Effective field theory of black hole perturbations with timelike scalar profile

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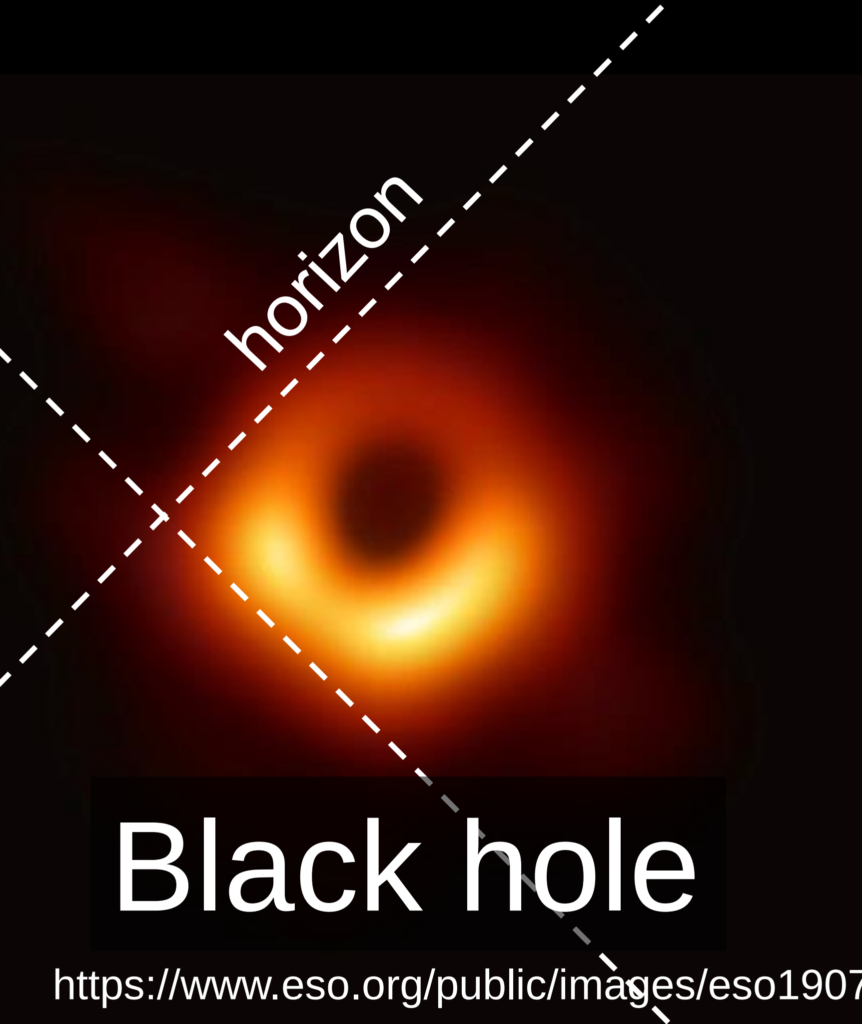
Ref. arXiv: 2204.00228 w/ V.Yingcharoenrat
arXiv: 2208.02943 w/ K.Takahashi & V.Yingcharoenrat
arXiv: 2304.14304 w/ K.Takahashi & K.Tomikawa & V.Yingcharoenrat
Also Arkani-Hamed, Cheng, Luty and Mukohyama 2004 (hep-th/0312099)
Mukohyama 2005 (hep-th/0502189)

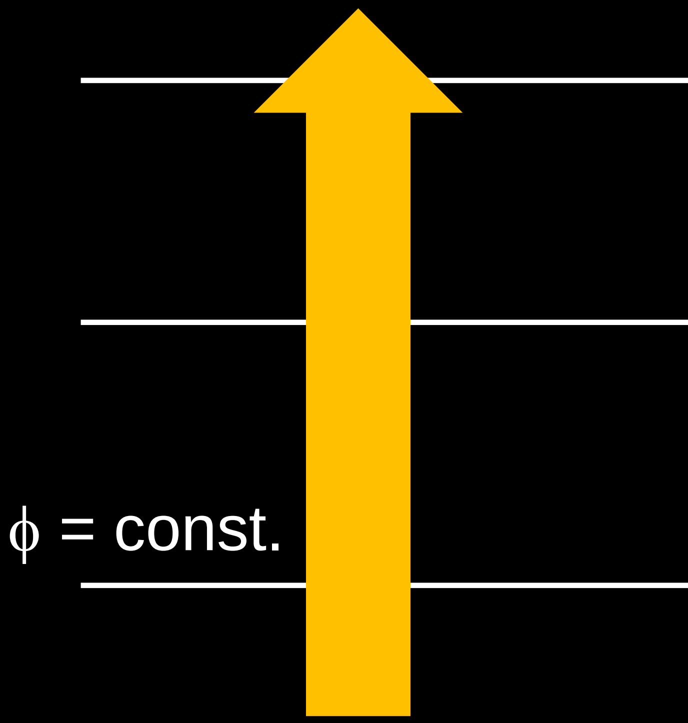
- Cosmology and black holes (BHs) play as important roles in gravitational physics as blackbody radiation and hydrogen atoms did in quantum mechanics.
- In cosmology a time-dependent scalar field can act as dark energy (DE), while BHs serve as probes of strong gravity. We then hope to learn something about the EFT of DE by BHs.
- This would require **the scalar field profile to be timelike near BH**. Otherwise, the two EFTs, one for DE and the other for BH, can be unrelated to each other (unless a UV completion is specified).

Timelike gradient

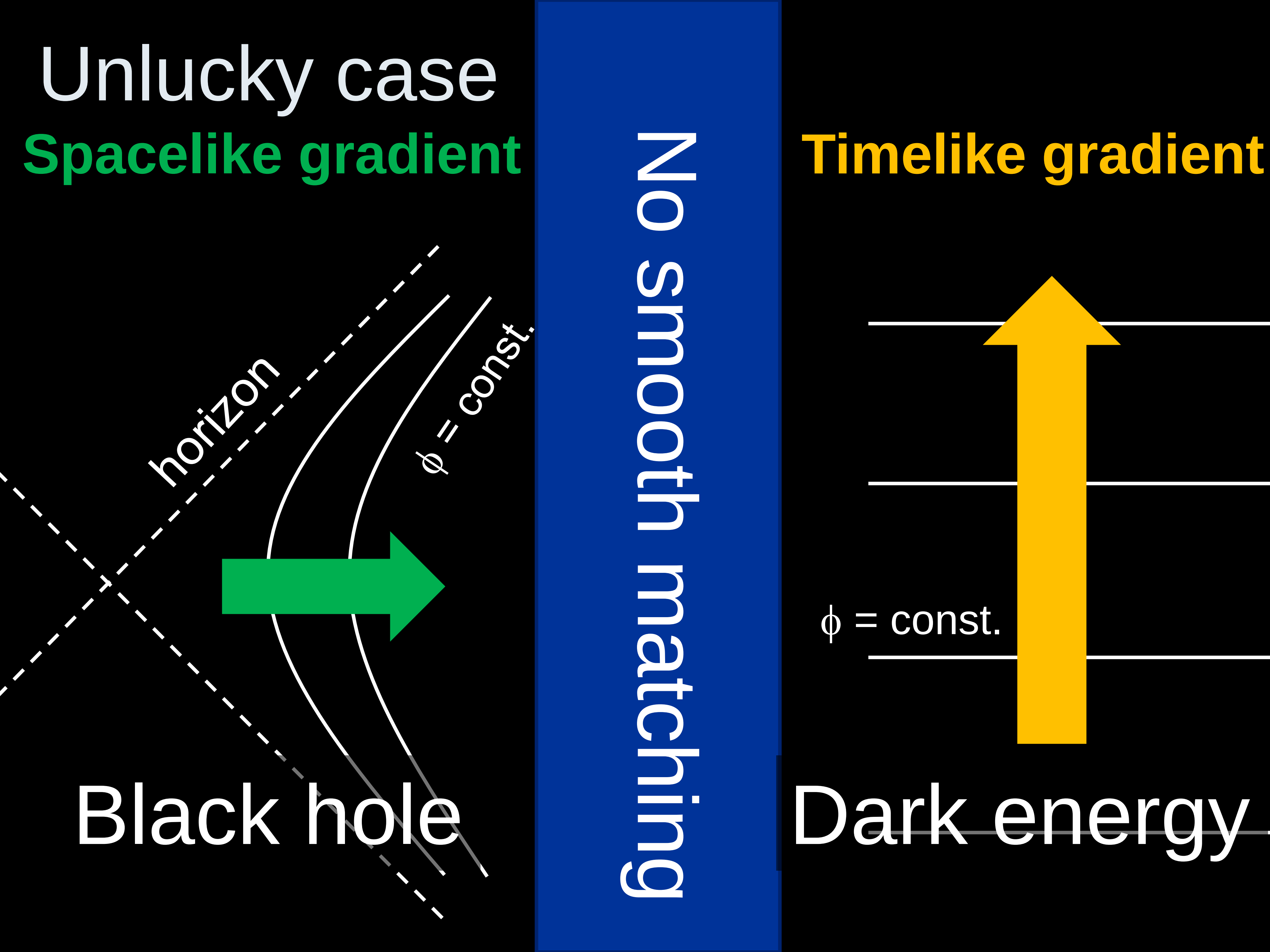


Black hole

https://www.eso.org/public/images/eso1907a/

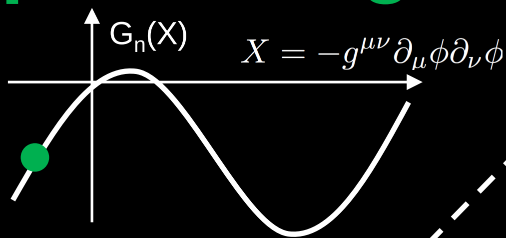


Dark energy


Unlucky case
Spacelike gradient
horizon
ϕ = const.
Black hole
No smooth matching
Timelike gradient
ϕ = const.
Dark energy

Unlucky case

Spacelike gradient

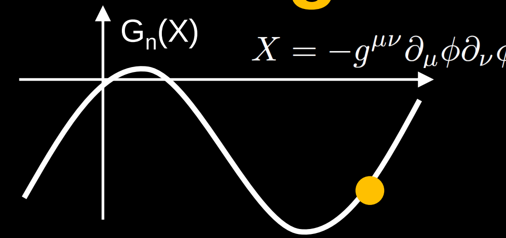


Taylor expansion around $X=X_{BH}<0$
$(\beta_1, \beta_2, \beta_3, \ldots)$

Black hole

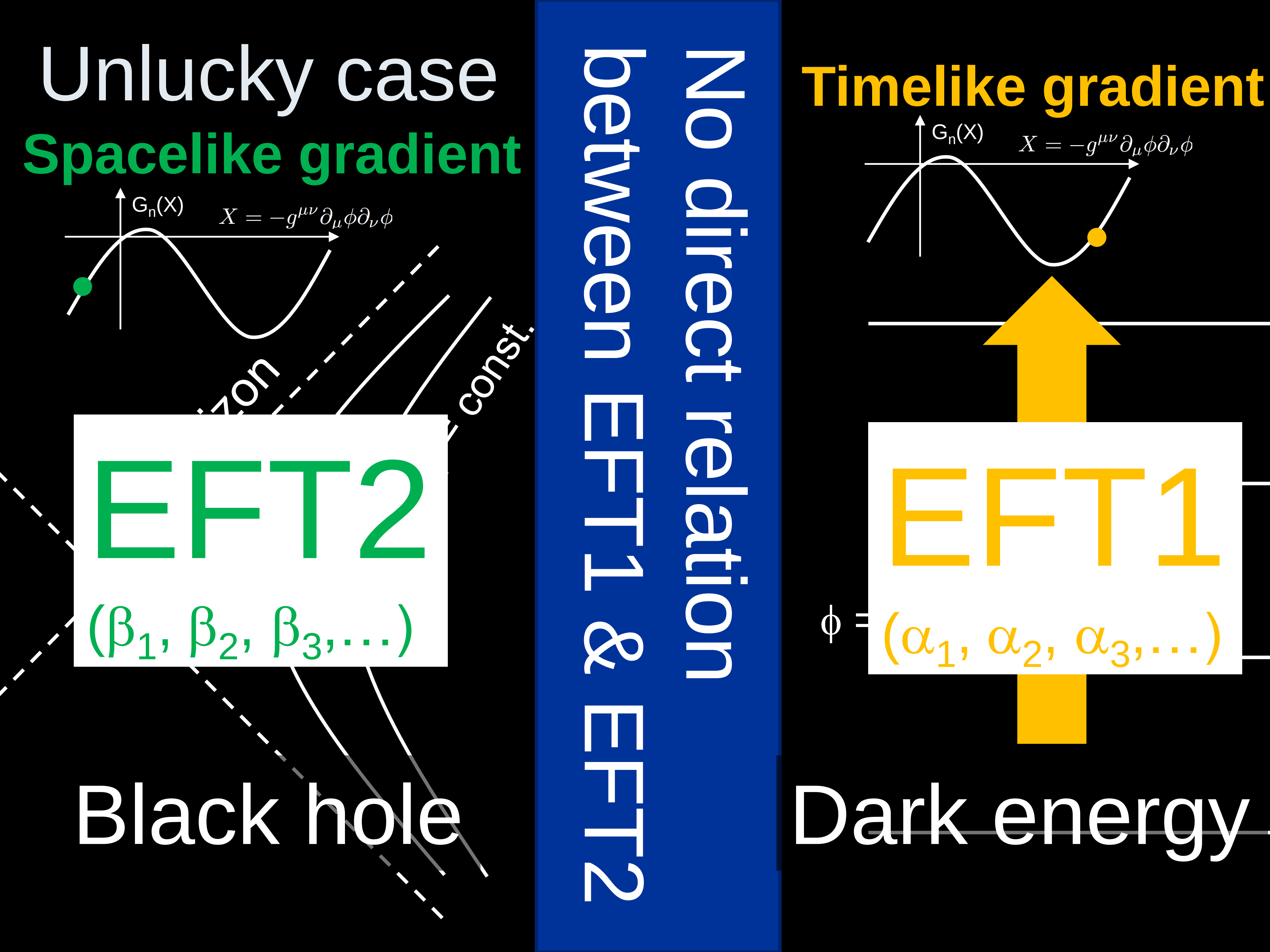
No direct relation between Taylor coefficients

Timelike gradient

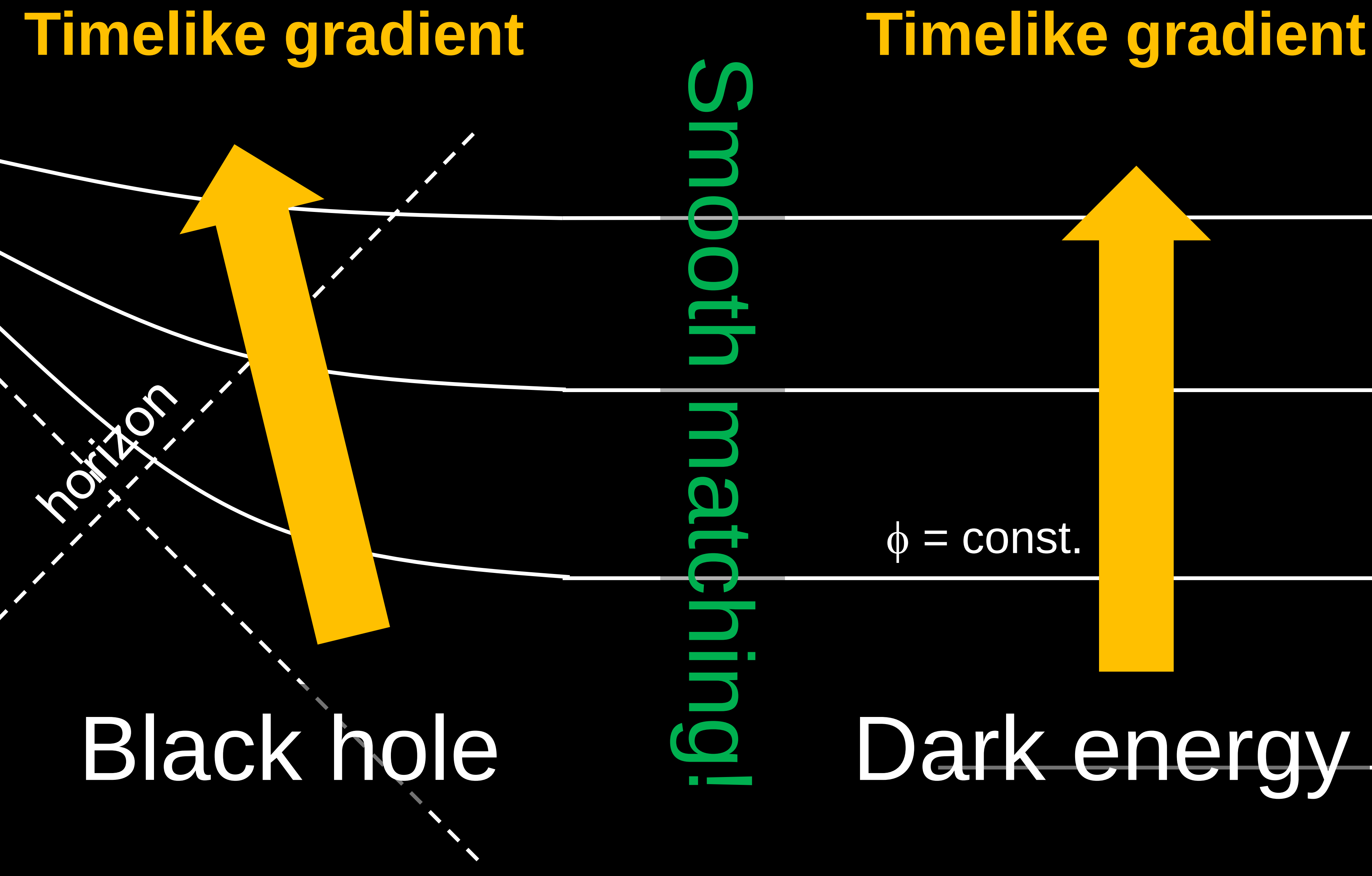


Taylor expansion around $X=X_{DE}>0$
$(\alpha_1, \alpha_2, \alpha_3, \ldots)$

Dark energy


Unlucky case
Spacelike gradient
G_n(X)
$X = -g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi$
EFT2
$(\beta_1, \beta_2, \beta_3, \ldots)$
Black hole
No direct relation between EFT1 & EFT2
Timelike gradient
G_n(X)
$X = -g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi$
EFT1
$(\alpha_1, \alpha_2, \alpha_3, \ldots)$
Dark energy

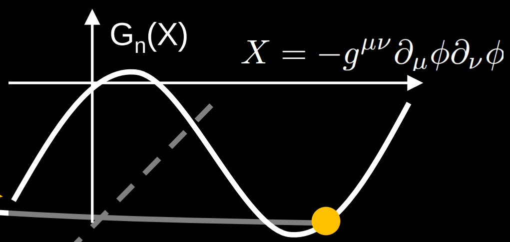
Lucky case



Timelike gradient
Timelike gradient
Smooth matching!
horizon
ϕ = const.
Black hole
Dark energy

Lucky case

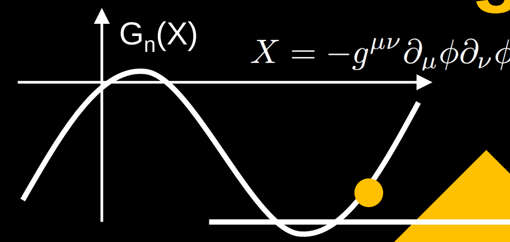
Timelike gradient



Taylor expansion around $X=X_{BH}>0$ $(\alpha'_1, \alpha'_2, \alpha'_3, \ldots)$

Black hole

Timelike gradient

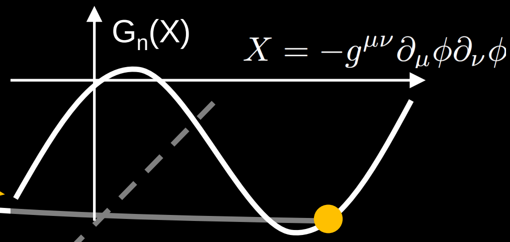


Taylor expansion around $X=X_{DE}>0$ $(\alpha_1, \alpha_2, \alpha_3, \ldots)$

Dark energy

Lucky case

Timelike gradient

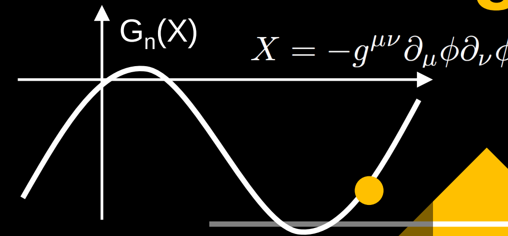


EFT

$(\alpha_1(t,\mathbf{x}^i),\ \alpha_2(t,\mathbf{x}^i),\ \alpha_3(t,\mathbf{x}^i),\ldots)$

Black hole

Timelike gradient



EFT

$(\alpha_1(t,\mathbf{x}^i),\ \alpha_2(t,\mathbf{x}^i),\ \alpha_3(t,\mathbf{x}^i),\ldots)$

Dark energy

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- In cosmology a time-dependent scalar field can act as dark energy (DE), while BHs serve as probes of strong gravity. We then hope to learn something about the EFT of DE by BHs.
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EFT of scalar-tensor gravity with timelike scalar profile

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

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

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

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

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

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]
- Even-parity perturbation around spherical BH
  [work in progress w/ K.Takahashi & V.Yingcharoenrat]
- Tidal Love number of spherical BH
  [work in progress w/ C.GharibAliBarura & H.Kobayashi & N.Oshita & K.Takahashi & V.Yingcharoenrat]
- Future works include Rotating BH, BH with scalar accretion [c.f. arXiv:1304.6287 by Chadburn & Gregory; arXiv:1804.03462 by Gregory, Kastor & Traschen], BH formation, etc…

Summary

- 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.
- If we want to learn something about the EFT of DE from BH then we need to consider BH solutions with timelike scalar profile.
- EFT of scalar-tensor gravity with timelike scalar profile on arbitrary background was developed. Consistency relations among EFT coefficients ensure the spatial diffeo invariance. Applicable to BHs with scalar field DE.

Thank you!

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K.Tomikawa

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