensor Theories

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理論懇シンポジウム 2019年12月25~27日

修正重力理論

- **後期加速膨張の存在**
  - ・後期加速膨張 (Ia Supernova, LSS, CMB)
  - ・一般相対論では、後期加速膨張 = 宇宙項

    → 宇宙項問題, coincidence, …

- **修正重力理論 (宇宙項の代替として)**
  - ・宇宙論的スケール: 後期加速膨張
  - ・小スケール: スクリーニング機構 → ニュートンの逆二乗則を回復
  - ・重力理論の拡張　〜　新しい自由度の追加

    → シンプルな拡張: スカラーテンソル理論 ($g_{\mu\nu} + \phi$)

Horndeski theory

Horndeski (1972) , Kobayashi+ (2011) , Deffyet+ (2011)

$$\begin{aligned}\mathscr{L} &= G_2(\phi, X) - G_3(\phi, X)\Box\phi \\ &+ G_4(\phi, X)R + G_{4X}\left[(\Box\phi)^2 - \phi_{\mu\nu}^2\right] \\ &+ G_5(\phi, X)G^{\mu\nu}\phi_{\mu\nu} - \frac{G_{5X}}{6}\left[(\Box\phi)^3 - 3(\Box\phi)\phi_{\mu\nu}^2 + 2\phi_{\mu\nu}^3\right]\end{aligned}$$

$$\nabla_\mu\phi = \phi_\mu, \nabla_\nu\nabla_\mu\phi = \phi_{\mu\nu}, \nabla^\mu\nabla_\mu\phi = \Box\phi$$

$$X = -\frac{1}{2}g^{\mu\nu}\nabla_\mu\phi\nabla_\nu\phi$$

✓運動方程式が2階の最も一般的なスカラーテンソル理論 (2+1自由度).

✓ 任意関数の形を決めると具体的なモデルを再現　(例) f(R), DGP

✓ 加速膨張解が存在　(例) De Felice-Tsujikawa (2009, 2010)

✓ 小スケールでスカラー場の伝搬を抑える → Vainshtein screening

($\Box\phi$を含む非線形相互作用)

Kimura+ (2012), Narikawa+ (2013), Koyama+ (2013)

Whether go beyond Horndeski or not?

- **Horndeski theory**:
  運動方程式が**2階**の最も一般的なスカラーテンソル理論

- General higher-order EoMs: Ostrogradsky ghost Ostrogradsky (1850)

↓ 縮退条件 (式の組み合わせで高階微分を消す)

2nd-order system

<u>D</u>egenerate <u>H</u>igher <u>O</u>rder <u>S</u>calar-<u>T</u>ensor (**DHOST**) theories

Langlois-Noui (2015,16), Crisostomi+ (2016)

Quadratic DHOST

Langlois-Noui (2015,2016), Crisostomi+ (2016)

- G_4 の一般化 （G_2, G_3 + **6** funcs. ） $\nabla_\mu\phi = \phi_\mu, \nabla_\nu\nabla_\mu\phi = \phi_{\mu\nu}, \phi^\mu{}_\mu = \Box\phi$

$$\mathcal{L} = G_2(\phi, X) - G_3(\phi, X)\Box\phi$$
$$+f(\phi, X)R + \sum_{i=1}^{5}\mathcal{L}_i$$

$\sim (\nabla\nabla\phi)^2$

$$\mathcal{L}_1 = A_1(\phi, X)\phi_{\mu\nu}\phi^{\mu\nu}$$
$$\mathcal{L}_2 = A_2(\phi, X)(\Box\phi)^2$$
$$\mathcal{L}_3 = A_3(\phi, X)\Box\phi\phi^\mu\phi_{\mu\nu}\phi^\nu$$
$$\mathcal{L}_4 = A_4(\phi, X)\phi^\mu\phi_{\mu\rho}\phi^{\rho\nu}\phi_\nu$$
$$\mathcal{L}_5 = A_5(\phi, X)(\phi^\mu\phi_{\mu\nu}\phi^\nu)^2$$

- healthy higher-order theory

縮退条件:

3 relations between f and A_i

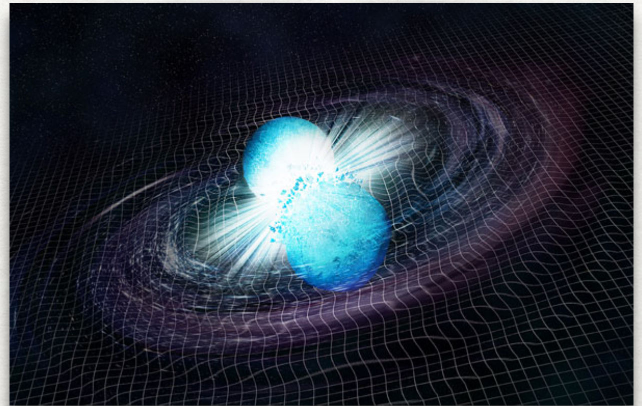
⇒ independent funcs. G_2, G_3 and f, A_1, A_3 (6 -3 =**3**)

重力波からの制限

- GW170817, GRB 170817: NS-NS merger   Abbott+ (2017)

$$|c_{\mathrm{GW}}^2 - 1| < \mathcal{O}(10^{-15})$$ ほぼ光速

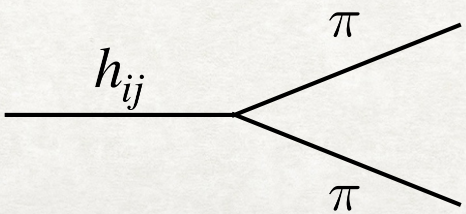
$$c_{\mathrm{GW}}^2 = 1 \quad \Leftrightarrow \quad A_1 = 0$$



- Catastrophic GWs decay into scalar field   Creminelli+ (2018, 19)

$$H_{int} \sim A_3 \, \ddot{h}_{ij} \partial_i \pi \partial_j \pi \quad \rightarrow \quad \frac{\Gamma_{h\pi\pi}}{H_0} \sim A_3 \left(\frac{\omega_{\mathrm{GW}}}{H_0} \right)^2 \ll 1 \quad \rightarrow \quad A_3 = 0$$

要請



DHOST theory evading GW constraints

Creminelli+ (2018, 2019)

$c_{\rm GW} = 1$ ($A_1 = 0$) + **no GW decay** ($A_3 = 0$)

$$\mathcal{L} = G_2(\phi, X) - G_3(\phi, X)\Box\phi + f(\phi, X)R + \frac{3f_X^2}{2f}\phi^\mu\phi_{\mu\rho}\phi^{\nu\rho}\phi_\nu$$

Our work

Toward tests of DHOST theory evading GW constraints

- **仕事1: 線形密度揺らぎからの制限**
- **仕事2: 非線形密度揺らぎへの影響 (matter bispectrum)**

仕事1: 線形密度揺らぎ
からの制限

SH, T. Kobayashi, D. Yamauchi, S. Yokoyama,
Phys. Rev. D 99 (2019) no.10, 104051

Setup

- Quadratic DHOST, sub-horizon ($aH \ll k$)，物質優勢以降

- **perturbations** (一様等方時空＋摂動)

$$ds^2 = -(1+2\Phi)dt^2 + a^2(t)(1-2\Psi)d\boldsymbol{x}^2.$$

$$\phi(t,\boldsymbol{x}) = \overline{\phi}(t) + \pi(t,\boldsymbol{x}),\ \ \rho(t,\boldsymbol{x}) = \overline{\rho}(t)[1+\delta(t,\boldsymbol{x})].$$

- **Quasi-static approximation (QSA)** ← 仮定

$$|\dot{\epsilon}| \approx |H\epsilon|,\ \ \epsilon = \Psi, \Phi, \boldsymbol{\pi}$$

$$|\dot{\Psi}|^2, |\dot{\Phi}|^2, |\dot{\pi}|^2 \ll k^2\Psi^2, k^2\Phi^2, k^2\boldsymbol{\pi}^2$$

Evolution of density fluctuations

- Perturbative expansion: $\epsilon = \epsilon_1$, $\epsilon = \Phi, \Psi, \pi, \delta$

- **EoMs**: $\delta\Phi, \delta\Psi, \delta\pi \quad \Rightarrow \quad \Phi_1$

  ↑ **include the effect of modified gravity**
  (modified Poisson eq., anisotropic stress)

- Fluid equations:
  continuity/ Eular
  (standard forms)

$$\frac{\partial \delta(t,\boldsymbol{x})}{\partial t} + \frac{1}{a}\partial_i[(1+\delta)u^i(t,\boldsymbol{x})] = 0,$$

$$\frac{\partial u^i}{\partial t} + Hu^i + \frac{1}{a}u^j\partial_j u^i = -\frac{1}{a}\partial^i\Phi(t,\boldsymbol{x})$$

u^i : velocity field

$\Rightarrow$ **evolution equation of density flues.**

1st-order solution

Kobayashi+ (2015), D'Amico+ (2017), Crisostomi-Koyama (2017), Hirano+ (2019)

$$\ddot{\delta}_1 + (2+\varsigma)H\dot{\delta}_1 - 4\pi G_{\rm eff}\rho_{\rm m}\delta_1 = 0$$

- $G_{\rm eff}(t)$: G (GR) , $G_{\rm eff} \neq G$ (Horndeski, DHOST)
  $\varsigma(t)$: 0 (GR, Horndeski), $\varsigma \neq 0$ (DHOST)

- growing mode: $\delta_1(\mathbf{p},t) = D_+(t)\delta_L(\mathbf{p})$
  $D_+(t)$: growth factor, $\delta_L(\mathbf{p})$: initial density fluc.

Linear growth of density flucs.

- Linear growth rate $f := \frac{\dot{D}_+}{D_+ H}$ (物質優勢期で$f = 1$)

- Growth index $\gamma := \left.\frac{\mathrm{d}\ln f}{\mathrm{d}\ln \Omega_\mathrm{m}}\right|_{\Omega_\mathrm{m}=1}$ $\left(\Omega_m := \frac{\rho_\mathrm{m}}{3M_\mathrm{pl}^2 H^2}\text{, 物質優勢期で1}\right)$

$$\gamma_\mathrm{GR} = 6/11 = 0.545$$

- Observational data

BOSS DR12	Sanchez+ (2016)	$\gamma = 0.609 \pm 0.079$
BOSS DR14	Zhao+ (2018)	$\gamma = 0.580 \pm 0.082$

やったこと

Hirano+ (2019)

- Typical DHOST models

✔ GW170817, GRB 170817 $c_{\rm GW}^2 = 1$

✔ $G_2(\phi, X) = X^p,\ p = \text{const.}$

✔ tracker ansatz: $H\dot{\phi}^q = \text{const.}$ e.g.) De Felice-Tsujikawa (2010, 2011)

✔ models with $\alpha_H := -\dfrac{2Xf_X}{f} = c_H(1-\Omega_{\rm m}),\ \beta_1 := \dfrac{X}{f}(f_X + XA_3) = \beta(1-\Omega_{\rm m})$

↑ DHOST固有の

やったこと

Hirano+ (2019)

- Typical DHOST models

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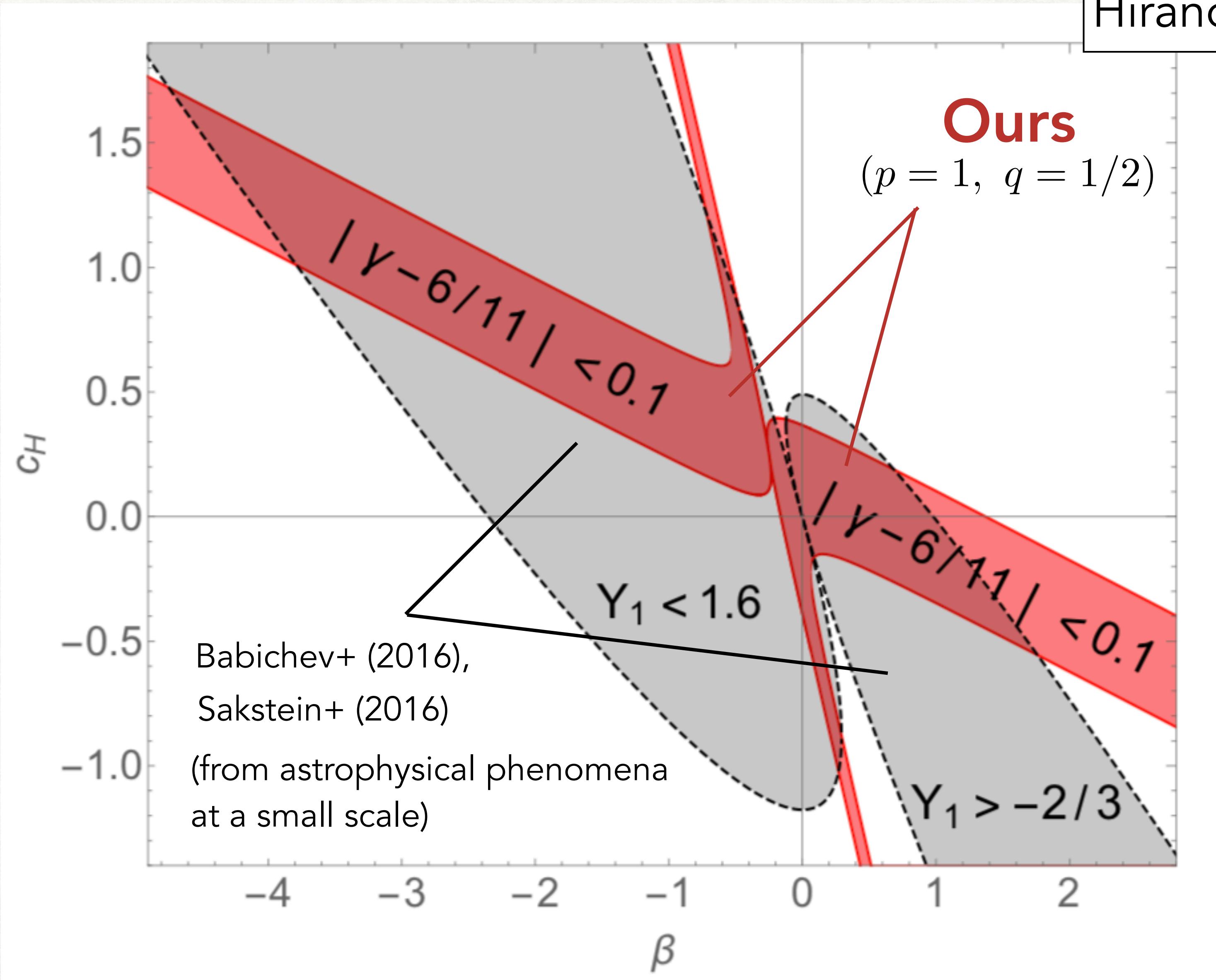
↑ DHOST固有の

$\gamma = \gamma(p, q, c_H, \beta)$を計算し、given p, qの下、c_H-β 平面に

$|\gamma - 6/11| < 0.1$ の領域をプロット.

Comparison to that of previous works

Hirano+ (2019)



Comparison to that of previous works

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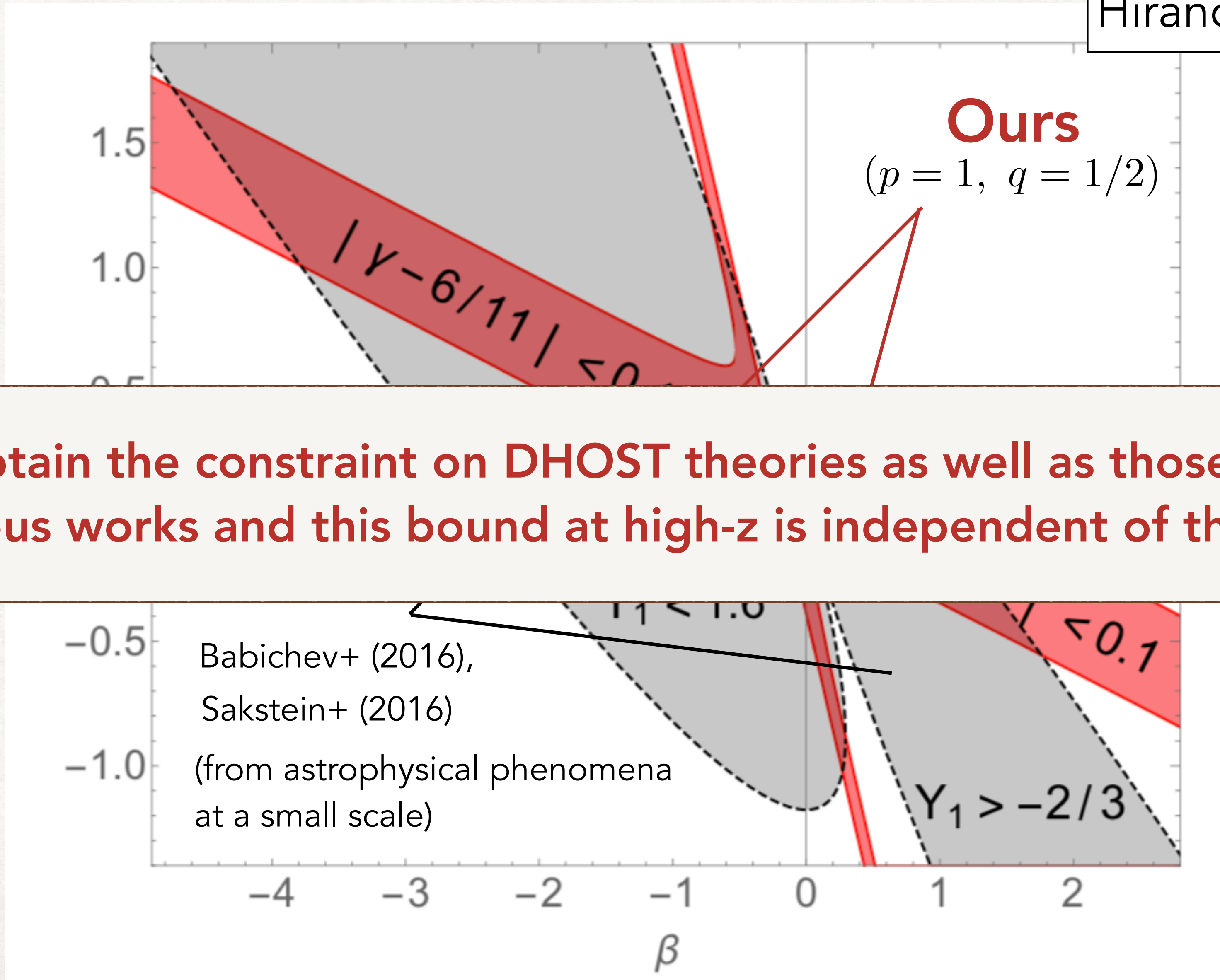

We obtain the constraint on DHOST theories as well as those of previous works and this bound at high-z is independent of those!

仕事2: 非線形密度揺らぎへの影響

SH, T. Kobayashi, H. Tashiro, S. Yokoyama,
Phys. Rev. D 97 (2018) no.10, 103517

Evolution of density fluctuations

- Perturbative expansion: $\epsilon = \epsilon_1 + \epsilon_2$, $\epsilon = \Phi, \Psi, \pi, \delta$

- **EoMs**: $\delta\Phi, \delta\Psi, \delta\pi \quad \Rightarrow \quad \Phi_1, \Phi_2$

  ↑ **include the effect of modified gravity**
  (modified Poisson eq., anisotropic stress)

- Fluid equations:
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  u^i : velocity field

$$\frac{\partial \delta(t,\boldsymbol{x})}{\partial t} + \frac{1}{a}\partial_i[(1+\delta)u^i(t,\boldsymbol{x})] = 0,$$

$$\frac{\partial u^i}{\partial t} + Hu^i + \frac{1}{a}u^j\partial_j u^i = -\frac{1}{a}\partial^i \Phi(t,\boldsymbol{x})$$

$\Rightarrow$ **evolution equation of density flues.**

2nd-order solution

Hirano+ (2018), Crisostomi+ (2019)

$$\ddot{\delta}_2 + (2+\varsigma)H\dot{\delta}_2 - 4\pi G_{\rm eff}\rho_{\rm m}\delta_2 = S_\delta \quad \leftarrow \delta_1^2$$

Primordial fluc. : Gaussian ⇒ inhomogeneous sol.

$$\Rightarrow \quad \delta_2(\boldsymbol{p},t) = D_+^2(t)\left[\kappa(t)\mathcal{W}_\alpha(\boldsymbol{p}) - \frac{2}{7}\lambda(t)\mathcal{W}_\gamma(\boldsymbol{p})\right]$$

$$\mathcal{W}_i(\boldsymbol{p}) = \frac{1}{(2\pi)^3}\int d^3k_1 d^3k_2\,\delta^{(3)}(\boldsymbol{k}_1+\boldsymbol{k}_2-\boldsymbol{p})\,i(\boldsymbol{k}_1,\boldsymbol{k}_2)\delta_L(\boldsymbol{k}_1)\delta_L(\boldsymbol{k}_2)$$

$i=\alpha,\gamma$, $\alpha(\mathbf{k}_1,\mathbf{k}_2) = 1 + \frac{(\boldsymbol{k}_1\cdot\boldsymbol{k}_2)(k_1^2+k_2^2)}{2k_1^2k_2^2}$, $\gamma(\mathbf{k}_1,\mathbf{k}_2) = 1 - \frac{(\boldsymbol{k}_1\cdot\boldsymbol{k}_2)^2}{k_1^2k_2^2}$

$\lambda(t)$: 1 (GR) , $\lambda \neq 1$ (Horndeski, DHOST)

New! $\kappa(t)$: 1 (GR, Horndeski), $\kappa \neq 1$ (DHOST)

Matter bispectrum

cf) Scoccimarro+ (1998)
Barnardeau+ (2000)

- **3pt correlation function: bispectrum**

$$\langle \delta(t,\boldsymbol{k}_1)\delta(t,\boldsymbol{k}_2)\delta(t,\boldsymbol{k}_3)\rangle := (2\pi)^3\delta(\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{k}_3)B(t,\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3)$$

$\langle \delta_2\delta_1\delta_1\rangle$: **leading order (tree-level)**

Matter bispectrum

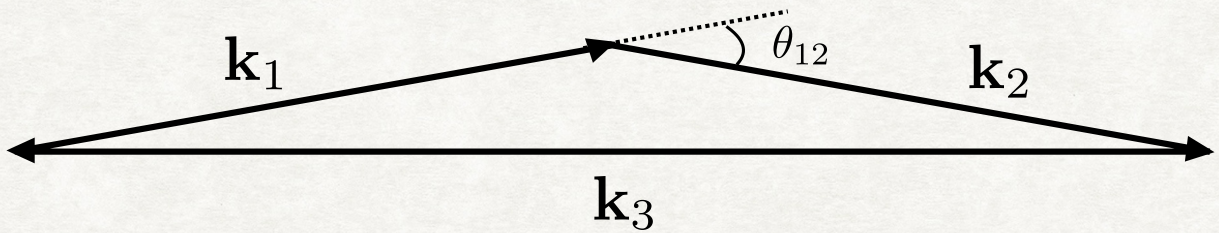
cf) Scoccimarro+ (1998)
Barnardeau+ (2000)

- **Reduced bispectrum**

$$Q_{123}(t,k_1,k_2,k_3) = \frac{B(t,k_1,k_2,k_3)}{D_+^4(t)[P_{11}(k_1)P_{11}(k_2) + 2\text{ cyclic terms}]}$$

only depends on the time evolution of κ and λ

✓ $\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3 = \mathbf{0} \Rightarrow$ $\boldsymbol{k}_1 = (0,0,k_1)$, $\boldsymbol{k}_2 = (0, k_2 \sin\theta_{12}, k_2\cos\theta_{12})$,
$\boldsymbol{k}_3 = (0, -k_2\sin\theta_{12}, -k_1 - k_2\cos\theta_{12})$



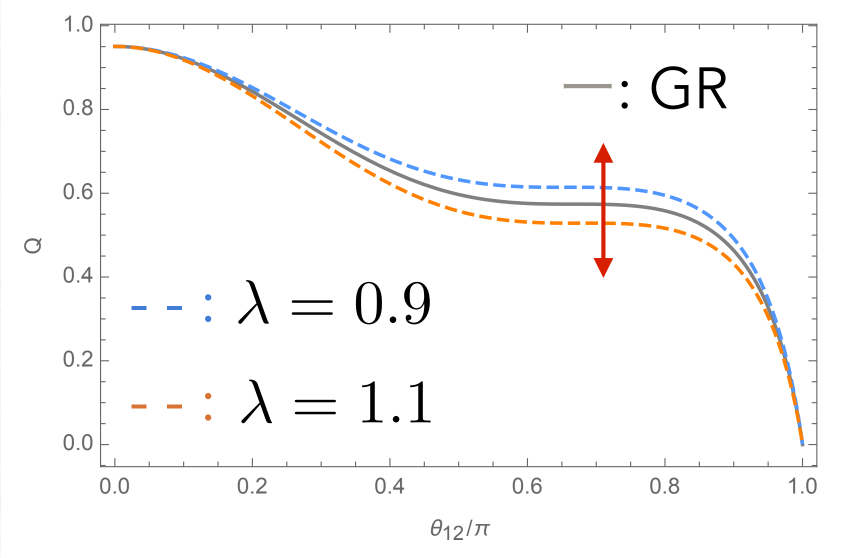
✓ We estimate matter bispectrum on the given κ, λ (z=0)
at $k_1 = k_2 = 0.01h/\mathrm{Mpc}$ and $k_1 = 5k_2 = 0.05h/\mathrm{Mpc}$.
(cosmological parameters: Planck 2015)

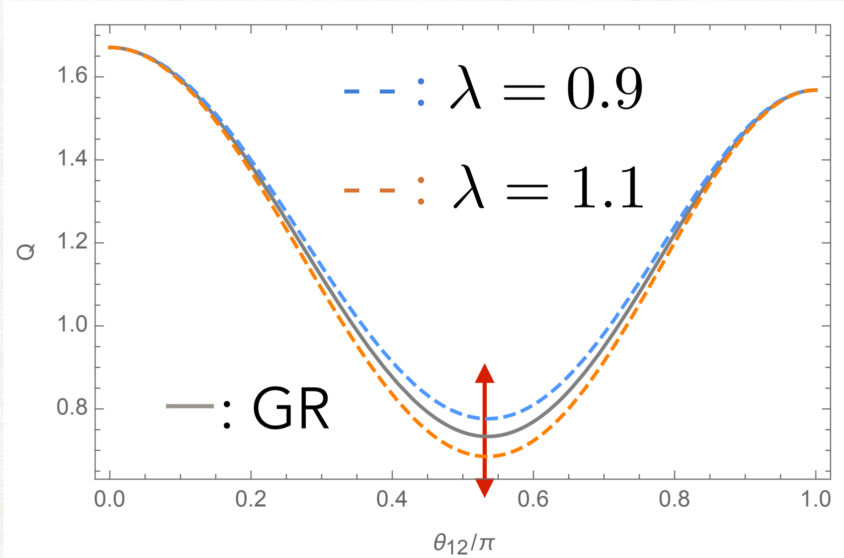
k-dependence

Hirano+ (2018)

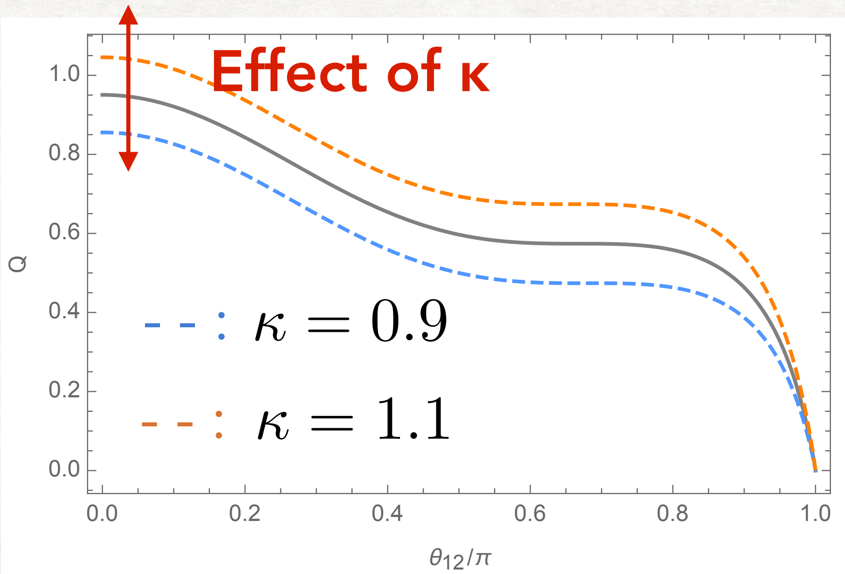
$k_1 = k_2 = 0.01h/Mpc$ | $k_1 = 5k_2 = 0.05h/Mpc$

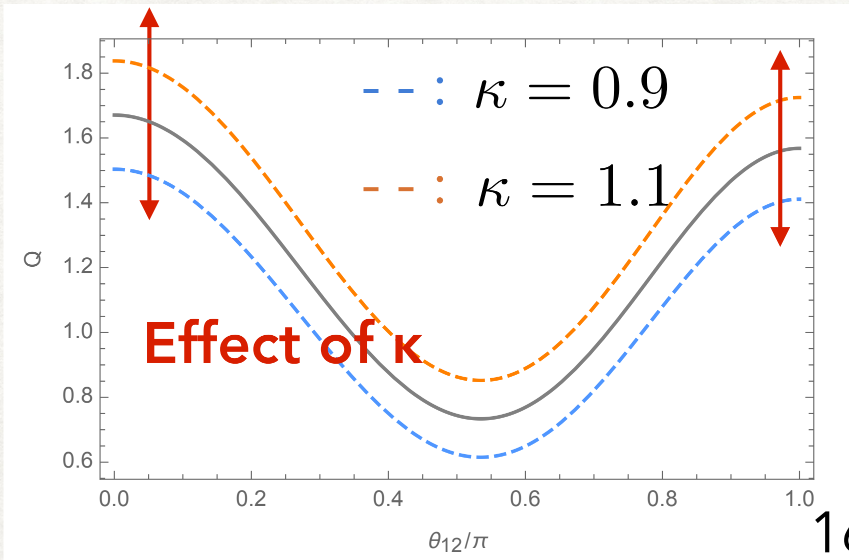
$\kappa = 1$
(Horndeski)





$\lambda = 1$
(DHOST)





k-dependence

Hirano+ (2018)

$k_1 = k_2 = 0.01h/Mpc$ $k_1 = 5k_2 = 0.05h/Mpc$

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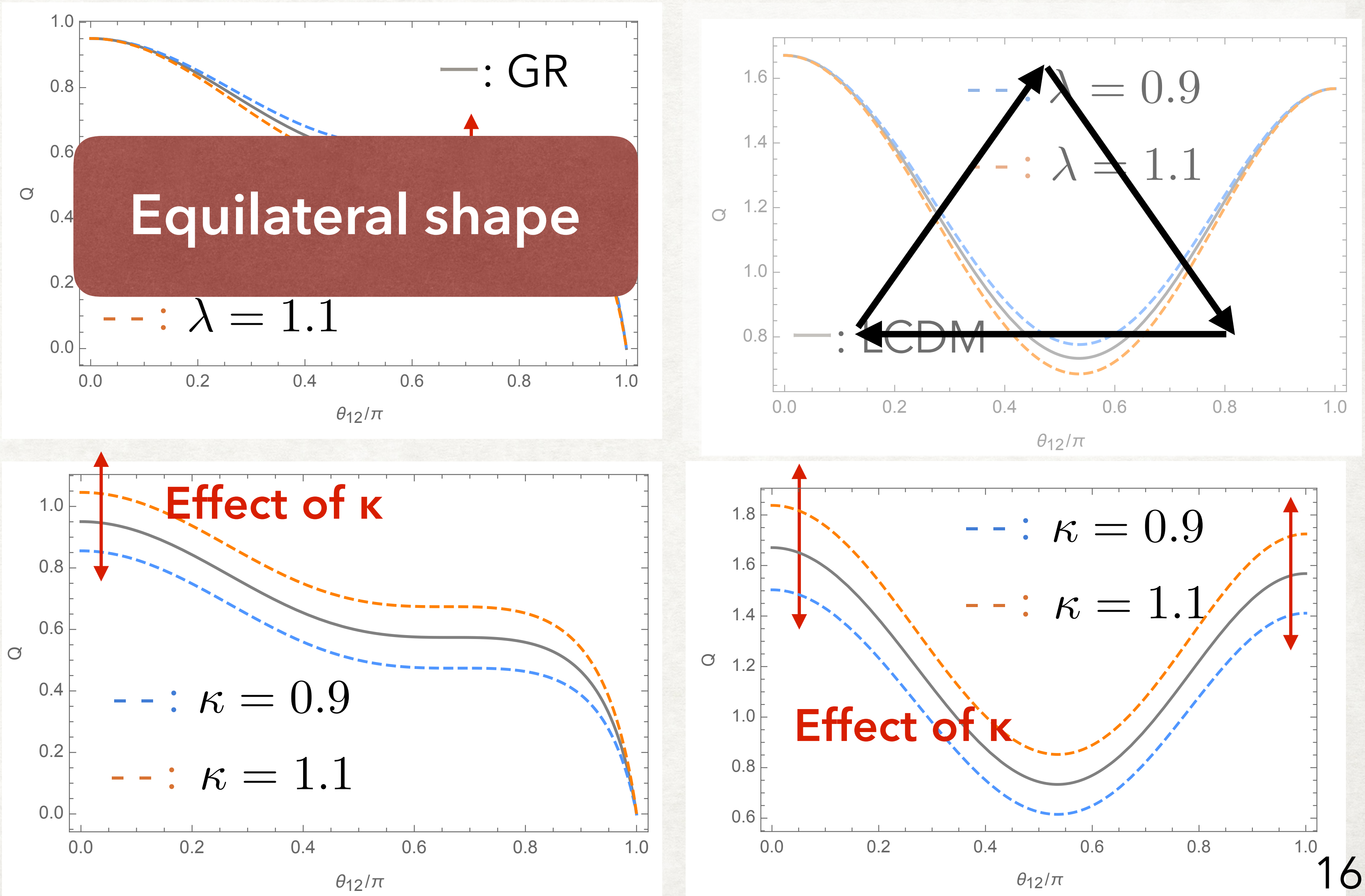
$\lambda = 1$
(DHOST)



k-dependence

Hirano+ (2018)

$k_1 = k_2 = 0.01h/Mpc$ $\qquad$ $k_1 = 5k_2 = 0.05h/Mpc$

$\kappa = 1$
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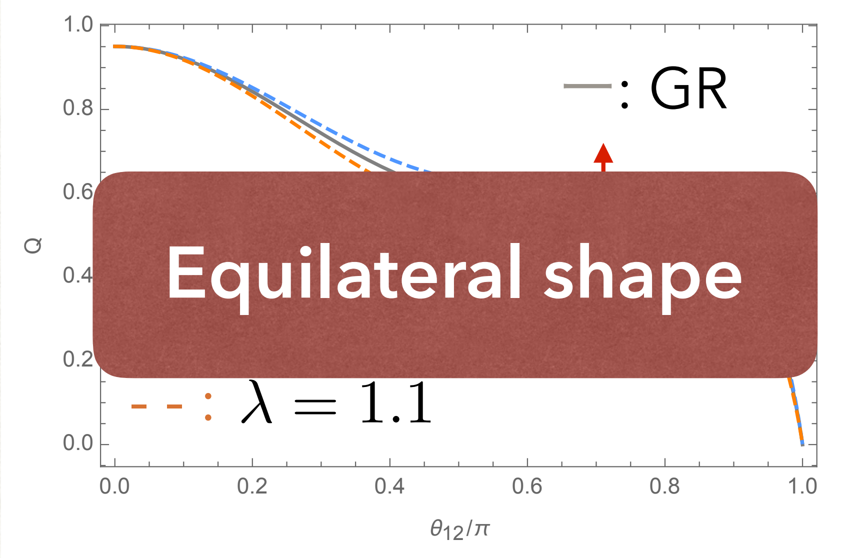

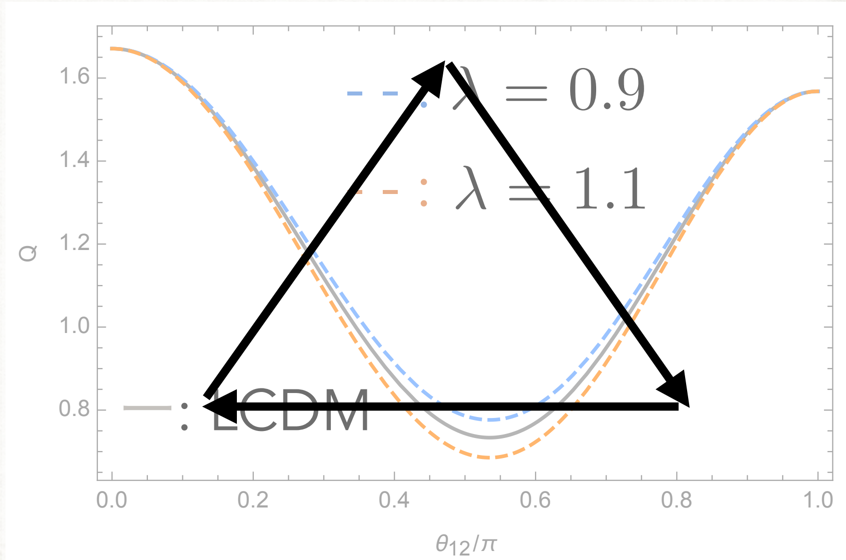

$\lambda = 1$
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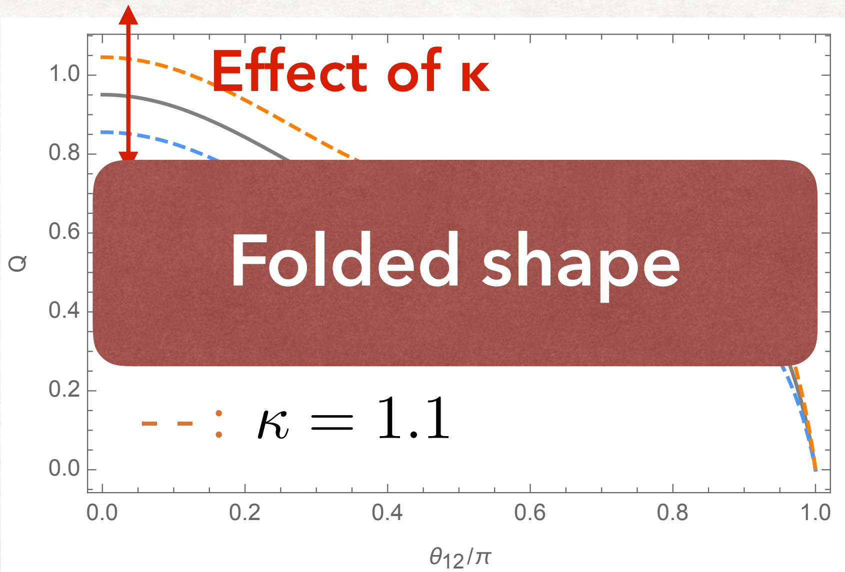

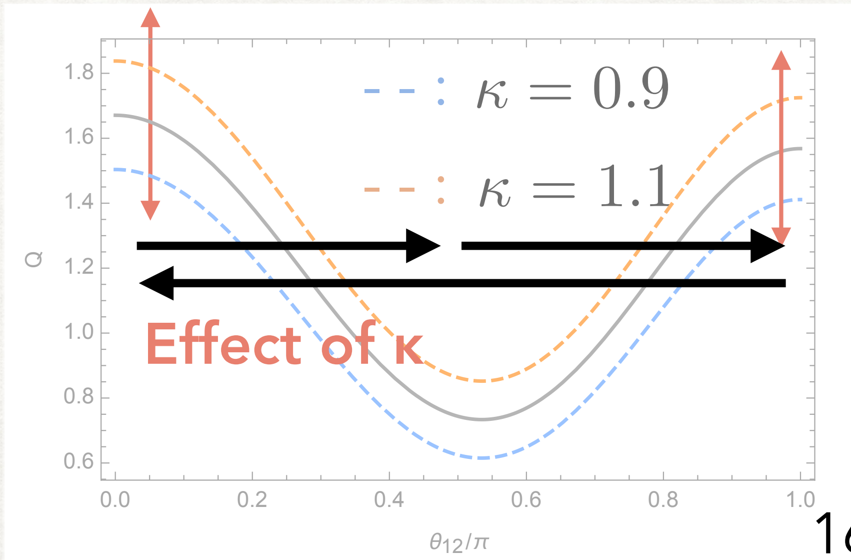

Summary

- **修正重力理論**　大スケール→後期加速膨張
  小スケール→修正の影響を遮蔽するスクリーニング
- **DHOST理論**　現在最も広いスカラーテンソル理論
  重力波の制限も突破
- **仕事1: 線形密度揺らぎを用いたDHOSTの制限**
  →growth index γを用いることで典型的なモデルに制限
- **仕事2: バイスペクトルにおけるDHOSTの影響**
  →波数空間でfolded typeのピークを持つ