Extending EFT of inflation/dark energy to black hole with timelike scalar profile

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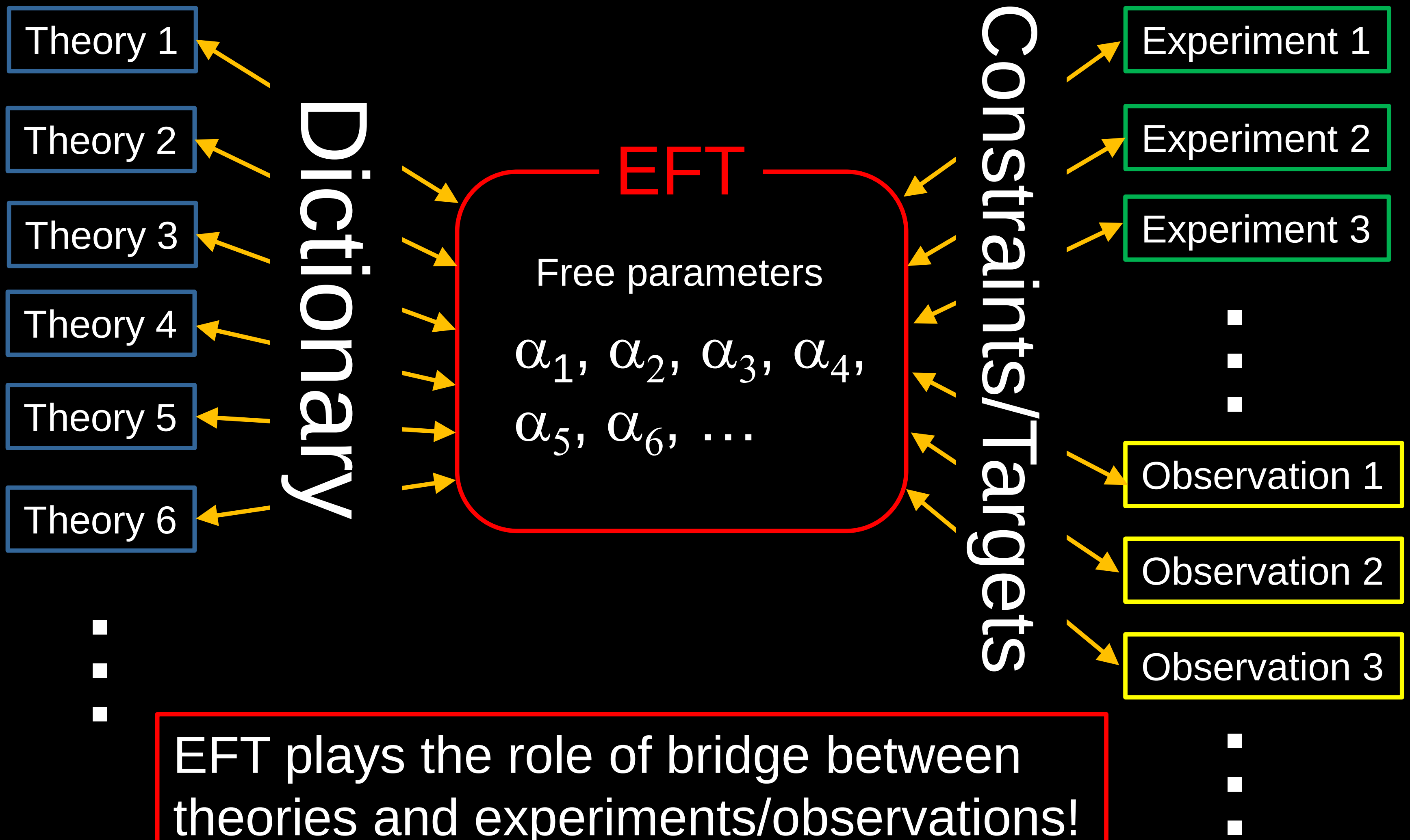
Refs. arXiv: 2204.00228 w/ V.Yingcharoenrat
arXiv: 2208.02943 w/ K.Takahashi, V.Yingcharoenrat
arXiv: 2304.14304 w/ K.Takahashi, K.Tomikawa, V.Yingcharoenrat
arXiv: 2405.10813 w/ C.G.A.Barura, H.Kobayashi, N.Oshita, K.Takahashi, V.Yingcharoenrat
arXiv: 2406.04525 w/ N.Oshita and K.Takahashi
arXiv: 2407.15123 w/ E.Seraille, K.Takahashi , V.Yingcharoenrat
arXiv: 2503.00520 w/ K.Takahashi, K.Tomikawa, V.Yingcharoenrat

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

Effective field theory (EFT) approach



Theory 1

Theory 2

Theory 3

Theory 4

Theory 5

Theory 6

⋮

Dictionary

EFT

Free parameters

$\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6, \dots$

Constraints/Targets

Experiment 1

Experiment 2

Experiment 3

⋮

Observation 1

Observation 2

Observation 3

⋮

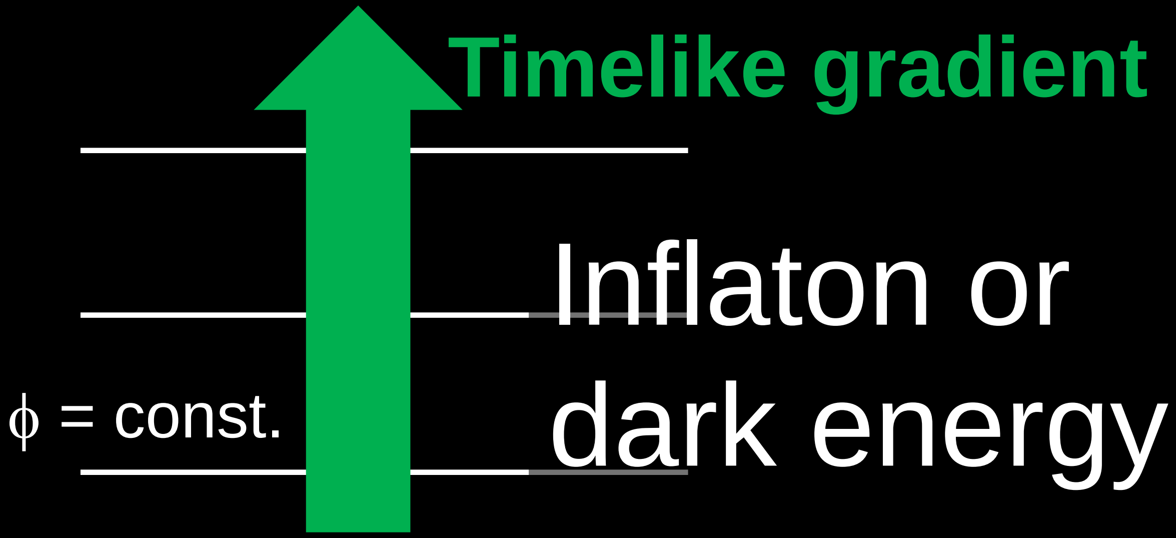
EFT plays the role of bridge between theories and experiments/observations!

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)

EFT of scalar-tensor gravity with timelike scalar profile

- **Scalar-tensor gravity contains majority of inflation & dark energy models**
- **Inflaton/dark energy has timelike derivative**
- **Time diffeo is broken by the scalar profile but spatial diffeo is preserved.**



Timelike gradient

ϕ = const.

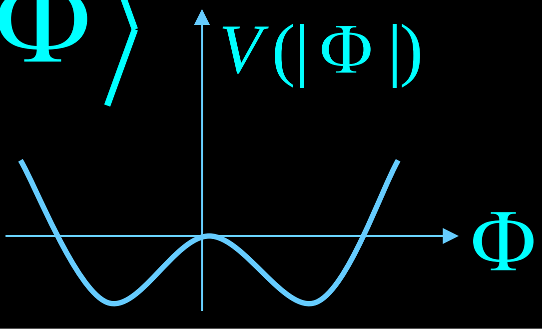
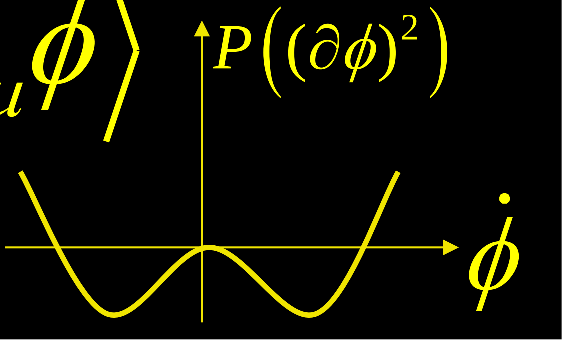
Inflaton or dark energy

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	$\left\langle \Phi \right\rangle$ 	$\left\langle \partial_\mu \phi \right\rangle$ 
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

➡

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

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

$$\left\{\begin{array}{l}(h_{00})^2 \quad \textbf{OK} \\ \cancel{(h_{0i})^2} \\ K^2, K^{ij}K_{ij} \quad \textbf{OK}\end{array}\right.$$

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

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

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

Action invariant under ξⁱ

$$\begin{cases} \left(h_{00}\right)^2 & \textbf{OK} \\ \xcancel{\left(h_{0i}\right)^2} & \\ K^2, K^{ij}K_{ij} & \textbf{OK} \end{cases}$$

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

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

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

Action for π

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

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

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

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]

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

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

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

2 types of 3-point interactions

→ 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

$$\langle \zeta_{\vec k_1}(t)\,\zeta_{\vec k_2}(t)\,\zeta_{\vec k_3}(t)\rangle = (2\pi)^3\delta^3(\vec k_1+\vec k_2+\vec k_3)B_\zeta$$

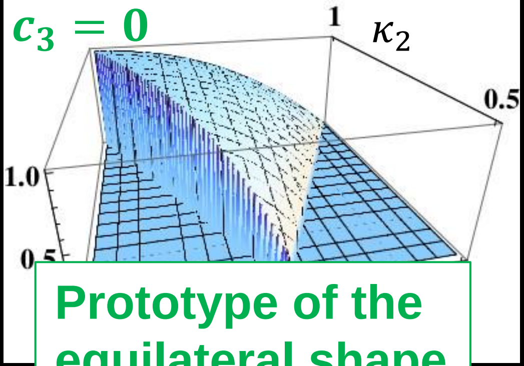
c_s^2 → size of non-Gaussianity

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

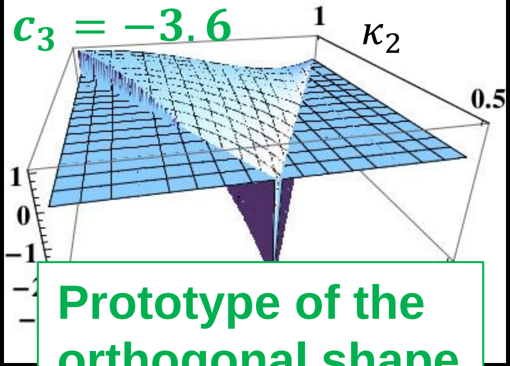
$$f_{NL}^{\dot\pi(\partial_i\pi)^2} = \frac{85}{324}\left(1-\boxed{\frac{1}{c_s^2}}\right) \qquad f_{NL}^{\dot\pi^3} = \frac{5\boxed{c_3}}{81}\left(1-\boxed{\frac{1}{c_s^2}}\right) \qquad \propto \frac{1}{c_s^2}$$ **for small c_s^2**

c_3 → shape of non-Gaussianity

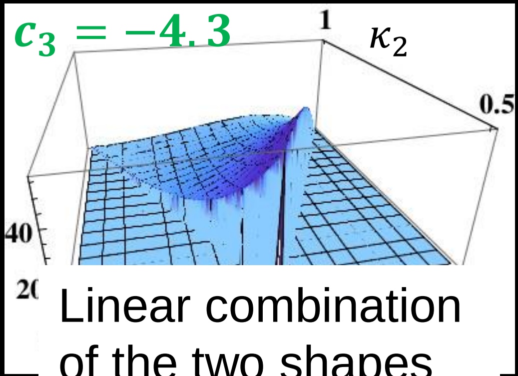
plots of $B_\zeta(k,\kappa_2 k,\kappa_3 k)/B_\zeta(k,k,k)$


$c_3 = 0$

Prototype of the equilateral shape


$c_3 = -3.6$

Prototype of the orthogonal shape


$c_3 = -4.3$

Linear combination of the two shapes

Parametrization tailored to 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. Otherwise, the basic construction is the same as EFT of inflation.
- Implemented in Boltzmann codes, e.g. EFTCAMB [Hu, Raveri, Frusciante, Silvestri 2014].
- Constraint on c_{GW} by GW170817 imposed [Creminelli and Vernizzi 2017, Ezquiaga and Zumalacárregui 2017] .
- Will be used to interpret data from future observations.

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- Majorities of inflation/DE models are described by scalar-tensor gravity with timelike scalar profile.
- Ghost condensation universally describes all scalar-tensor 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. They have been used to interpret observational data. Adopted by e.g. ESA’s Planck team.

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Of course, this is not the end of the story!

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- Ghost condensation universally describes scalar-tensor gravity with timelike scalar profile on Minkowski background respecting time translation / reflection symmetry (up to shift / reflection of the scalar).
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Extension of EFT of inflation/DE to arbitrary background

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EFT on arbitrary background = EFT of black hole perturbation with timelike scalar profile

Mukohyama and Yingcharoenrat, JCAP 09 (2022) 010

- EFT of scalar-tensor gravity with timelike scalar profile on arbitrary background was developed.
- Can describe all scalar-tensor gravity with timelike scalar profile.
- Applied to black holes in the presence of dark energy.

It was not straightforward…

- General action in the unitary gauge (ϕ = τ)

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

- 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.)

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]

QNM of stealth Schwarzschild BH

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

- Background with 2m=1
  $A(r) = B(r) = 1 - 1/r$

$$ds^2 = -A(r)dt^2 + \frac{dr^2}{B(r)} + r^2 d\Omega^2$$

- Set $p_4 = 0$ to make $c_T{}^2$ finite @ r→∞
- Generalized Regge-Wheeler potential

$$V_{\rm eff}(r) = (1+\alpha_{\rm T})f(r)\left[\frac{\ell(\ell+1)}{r^2} - \frac{3r_g}{r^3}\right] \quad f(r) = 1 - r_g/r$$

$$\alpha_{\rm T} \equiv c_{\rm T}^2 - 1 = \alpha/(M_\star^2 - \alpha) \qquad r_g \equiv r_{\rm H}/(1+\alpha_{\rm T})$$

- QNM frequency

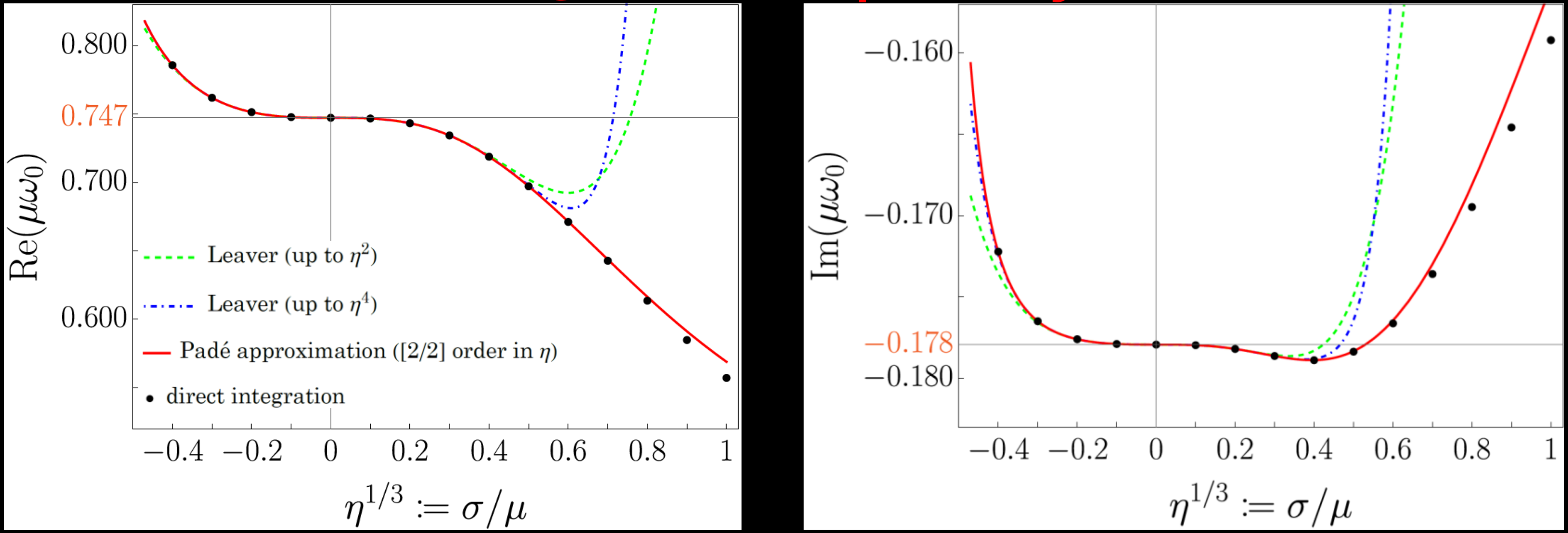
$$\omega = \omega_{\rm GR}(1+\alpha_{\rm T})^{3/2}$$

$$\rightarrow \omega_{\rm GR} \quad (c_T{}^2 \rightarrow 1)$$

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]

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 $x \equiv r/r_g$

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

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

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

- Static tidal Love numbers are non-vanishing

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

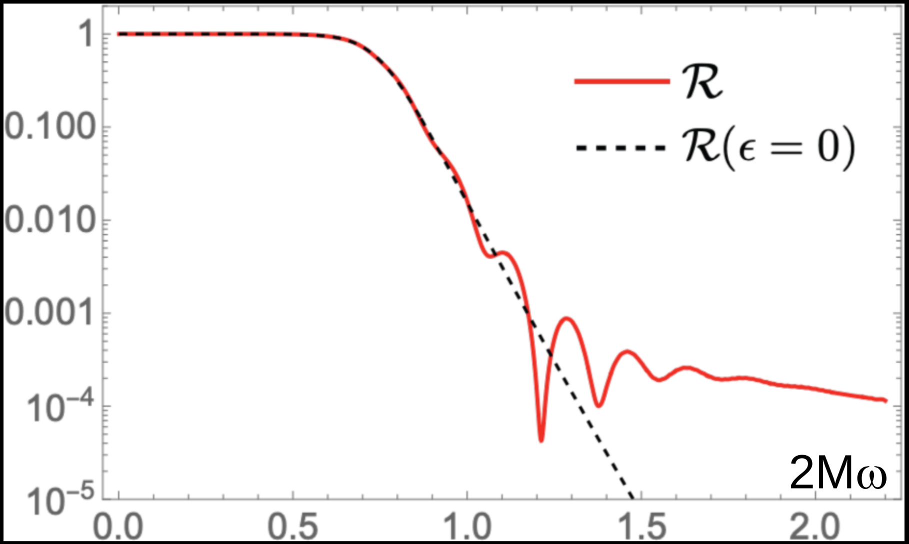
$$K_{\ell=3} = \frac{5}{42}\eta + \frac{1417}{504}\eta^2 - \frac{1285}{1008}\eta^3 + \frac{3713}{4032}\eta^4 + \cdots$$

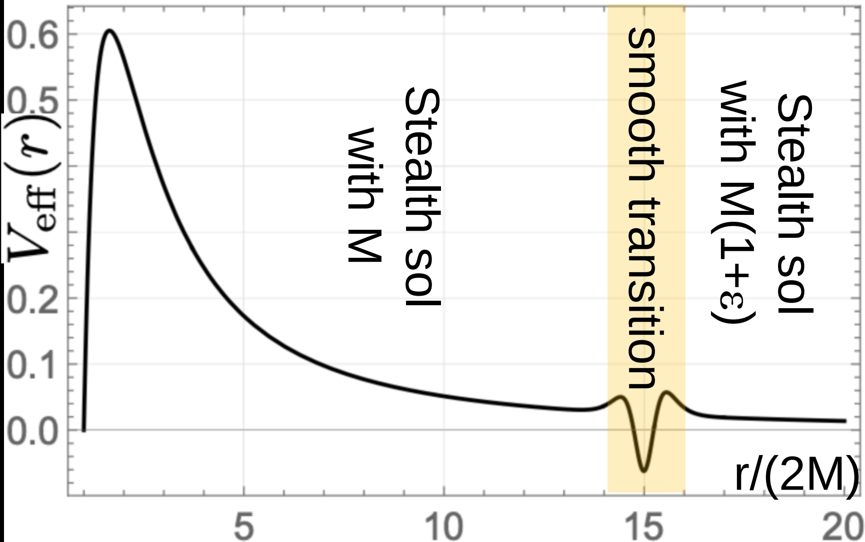
$$K_{\ell=4} = \frac{23}{840}\eta + \left(\frac{110051}{50400} - \frac{24}{25}\log x\right)\eta^2 + \cdots$$

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

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

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Conformal/disformal transformation

[arXiv: 2407.15123 w/E.Seraille, K.Takahashi & V.Yingeharoenrat]

- EFT of DE is usually written in Jordan frame, to which matter minimally couple
- EFT of BH perturbations is studied mainly in an almost Einstein frame (with constant coefficient of 4d Ricci scalar)
- In order to bridge these EFTs, one needs to know how EFT coefficients are mapped under conformal/disformal transformations

$$\hat{g}_{\mu\nu} = f_0(\Phi, X) g_{\mu\nu} + f_1(\Phi, X) \partial_\mu \Phi \partial_\nu \Phi$$

GW speed near BH

[arXiv: 2407.15123 w/E.Seraille, K.Takahashi & V.Yingeharoenrat]

- GW170817 → $|c_{GW} - 1| < 10^{-15}$ @ cosmological scale → constraint on DE/MG models
- Typically, one requires $c_{GW}=1$ on FLRW for all $H(t)$ & $\phi(t)$ @ low E
- Does this imply $c_{GW}=1$ around BH @ low E?
- Yes, in Horndeski theory $[G_{4,X}=0=G_5]$.
- No, in general, e.g. in cubic HOST theories.
- In EFT, the following operator does the job.

$$M_6(y)\bar{\sigma}^{\mu}_{\nu}\delta K^{\nu}_{\alpha}\delta K^{\alpha}_{\mu}$$

$\bar{\sigma}^{\mu}_{\nu}$ traceless part of background K^{μ}_{ν}

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- Even-parity perturbation around spherical BH
  [arXiv: 2503.00520 & work in progress w/ K.Takahashi & K.Tomikawa & V.Yingcharoenrat]
- Rotating BH
  [work in progress w/ N.Oshita & K.Takahashi & Z.Wang & V.Yingcharoenrat]

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

EFT on cosmological background = EFT of inflation/dark energy

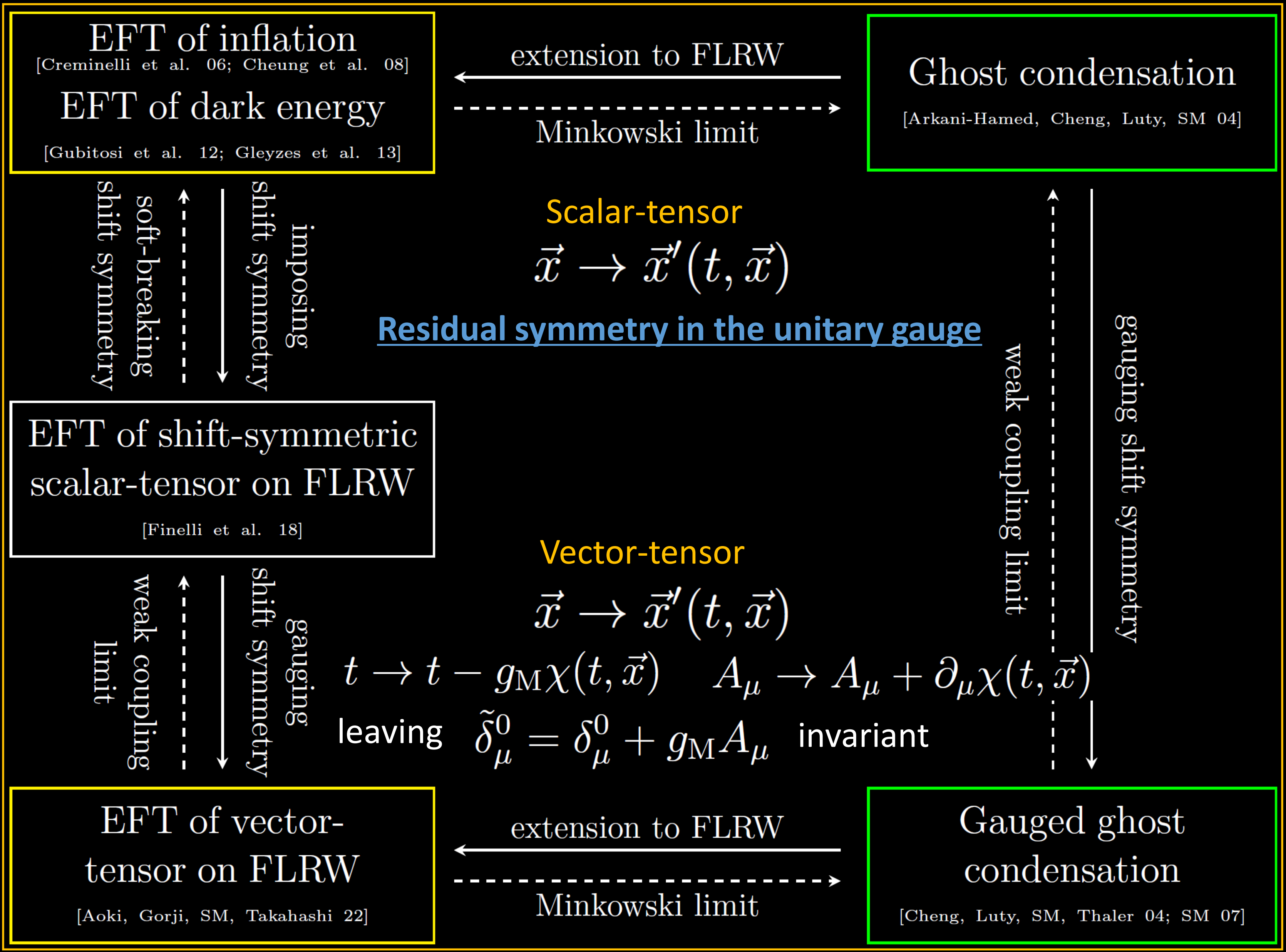
Creminelli, Luty, Nicolis and Senatore 2006; Cheung, Creminelli, Fitzpatrick, Kaplan and Senatore 2007; Gubitosi, Piazza, Vernizzi 2012; Gleyzes, Langlois, Piazza, Vernizzi 2013

EFT on arbitrary background = EFT of black hole perturbation with timelike scalar profile

Mukohyama and Yingcharoenrat, JCAP 09 (2022) 010

- EFT of scalar-tensor gravity with timelike scalar profile on arbitrary background was developed.
- Can describe all scalar-tensor gravity with timelike scalar profile.
- Applied to black holes in the presence of dark energy.
- Any other applications? Further extensions?

Further extension of the web of EFTs



EFT of inflation

[Creminelli et al. 06; Cheung et al. 08]

EFT of dark energy

[Gubitosi et al. 12; Gleyzes et al. 13]

extension to FLRW

Minkowski limit

Ghost condensation

[Arkani-Hamed, Cheng, Luty, SM 04]

soft-breaking shift symmetry

imposing shift symmetry

weak coupling limit

gauging shift symmetry

EFT of shift-symmetric scalar-tensor on FLRW

[Finelli et al. 18]

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[Aoki, Gorji, SM, Takahashi 22]

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Residual symmetry in the unitary gauge

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

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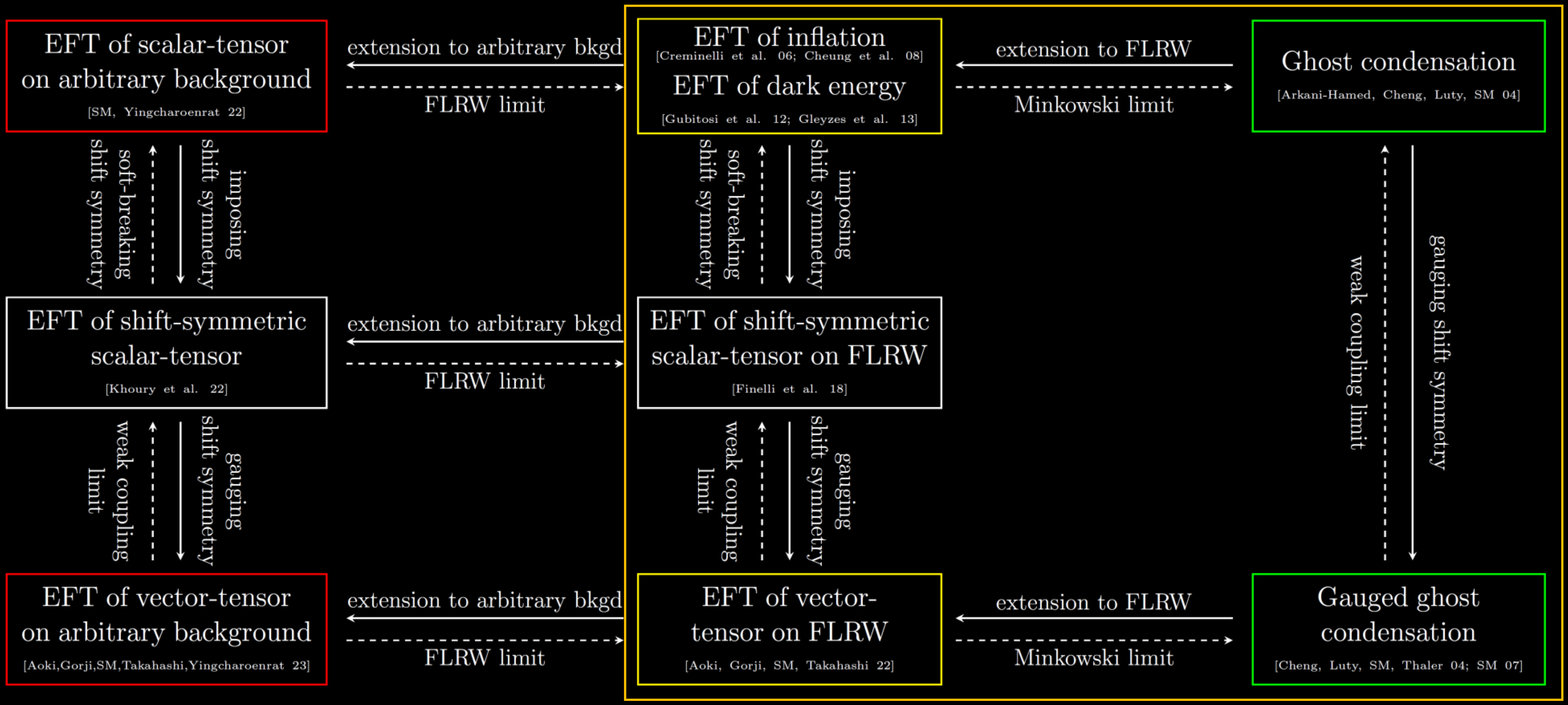

EFT of scalar-tensor on arbitrary background
[SM, Yingcharoenrat 22]

extension to arbitrary bkgd
FLRW limit

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imposing shift symmetry

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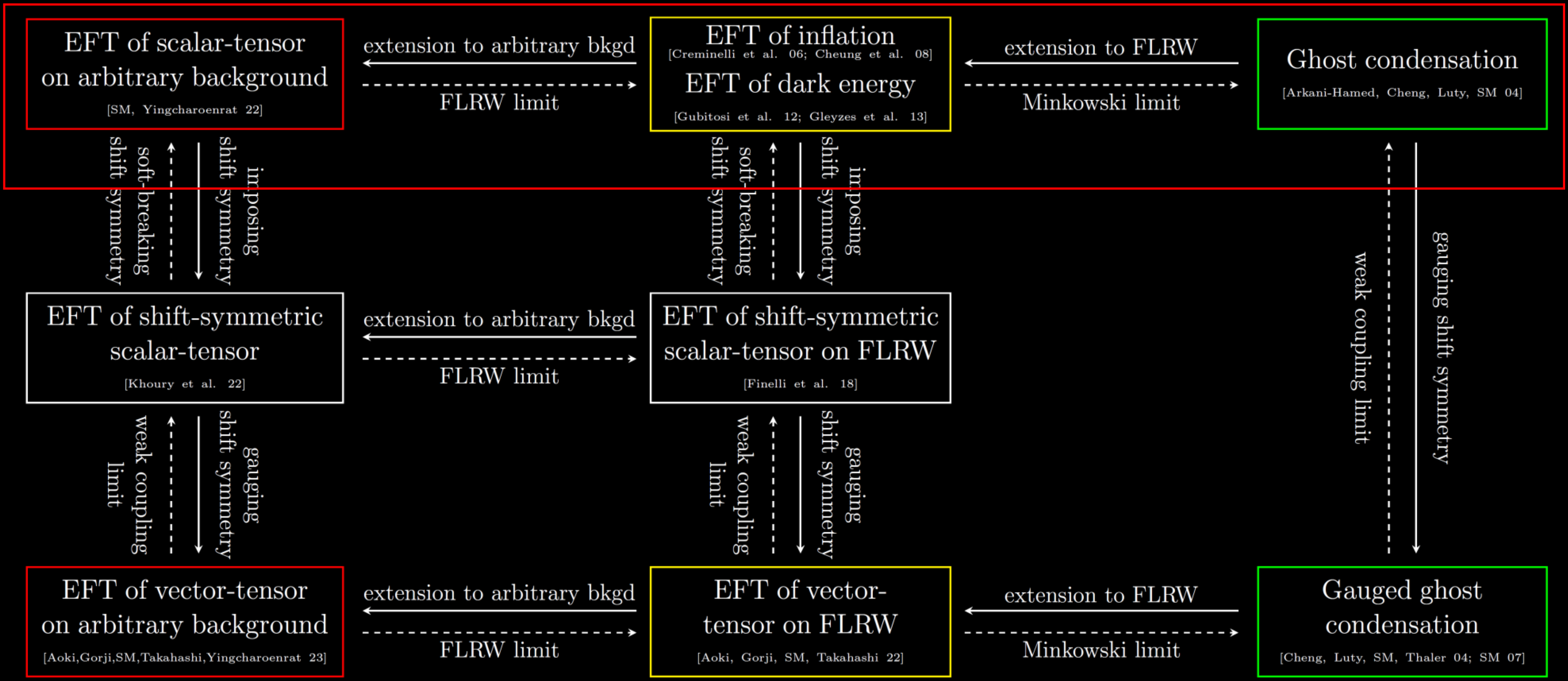

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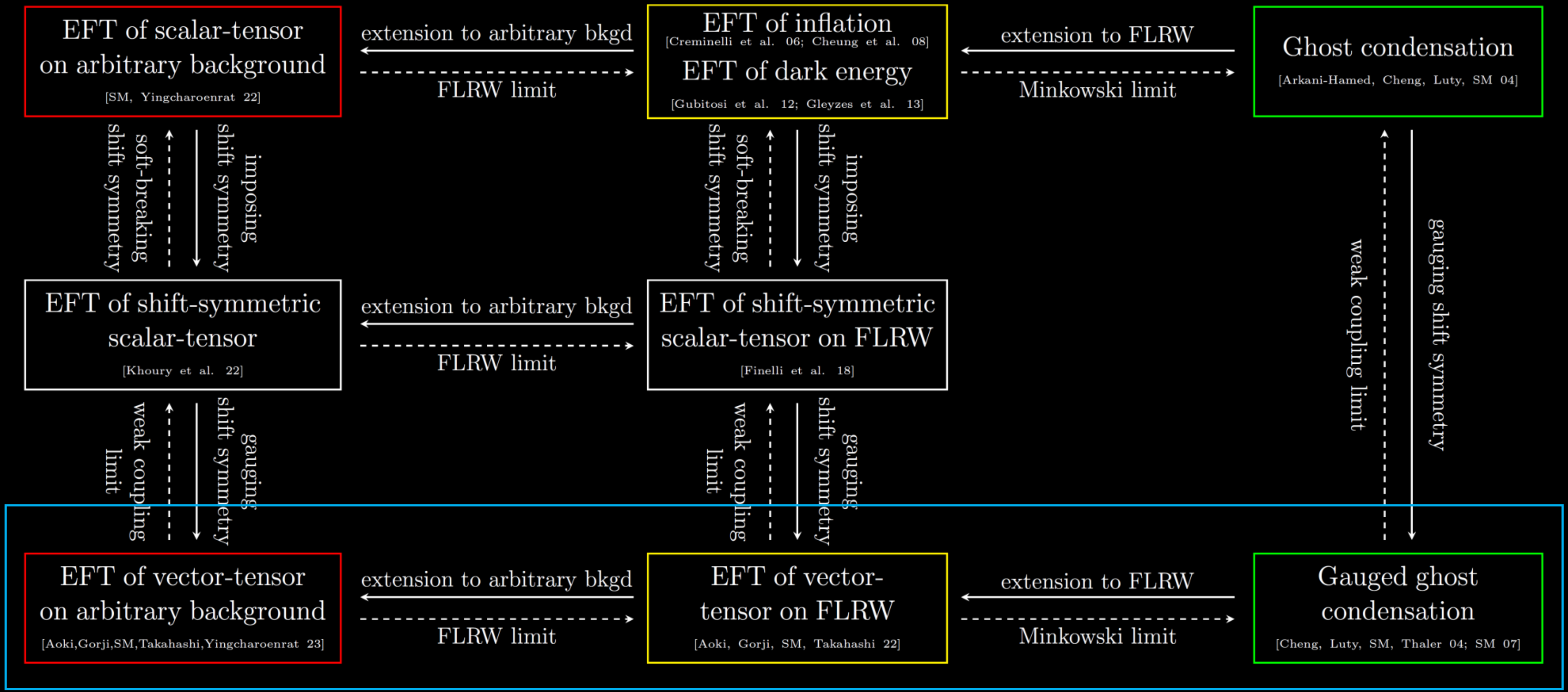

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See also "CMB spectrum in unified EFT of dark energy: scalar-tensor and vector-tensor theories", arXiv: 2405.04265

Thank you!


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N.Oshita

Refs. 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: 2407.15123 w/ E.Seraille, K.Takahashi , V.Yingcharoenrat
arXiv: 2503.00520 w/ K.Takahashi, K.Tomikawa, V.Yingcharoenrat

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