Title: Conference Talk

Speakers:

Collection: 50 Years of Horndeski Gravity: Exploring Modified Gravity

Date: July 18, 2024 - 11:00 AM

URL: https://pirsa.org/24070048

Extending EFT of inflation/dark energy to arbitrary background with timelike scalar profile

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COSMO'24

Oct 21 - 25, 2024 | Kyoto University

Venue:
The clock tower in the main campus of Kyoto University, Kyoto, Japan.

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Collaborators


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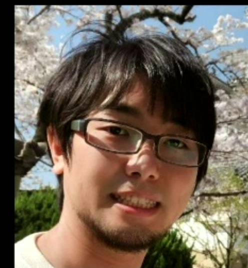
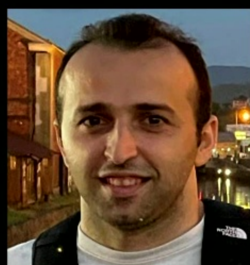

K.Aoki


E.Seraille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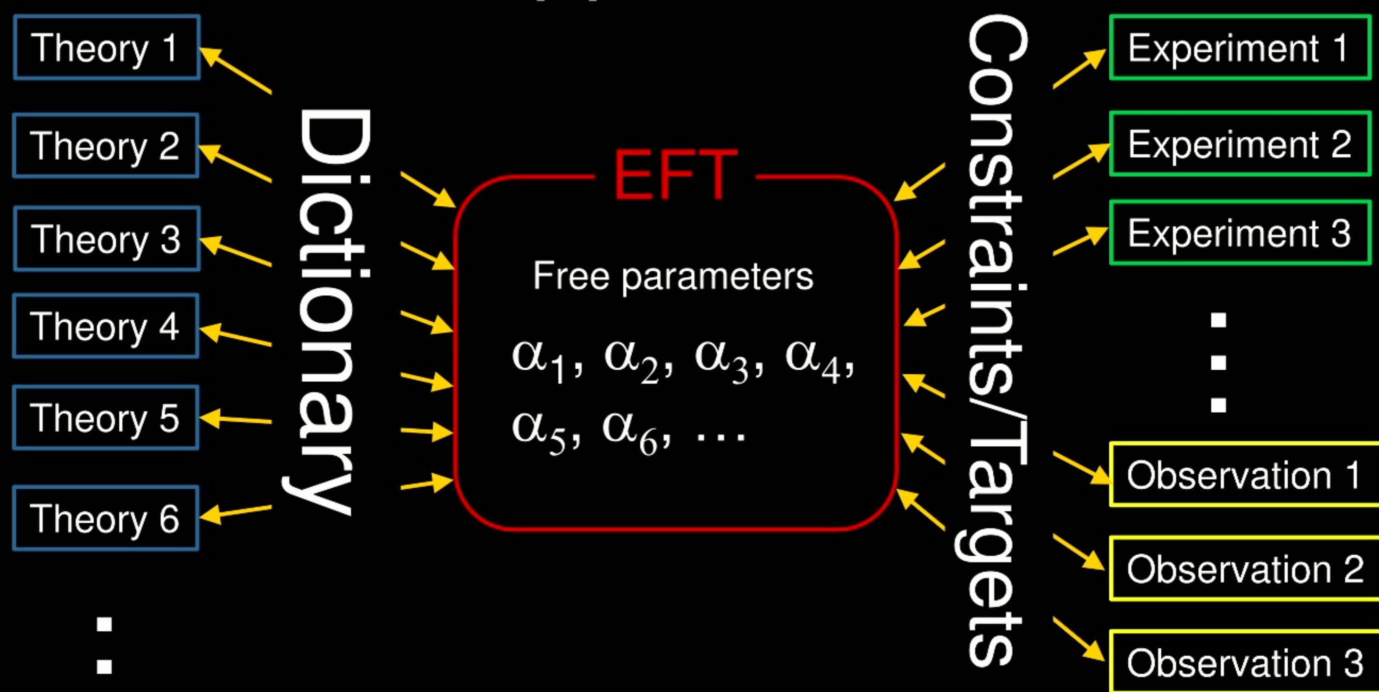
Ref.
arXiv: 2204.00228 w/ V.Yingcharoenrat
arXiv: 2208.02943 w/ K.Takahashi, V.Yingcharoenrat
arXiv: 2304.14304 w/ K.Takahashi, K.Tomikawa, V.Yingcharoenrat
arXiv: 2405.10813 w/ C.G.A.Barura, H.Kobayashi, N.Oshita, K.Takahashi, V.Yingcharoenrat
arXiv: 2406.04525 w/ N.Oshita and K.Takahashi
arXiv: 2407.xxxxx w/ E.Seraille, K.Takahashi , V.Yingcharoenrat
arXiv: 2111.08119 w/ K.Aoki, M.A.Gorji, K.Takahashi
arXiv: 2311.06767 w/ K.Aoki, M.A.Gorji, K.Takahashi, V.Yingcharoenrat

Also
Arkani-Hamed, Cheng, Luty and Mukohyama 2004 (hep-th/0312099)
Mukohyama 2005 (hep-th/0502189)

Scalar-tensor gravity

- Contains majority of inflation & dark energy models
- Contains GR + a scalar field as a special case
- Metric $g_{\mu\nu}$ + scalar field ϕ
- Jordan (1955), Brans & Dicke (1961), Bergmann (1968), Wagoner (1970), …
- Most general scalar-tensor theory of gravity with 2nd order covariant EOM: Horndeski (1974)
- DHOST theories beyond Horndeski: Langlois & Noui (2016)
- U-DHOST theories beyond DHOST: DeFelice, Langlois, Mukohyama, Noui & Wang (2018)
- All of them (and more) are universally described by an effective field theory (EFT)

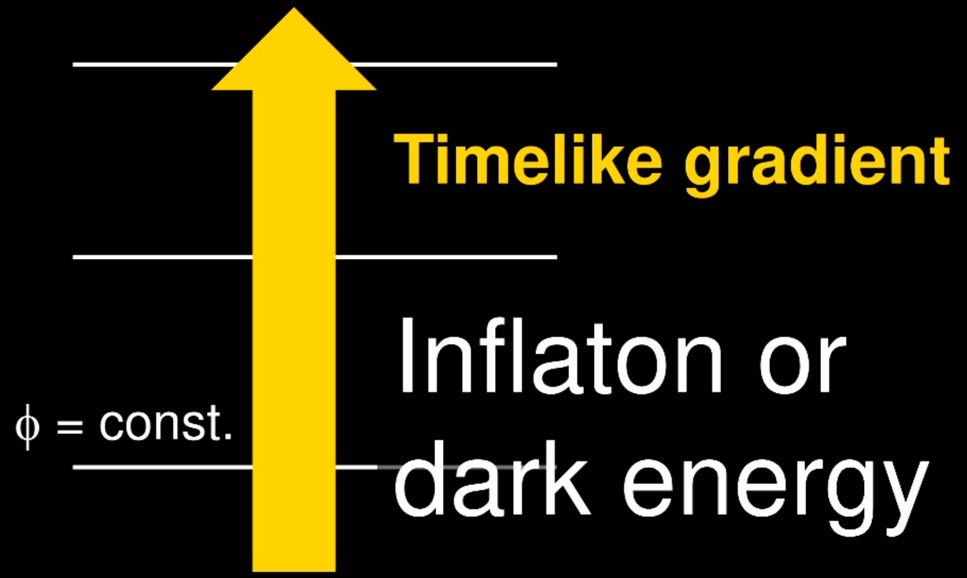
Effective field theory (EFT) approach



EFT plays the role of bridge between theories and experiments/observations!

EFT of scalar-tensor gravity with timelike scalar profile

- Inflaton/dark energy has timelike derivative
- Time diffeo is broken by the scalar profile but spatial diffeo is preserved.



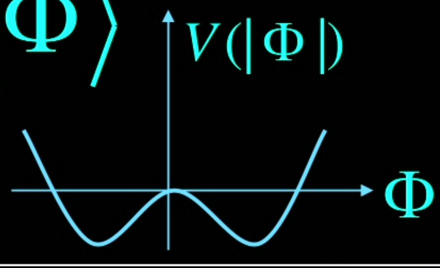
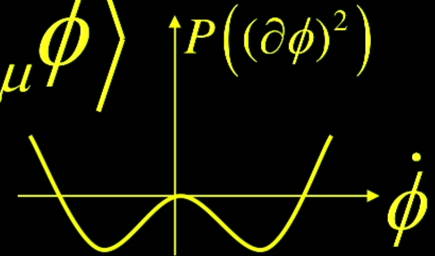
EFT of scalar-tensor gravity with timelike scalar profile

- **Time diffeo is broken by the scalar profile but spatial diffeo is preserved.**
- All terms that respect spatial diffeo must be included in the EFT action.
- Derivative & perturbative expansions
- Diffeo can be restored by introducing NG boson

EFT on Minkowski background

= ghost condensation

Arkani-Hamed, Cheng, Luty and Mukohyama, JHEP 0405:074,2004

	Higgs mechanism	Ghost condensate Arkani-Hamed, Cheng, Luty and Mukohyama 2004
Order parameter	$\langle \Phi \rangle$ 	$\langle \partial_\mu \phi \rangle$ 
Instability	Tachyon $-\mu^2\Phi^2$	Ghost $-\dot{\phi}^2$
Condensate	V'=0, V''>0	P'=0, P''>0
Broken symmetry	Gauge symmetry	Time diffeomorphism
Force to be modified	Gauge force	Gravity
New force law	Yukawa type	Newton+Oscillation

EFT of ghost condensation =

EFT of scalar-tensor gravity with timelike scalar profile on Minkowski background

Arkani-Hamed, Cheng, Luty and Mukohyama 2004

Backgrounds characterized by

- ✧ $\langle \partial_\mu \phi \rangle = const \neq 0$ and timelike
- ✧ Minkowski metric

t → t + const & t → -t   unbroken

up to ϕ → ϕ + const & ϕ → -ϕ

$$L_{eff} = L_{EH} + M^4 \left\{ \left(h_{00} - 2\dot{\pi} \right)^2 - \frac{\alpha_1}{M^2}\left(K + \vec{\nabla}^2 \pi \right)^2 - \frac{\alpha_2}{M^2}\left(K^{ij} + \vec{\nabla}^i \vec{\nabla}^j \pi \right)\left(K_{ij} + \vec{\nabla}_i \vec{\nabla}_j \pi \right) + \cdots \right\}$$

Gauge choice: $\phi(t,\vec{x}) = t.$ $\pi \equiv \delta\phi = 0$

(Unitary gauge)

Residual symmetry: $\vec{x} \to \vec{x}'(t,\vec{x})$

➡ Write down most general action invariant under this residual symmetry.

(➡ Action for π: undo unitary gauge!)

Start with flat background $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$

$$\delta h_{\mu\nu} = \partial_\mu \xi_\nu + \partial_\nu \xi_\mu$$

Under residual ξ^i

$$\delta h_{00} = 0, \delta h_{0i} = \partial_0 \xi_i, \delta h_{ij} = \partial_i \xi_j + \partial_j \xi_i$$

Action invariant under ξ^i

$$\begin{cases} (h_{00})^2 & \text{OK} \\ \cancel{(h_{0i})^2} & \\ K^2, K^{ij}K_{ij} & \text{OK} \end{cases}$$

Beginning at quadratic order, since we are assuming flat space is good background.

$$K_{ij} = \frac{1}{2}\left(\partial_0 h_{ij} - \partial_j h_{0i} - \partial_i h_{0j}\right)$$

$$\Rightarrow \quad L_{eff} = L_{EH} + M^4 \left\{ (h_{00})^2 - \frac{\alpha_1}{M^2} K^2 - \frac{\alpha_2}{M^2} K^{ij} K_{ij} + \cdots \right\}$$

Action for π

$$\xi^0 = \pi \quad \begin{cases} h_{00} \to h_{00} - 2\partial_0 \pi \\ K_{ij} \to K_{ij} + \partial_i \partial_j \pi \end{cases}$$

$$\Rightarrow \quad L_{eff} = L_{EH} + M^4 \left\{ (h_{00} - 2\dot{\pi})^2 - \frac{\alpha_1}{M^2}\left(K + \vec{\nabla}^2 \pi\right)^2 - \frac{\alpha_2}{M^2}\left(K^{ij} + \vec{\nabla}^i \vec{\nabla}^j \pi\right)\left(K_{ij} + \vec{\nabla}_i \vec{\nabla}_j \pi\right) + \cdots \right\}$$

$$
\left.\begin{aligned}
E &\to rE \\
dt &\to r^{-1} dt \\
dx &\to r^{-1/2} dx \\
\pi &\to r^{1/4} \pi
\end{aligned}\right\}
$$

Make invariant ➡ $\int dt d^3x \left[\frac{1}{2}\dot{\pi}^2 - \frac{\alpha(\vec{\nabla}^2 \pi)^2}{M^2} + \cdots \right]$

Leading nonlinear operator in infrared $\int dt d^3x \frac{\dot{\pi}(\nabla \pi)^2}{\tilde{M}^2}$

has scaling dimension 1/4. **(Barely) irrelevant**

⇨ Good low-E effective theory
Robust prediction

e.g. Ghost inflation [Arkani-hamed, Creminelli, Mukohyama, Zaldarriaga 2004]

Extension to FLRW background = EFT of inflation/dark energy

Creminelli, Luty, Nicolis, Senatore 2006
Cheung, Creminelli, Fitzpatrick, Kaplan, Senatore 2007

- Action invariant under $x^i \rightarrow x^i(t,x)$
- Ingredients
  $g_{\mu\nu}, g^{\mu\nu}, R_{\mu\nu\rho\sigma}, \nabla_\mu,$ t & its derivatives
- 1st derivative of t

$$\partial_\mu t = \delta^0_\mu \qquad n_\mu = \frac{\partial_\mu t}{\sqrt{-g^{\mu\nu}\partial_\mu t \partial_\nu t}} = \frac{\delta^0_\mu}{\sqrt{-g^{00}}}$$

$$g^{00} \qquad h_{\mu\nu} = g_{\mu\nu} + n_\mu n_\nu$$

- 2nd derivative of t

$$K_{\mu\nu} \equiv h^\rho_\mu \nabla_\rho n_\nu$$

Unitary gauge action

$$I = \int d^4x\sqrt{-g}L(t, \delta^0_\mu, K_{\mu\nu}, g_{\mu\nu}, g^{\mu\nu}, \nabla_\mu, R_{\mu\nu\rho\sigma})$$

derivative & perturbative expansions

$$\begin{aligned} I &= M_{Pl}^2 \int dx^4\sqrt{-g}\left[\frac{1}{2}R + c_1(t) + c_2(t)g^{00} \right. \\ &\quad \left. + L^{(2)}(\tilde{\delta}g^{00}, \tilde{\delta}K_{\mu\nu}, \tilde{\delta}R_{\mu\nu\rho\sigma}; t, g_{\mu\nu}, g^{\mu\nu}, \nabla_\mu)\right] \\ L^{(2)} &= \lambda_1(t)(\tilde{\delta}g^{00})^2 + \lambda_2(t)(\tilde{\delta}g^{00})^3 + \lambda_3(t)\tilde{\delta}g^{00}\tilde{\delta}K^\mu_\mu \\ &\quad + \lambda_4(t)(\tilde{\delta}K^\mu_\mu)^2 + \lambda_5(t)\tilde{\delta}K^\mu_\nu\tilde{\delta}K^\nu_\mu + \cdots \end{aligned}$$

$$\tilde{\delta}g^{00} \equiv g^{00} + 1 \qquad \tilde{\delta}K_{\mu\nu} \equiv K_{\mu\nu} - H\gamma_{\mu\nu}$$

$$\tilde{\delta}\mathsf{R}_{\mu\nu\rho\sigma} \equiv \mathsf{R}_{\mu\nu\rho\sigma} - 2(H^2 + \mathfrak{K}/a^2)\gamma_{\mu[\rho}\gamma_{\sigma]\nu} + (\dot{H} + H^2)(\gamma_{\mu\rho}\delta^0_\nu\delta^0_\sigma + (3\text{perm.}))$$

Application: non-Gaussinity of inflationary perturbation $\zeta = -H\pi$

$$I_\pi = M_{Pl}^2 \int dt d^3\vec{x}\, a^3 \left\{ -\frac{\dot{H}}{c_s^2}\left(\dot{\pi}^2 - c_s^2 \frac{(\partial_i \pi)^2}{a^2}\right) - \dot{H}\left(\frac{1}{c_s^2} - 1\right)\left(\frac{c_3}{c_s^2}\dot{\pi}^3 - \dot{\pi}\frac{(\partial_i\pi)^2}{a^2}\right) + O(\pi^4, \tilde{\epsilon}^2) + L^{(2)}_{\delta K, \delta R} \right\}$$

➡ power spectrum

$$P_\zeta(\vec{k}) = \frac{\Delta}{k^3}, \quad \Delta = \left.\frac{H^4}{-4M_{Pl}^2 \dot{H} c_s}\right|_{c_s k \simeq aH}$$

➡ non-Gaussianity

$$\langle \zeta_{\vec{k}_1}(t)\, \zeta_{\vec{k}_2}(t)\, \zeta_{\vec{k}_3}(t) \rangle = (2\pi)^3 \delta^3(\vec{k}_1 + \vec{k}_2 + \vec{k}_3) B_\zeta$$

2 types of 3-point interactions

c_s^2 → size of non-Gaussianity

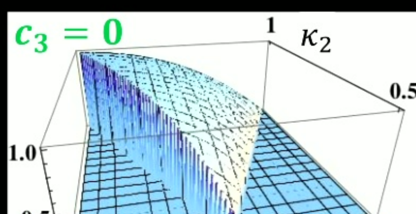
$$k^6 B_\zeta|_{k_1=k_2=k_3=k} = \frac{18}{5}\Delta^2\left(f_{NL}^{\dot{\pi}(\partial_i\pi)^2} + f_{NL}^{\dot{\pi}^3}\right)$$

$$f_{NL}^{\dot{\pi}(\partial_i\pi)^2} = \frac{85}{324}\left(1 - \frac{1}{c_s^2}\right) \qquad f_{NL}^{\dot{\pi}^3} = \frac{5c_3}{81}\left(1 - \frac{1}{c_s^2}\right)$$

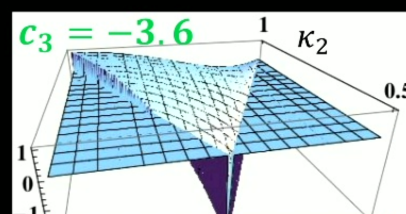
$\propto \frac{1}{c_s^2}$ for small c_s^2

c_3 → shape of non-Gaussianity

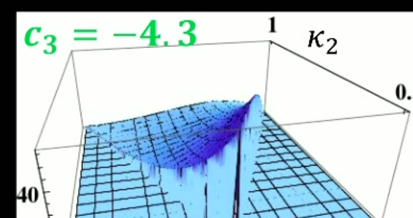
plots of $B_\zeta(k, \kappa_2 k, \kappa_3 k)/B_\zeta(k,k,k)$



Prototype of the equilateral shape



Prototype of the orthogonal shape



Linear combination of the two shapes

Parametrization suitable for DE → EFT of DE

Gubitosi, Piazza, Vernizzi 2012
Gleyzes, Langlois, Piazza, Vernizzi 2013

- Matter (in addition to DE) needs to be added → Jordan frame description is convenient
- In Jordan frame the coefficient of the 4d Ricci scalar is not constant.

$$S = \frac{1}{2}\int d^4x\sqrt{-g}\,\Big[\boxed{M_*^2 f R} - \rho_D + p_D - M_*^2(5H\dot{f} + \ddot{f}) - \Big(\rho_D + p_D + M_*^2(H\dot{f} - \ddot{f})\Big)\, g^{00}$$
$$+ M_2^4(\delta g^{00})^2 - \bar{m}_1^3\,\delta g^{00}\delta K - \bar{M}_2^2\,\delta K^2 - \bar{M}_3^2\,\delta K_\mu{}^\nu \delta K^\mu{}_\nu + m_2^2 h^{\mu\nu}\partial_\mu g^{00}\partial_\nu g^{00}$$
$$+ \lambda_1 \delta R^2 + \lambda_2 \delta R_{\mu\nu}\delta R^{\mu\nu} + \mu_1^2 \delta g^{00}\delta R + \gamma_1 C^{\mu\nu\rho\sigma}C_{\mu\nu\rho\sigma} + \gamma_2 \epsilon^{\mu\nu\rho\sigma}C_{\mu\nu}{}^{\kappa\lambda}C_{\rho\sigma\kappa\lambda}$$
$$+ \frac{M_3^4}{3}(\delta g^{00})^3 - \bar{m}_2^3\,(\delta g^{00})^2\delta K + \dots\Big]\,,$$

EFT of scalar-tensor gravity with timelike scalar profile

- **Time diffeo is broken by the scalar profile but spatial diffeo is preserved.**
- All terms that respect spatial diffeo must be included in the EFT action.
- Derivative & perturbative expansions
- Diffeo can be restored by introducing NG boson

EFT on Minkowski background = ghost condensation

Arkani-Hamed, Cheng, Luty and Mukohyama, JHEP 0405:074,2004

EFT on cosmological background = EFT of inflation/dark energy

Creminelli, Luty, Nicolis and Senatore 2006; Cheung, Creminelli, Fitzpatrick, Kaplan and Senatore 2007; Gubitosi, Piazza, Vernizzi 2012; Gleyzes, Langlois, Piazza, Vernizzi 2013

EFT on arbitrary background = Main subject of this talk

Mukohyama and Yingcharoenrat, JCAP 09 (2022) 010

It is not straightforward…

- General action in the unitary gauge ($\phi = \tau$)

$$S = \int d^4x \sqrt{-g}\ F(R_{\mu\nu\alpha\beta}, g^{\tau\tau}, K_{\mu\nu}, \nabla_\nu, \tau)$$

- Taylor expansion around the background

$$S = \int d^4x \sqrt{-g} \left[\bar{F} + \bar{F}_{g^{\tau\tau}} \delta g^{\tau\tau} + \bar{F}_K \delta K + \ \cdots \right]$$

- The whole action is invariant under 3d diffeo but **each term is not…**
- Each coefficient is a function of (τ, x^i) but cannot be promoted to an arbitrary function.

Solution: consistency relations

- The chain rule

$$\begin{cases} \dfrac{d}{dx^i}\bar{F} = \bar{F}_{g^{\tau\tau}}\dfrac{\partial \bar{g}^{\tau\tau}}{\partial x^i} + \bar{F}_K\dfrac{\partial \bar{K}}{\partial x^i} + \dots \\ \dfrac{d}{dx^i}\bar{F}_{g^{\tau\tau}} = \bar{F}_{g^{\tau\tau}g^{\tau\tau}}\dfrac{\partial \bar{g}^{\tau\tau}}{\partial x^i} + \bar{F}_{g^{\tau\tau}K}\dfrac{\partial \bar{K}}{\partial x^i} + \dots \\ \dfrac{d}{dx^i}\bar{F}_K = \bar{F}_{g^{\tau\tau}K}\dfrac{\partial \bar{g}^{\tau\tau}}{\partial x^i} + \bar{F}_{KK}\dfrac{\partial \bar{K}}{\partial x^i} + \dots \end{cases}$$

  relates x^i-derivatives of an EFT coefficient to other EFT coefficients, and leads to consistency relations.
- **The consistency relations ensure the spatial diffeo invariance.**
- Taylor coefficients should satisfy the consistency relations but are otherwise arbitrary.
- (No consistency relation for τ-derivatives.)

EFT action

$$S = \int d^4x\sqrt{-g}\Big[\frac{M_\star^2}{2}f(y)R - \Lambda(y) - c(y)g^{\tau\tau} - \beta(y)K - \alpha^\mu_\nu(y)\sigma^\nu_\mu - \gamma^\mu_\nu(y)r^\nu_\mu + \frac{1}{2}m_2^4(y)(\delta g^{\tau\tau})^2$$
$$+ \frac{1}{2}M_1^3(y)\delta g^{\tau\tau}\delta K + \frac{1}{2}M_2^2(y)\delta K^2 + \frac{1}{2}M_3^2(y)\delta K^\mu_\nu\delta K^\nu_\mu + \frac{1}{2}M_4(y)\delta K\delta^{(3)}R$$
$$+ \frac{1}{2}M_5(y)\delta K^\mu_\nu\delta^{(3)}R^\nu_\mu + \frac{1}{2}\mu_1^2(y)\delta g^{\tau\tau}\delta^{(3)}R + \frac{1}{2}\mu_2(y)\delta^{(3)}R^2 + \frac{1}{2}\mu_3(y)\delta^{(3)}R^\mu_\nu\delta^{(3)}R^\nu_\mu$$
$$+ \frac{1}{2}\lambda_1(y)^\nu_\mu\delta g^{\tau\tau}\delta K^\mu_\nu + \frac{1}{2}\lambda_2(y)^\nu_\mu\delta g^{\tau\tau}\delta^{(3)}R^\mu_\nu + \frac{1}{2}\lambda_3(y)^\nu_\mu\delta K\delta K^\mu_\nu + \frac{1}{2}\lambda_4(y)^\nu_\mu\delta K\delta^{(3)}R^\mu_\nu$$
$$+ \frac{1}{2}\lambda_5(y)^\nu_\mu\delta^{(3)}R\delta K^\mu_\nu + \frac{1}{2}\lambda_6(y)^\nu_\mu\delta^{(3)}R\delta^{(3)}R^\mu_\nu + \dots\Big],$$

- EFT coefficients should satisfy the consistency relations but are otherwise arbitrary
- One can restore 4d diffeo by Stueckelberg trick
- Easy to find dictionary between EFT coefficients and theory parameters
- Can be applied to arbitrary background with timelike scalar profile

EFT of scalar-tensor gravity with timelike scalar profile

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EFT on arbitrary background = Main subject of this talk

Mukohyama and Yingcharoenrat, JCAP 09 (2022) 010

Taylor expansion of the general action $S = \int d^4x\sqrt{-g}\; F(R_{\mu\nu\alpha\beta}, g^{\tau\tau}, K_{\mu\nu}, \nabla_\nu, \tau)$

$$S = \int d^4x\sqrt{-g}\left[\bar{F} + \bar{F}_{g^{\tau\tau}}\delta g^{\tau\tau} + \bar{F}_K \delta K + \quad \ldots\right]$$

Consistency relations ⬅ S is invariant under spatial diffeo but the background breaks it.

$$\frac{d}{dx^i}\bar{F} = \bar{F}_{g^{\tau\tau}}\frac{\partial \bar{g}^{\tau\tau}}{\partial x^i} + \bar{F}_K \frac{\partial \bar{K}}{\partial x^i} + \ldots$$

Stealth BH with $\phi = qt+\psi(r)$

- Schwarzschild in k-essence (Mukohyama 2005)
- Schwarzschild-dS in Horndeski theory (Babichev & Charmousis 2013, Kobayashi & Tanahashi 2014) Schwarzshild-dS in DHOST (Ben Achour & Liu 2019, Motohashi & Minamitsuji 2019)
- Kerr-dS in DHOST (Charmousis & Crisotomi & Gregory & Stergioulas 2019)
- However, perturbations around most of those stealth solutions are infinitely strongly coupled (de Rham & Zhang 2019) . This means the solutions cannot be trusted.
- Fortunately, Scordatura (= detuning of degeneracy condition) solves the strong coupling problem (Motohashi & Mukohyama 2019), if and only if the scalar profile is timelike.
- EFT of ghost condensation already includes scordatura (Arkani-Hamed & Cheng & Luty & Mukohyama 2004)
- Approximate Schwarzschild in ghost condensation (Mukohyama 2005). Also in quadratic HOST (DeFelice & Mukohyama & Takahashi, JCAP 03 (2023) 050).

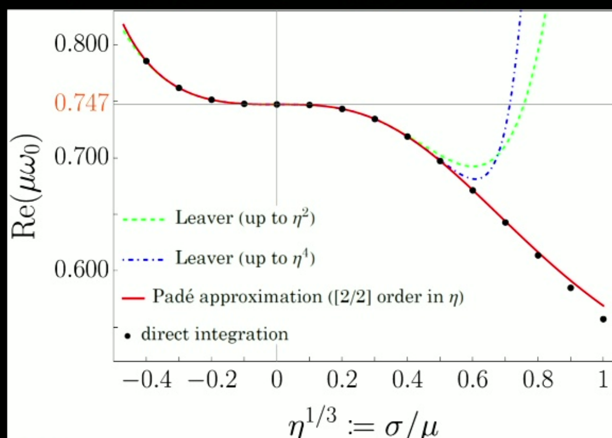
Applications to BHs with timelike scalar profile

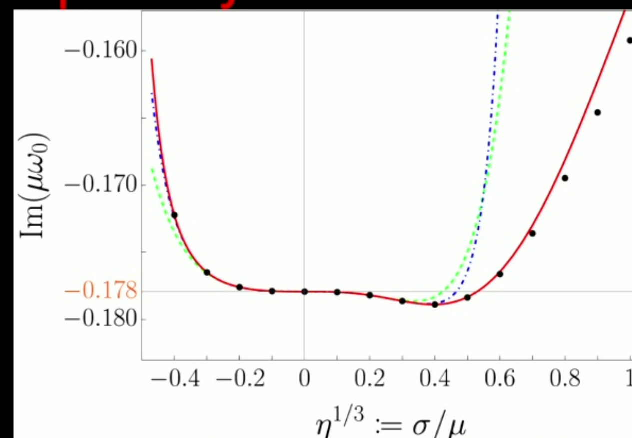
- Background analysis for spherical BH
  [arXiv: 2204.00228 w/ V.Yingcharoenrat]
- Odd-parity perturbation around spherical BH
  → Generalized Regge-Wheeler equation
  [arXiv: 2208.02943 w/ K.Takahashi & V.Yingcharoenrat]
  [see also arXiv: 2208.02823 by Khoury, Noumi, Trodden, Wong]
  → Quasi-normal mode
  [arXiv: 2304.14304 w/ K.Takahashi & K.Tomikawa & V.Yingcharoenrat]

QNM of Hayward BH

[arXiv: 2304.14304 w/ K.Takahashi & K.Tomikawa & V.Yingcharoenrat]

- Non-singular BH background $A = B = 1 - \frac{\mu r^2}{r^3 + \sigma^3}$
- Set $p_4 = M_3^2 = 0$ to ensure $c_T^2 = 1$ @ $r \to \infty$
- Fundamental QNM frequency





- Overtones show more prominent deviations

[Konoplya, arxiv: 2310.19205]

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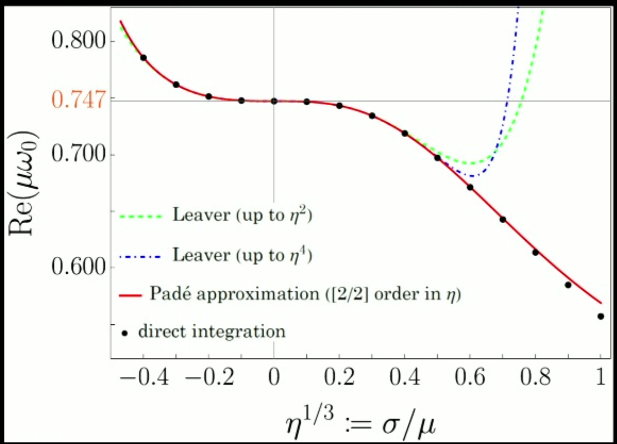

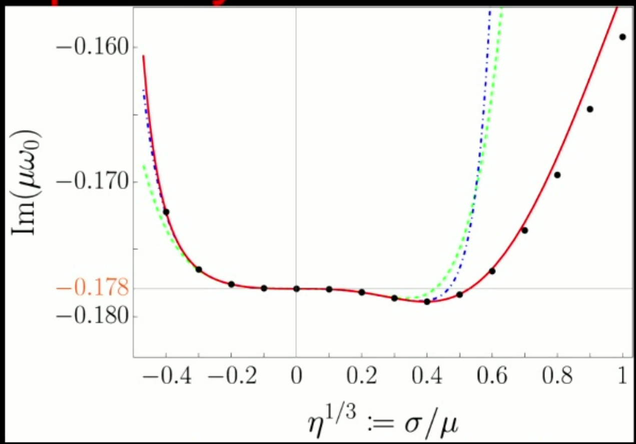

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  [see also arXiv: 2208.02823 by Khoury, Noumi, Trodden, Wong]
  → Quasi-normal modes deviate from GR
  [arXiv: 2304.14304 w/ K.Takahashi & K.Tomikawa & V.Yingcharoenrat]
  → Static Tidal Love number
  [arXiv: 2405.10813 w/C.G.A.Barura, H.Kobayashi, N.Oshita, K.Takahashi, V.Yingcharoenrat]

Tidal Love number of Hayward BH

[arXiv: 2405.10813 w/C.G.A.Barura, H.Kobayashi, N.Oshita, K.Takahashi, V.Yingcharoenrat]

- TLNs ← regularity @ horizon $\quad x \equiv r/r_g$

$$\tilde{\psi}(x) = x^{\ell+1}\left[1 + \mathcal{O}(x^{-1})\right] + K_\ell(\eta) x^{-\ell}\left[1 + \mathcal{O}(x^{-1})\right]$$

- Analytic continuation of multipole index l
  → Separation of growing & decaying sols.
- Expansion w.r.t. η

$$\eta \equiv \sigma^3/r_g^3 \qquad K_\ell(\eta) = \sum_{k\geq 0} \eta^k K_\ell^{(k)}$$

- Static tidal Love numbers are non-vanishing

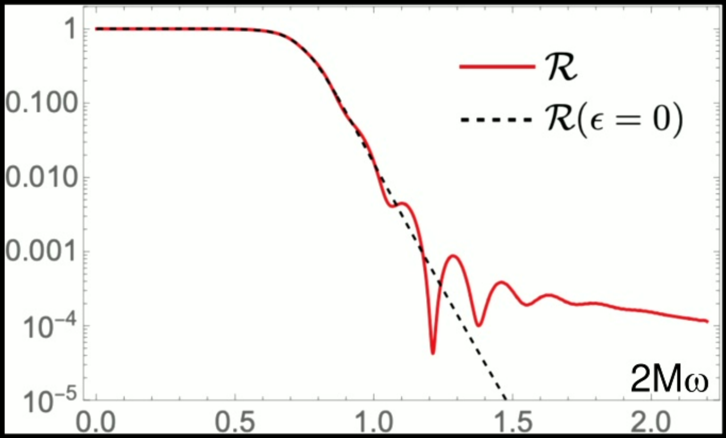
$$K_{\ell=2} = \frac{7}{20}\eta^2 - \frac{11}{20}\eta^3 + \frac{2}{5}\eta^4 + \cdots$$

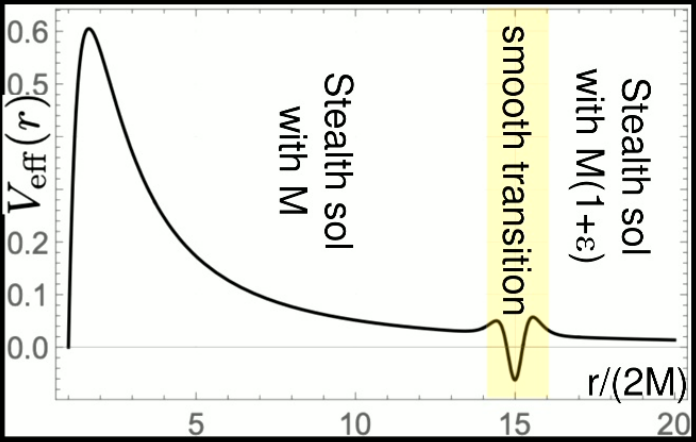
$$K_{\ell=3} = \frac{5}{42}\eta + \frac{1417}{504}\eta^2 - \frac{1285}{1008}\eta^3 + \frac{3713}{4032}\eta^4 + \cdots$$

$$K_{\ell=4} = \frac{23}{840}\eta + \left(\frac{110051}{50400} - \frac{24}{25}\log x\right)\eta^2 + \cdots \quad \text{logarithmic running}$$

(In)stability of greybody factor

[arXiv: 2406.04525 w/N.Oshita and K.Takahashi]





$$\mathcal{R}(\omega) := \left|\frac{A_{\rm out}}{A_{\rm in}}\right|^2 = 1 - \Gamma(\omega)$$

Reflectivity — Greybody factor

$$\psi_{\rm in} = \begin{cases} e^{-i\omega r_*} & \text{for } r_* \to -\infty, \\ A_{\rm out}(\omega)e^{i\omega r_*} + A_{\rm in}(\omega)e^{-i\omega r_*} & \text{for } r_* \to \infty, \end{cases}$$

Applications to BHs with timelike scalar profile

- Background analysis for spherical BH
  [arXiv: 2204.00228 w/ V.Yingcharoenrat]
- Odd-parity perturbation around spherical BH
  → Generalized Regge-Wheeler equation
  [arXiv: 2208.02943 w/ K.Takahashi & V.Yingcharoenrat]
  [see also arXiv: 2208.02823 by Khoury, Noumi, Trodden, Wong]
  → Quasi-normal modes deviate from GR
  [arXiv: 2304.14304 w/ K.Takahashi & K.Tomikawa & V.Yingcharoenrat]
  → Static Tidal Love numbers are non-vanishing
  [arXiv: 2405.10813 w/C.G.A.Barura, H.Kobayashi, N.Oshita, K.Takahashi, V.Yingcharoenrat]
  → (In)stability of greybody factors
  [arXiv: 2406.04525 w/N.Oshita and K.Takahashi]
- Even-parity perturbation around spherical BH
  [work in progress w/ K.Takahashi & K.Tomikawa & V.Yingcharoenrat]
- Rotating BH
  [work in progress w/ N.Oshita & K.Takahashi & Z.Wang & V.Yingcharoenrat]

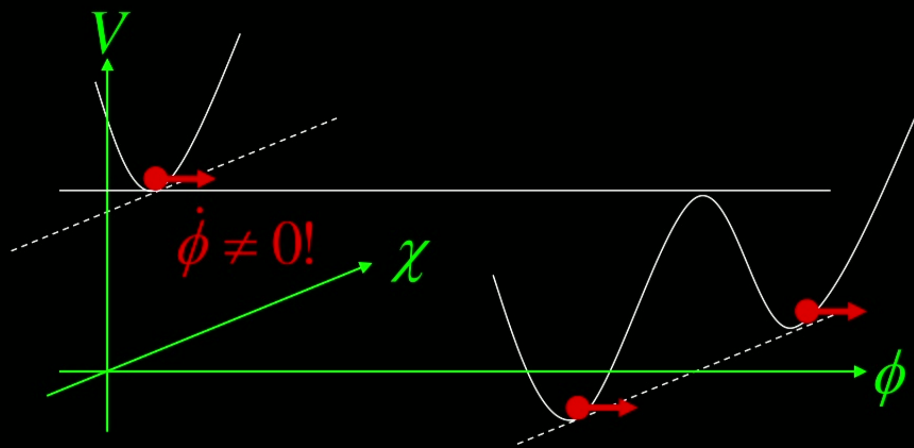
Extension of EFT of inflation to arbitrary background = EFT of BH perturbations

Mukohyama and Yingcharoenrat, JCAP 09 (2022) 010

- We call it EFT of BH perturbations simply because we applied it to BH in the presence of DE.
- Can be applied to any background as far as the scalar profile is timelike.
- Can be applied to e.g. astrophysics after inflation with ever rolling inflaton, such as ghost inflation.

Ghost inflation

Arkani-Hamed, Creminelli, Mukohyama and Zaldarriaga 2004



Similar to
hybrid inflation but
NOT SLOW ROLL

Scale-invariant perturbations

cf. tilted ghost inflation, Senatore (2004)

scaling dim of π

$$\frac{\delta\rho}{\rho} \sim \frac{H\delta\pi}{\dot{\phi}} \sim \left(\frac{H}{M}\right)^{5/4}$$

$$\delta\pi \sim M \cdot (H/M)^{1/4} \qquad \dot{\phi} \sim M^2$$

[compare $\frac{H}{M_{Pl}\sqrt{\varepsilon}}$]

Extension of EFT of inflation to arbitrary background = EFT of BH perturbations

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- We call it EFT of BH perturbations simply because we applied it to BH in the presence of DE.
- Can be applied to any background as far as the scalar profile is timelike.
- Can be applied to e.g. astrophysics after inflation with ever rolling inflaton, such as ghost inflation.
- Any other applications? Depending on them, we may have to change the name… Let's discuss!

SUMMARY

- Majorities of inflation/DE models are described by scalar-tensor gravity with timelike scalar profile.
- Ghost condensation universally describes all scalar-tensor theories of gravity with timelike scalar profile on Minkowski background respecting time translation / reflection symmetry (up to shift / reflection of the scalar).
- Extension of ghost condensation to FLRW backgrounds results in the EFT of inflation/DE.
- These EFTs provide universal descriptions of all scalar-tensor theories of gravity with timelike scalar profile on each background, including Horndeski theory, DHOST theory, U-DHOST theory, and more.

EFT of scalar-tensor gravity with timelike scalar profile

- **Time diffeo is broken by the scalar profile but spatial diffeo is preserved.**
- All terms that respect spatial diffeo must be included in the EFT action.
- Derivative & perturbative expansions
- Diffeo can be restored by introducing NG boson

EFT on Minkowski background = ghost condensation
Arkani-Hamed, Cheng, Luty and Mukohyama, JHEP 0405:074,2004

EFT on cosmological background = EFT of inflation/dark energy
Creminelli, Luty, Nicolis and Senatore 2006; Cheung, Creminelli, Fitzpatrick, Kaplan and Senatore 2007; Gubitosi, Piazza, Vernizzi 2012; Gleyzes, Langlois, Piazza, Vernizzi 2013

EFT on arbitrary background = EFT of BH perturbations
Mukohyama and Yingcharoenrat, JCAP 09 (2022) 010

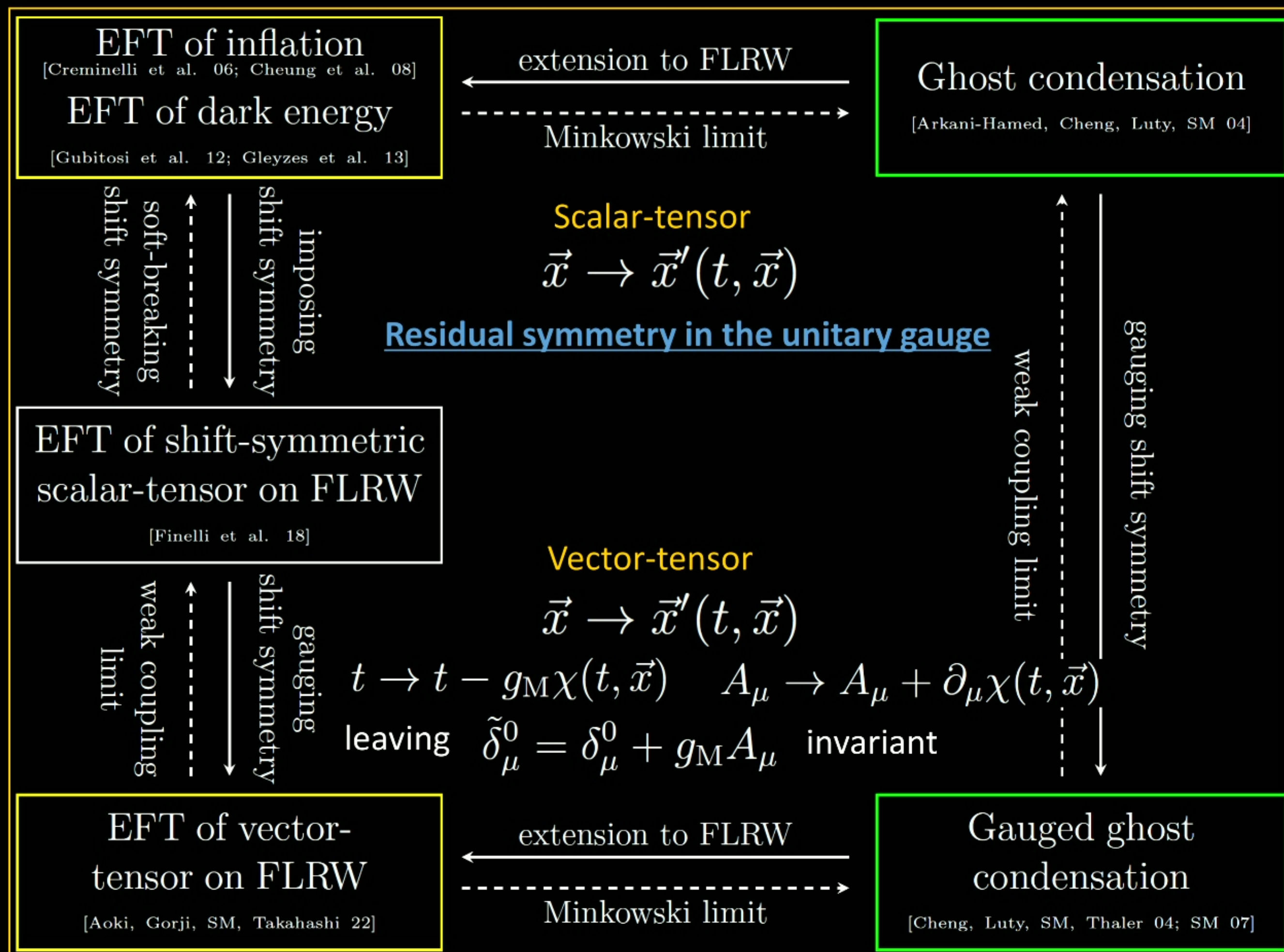
Taylor expansion of the general action $S = \int d^4x\sqrt{-g}\; F(R_{\mu\nu\alpha\beta}, g^{\tau\tau}, K_{\mu\nu}, \nabla_\nu, \tau)$

$$S = \int d^4x\sqrt{-g}\left[\bar{F} + \bar{F}_{g^{\tau\tau}}\delta g^{\tau\tau} + \bar{F}_K\delta K + \quad \ldots\right]$$

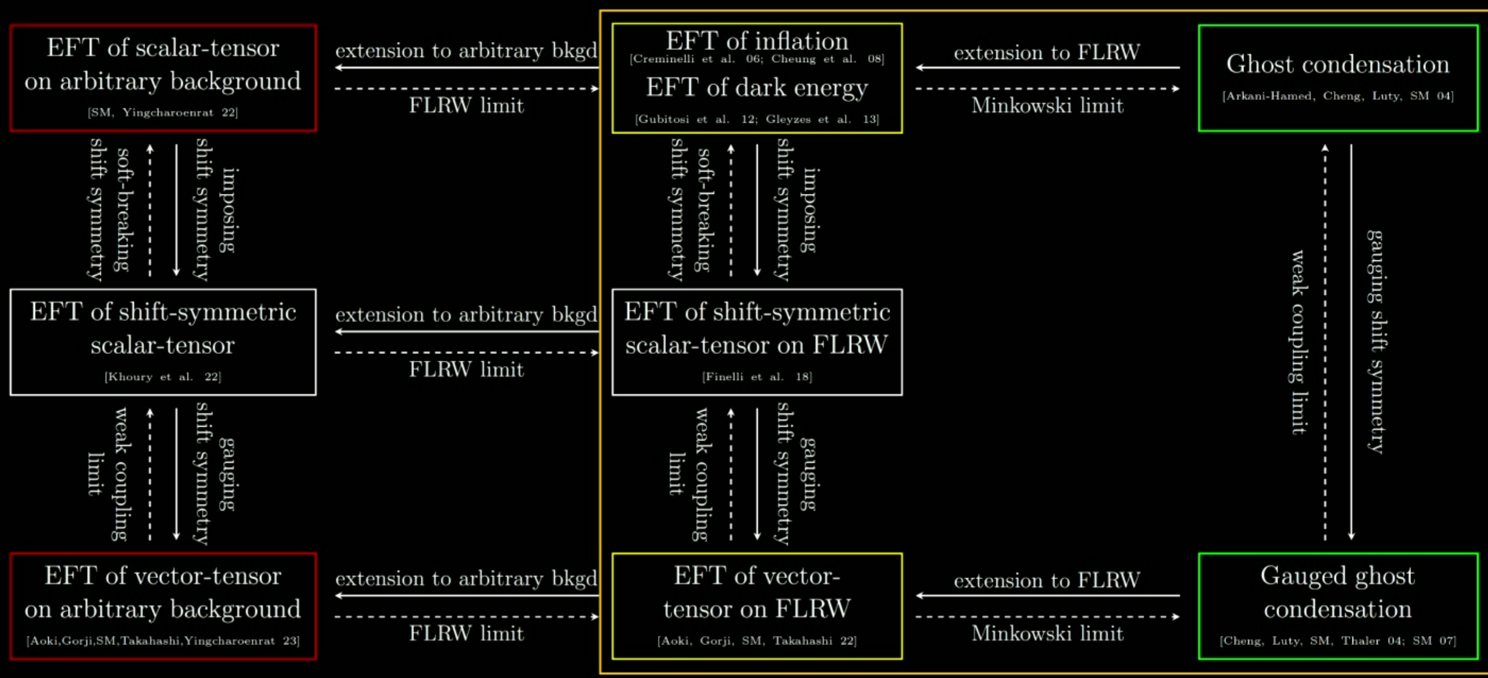
Consistency relations ⟸ S is invariant under spatial diffeo but the background breaks it.

$$\frac{d}{dx^i}\bar{F} = \bar{F}_{g^{\tau\tau}}\frac{\partial\bar{g}^{\tau\tau}}{\partial x^i} + \bar{F}_K\frac{\partial\bar{K}}{\partial x^i} + \ldots$$

Further extension of the web of EFTs



Further extension of the web of EFTs



Residual symmetry in the unitary gauge

Scalar-tensor

$$\vec{x} \to \vec{x}'(t, \vec{x})$$

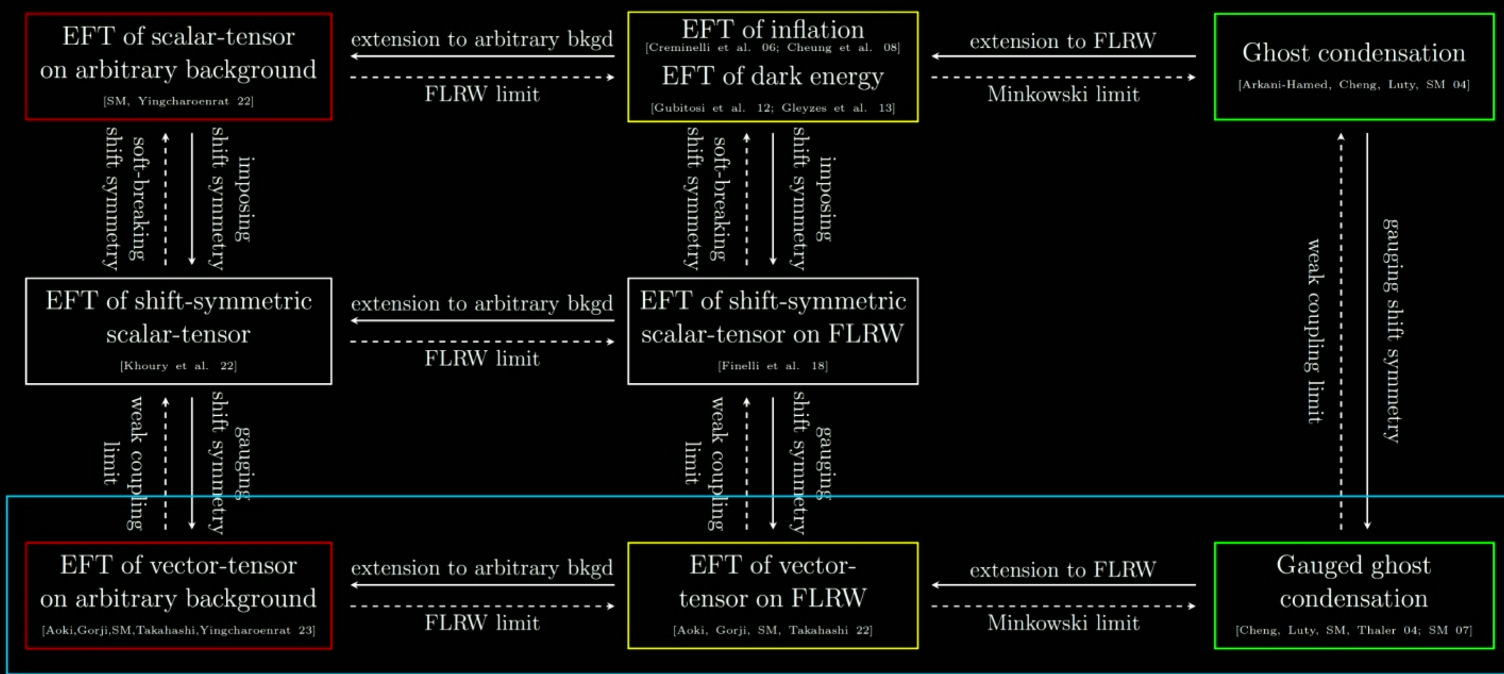
Vector-tensor

$$\vec{x} \to \vec{x}'(t, \vec{x})$$

$$t \to t - g_{\rm M}\chi(t, \vec{x}) \qquad A_\mu \to A_\mu + \partial_\mu \chi(t, \vec{x})$$

leaving $\tilde{\delta}^0_\mu = \delta^0_\mu + g_{\rm M} A_\mu$ invariant

Further extension of the web of EFTs



Residual symmetry in the unitary gauge

Scalar-tensor

$$\vec{x} \to \vec{x}'(t, \vec{x})$$

See also "CMB spectrum in unified EFT of dark energy: scalar-tensor and vector-tensor theories", arXiv: 2405.04265

Vector-tensor

$$\vec{x} \to \vec{x}'(t, \vec{x})$$

$$t \to t - g_M \chi(t, \vec{x}) \qquad A_\mu \to A_\mu + \partial_\mu \chi(t, \vec{x})$$

leaving $\tilde{\delta}^0_\mu = \delta^0_\mu + g_M A_\mu$ invariant

Thank you!

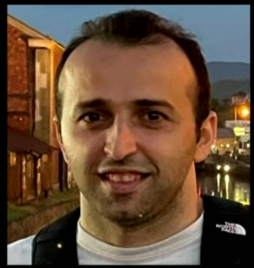

V.Yingcharoenrat


K.Takahashi


K.Tomikawa


K.Aoki


E.Seraille


M.A.Gorji


C.G.A.Barura


H.Kobayashi


N.Oshita

Ref.

scalar-tensor:
- arXiv: 2204.00228 w/ V.Yingcharoenrat
- arXiv: 2208.02943 w/ K.Takahashi, V.Yingcharoenrat
- arXiv: 2304.14304 w/ K.Takahashi, K.Tomikawa, V.Yingcharoenrat
- arXiv: 2405.10813 w/ C.G.A.Barura, H.Kobayashi, N.Oshita, K.Takahashi, V.Yingcharoenrat
- arXiv: 2406.04525 w/ N.Oshita and K.Takahashi
- arXiv: 2407.xxxxx w/ E.Seraille, K.Takahashi , V.Yingcharoenrat

vector-tensor:
- arXiv: 2111.08119 w/ K.Aoki, M.A.Gorji, K.Takahashi
- arXiv: 2311.06767 w/ K.Aoki, M.A.Gorji, K.Takahashi, V.Yingcharoenrat

Also
- Arkani-Hamed, Cheng, Luty and Mukohyama 2004 (hep-th/0312099)
- Mukohyama 2005 (hep-th/0502189)