Probing Dark Energy with Black Holes

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MARIE CURIE ACTIONS

FZU Fyzikální ústav Akademie věd České republiky

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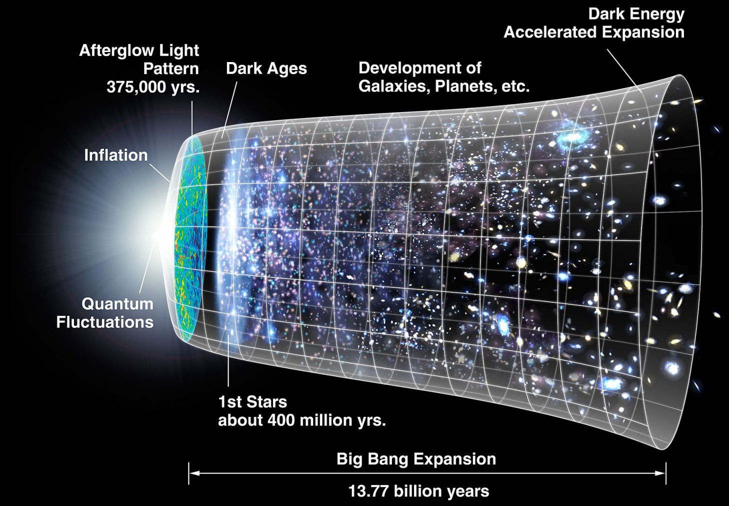
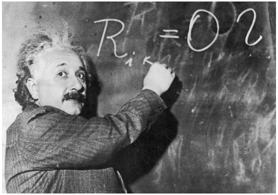
Seminar of Division of Elementary Particle Physics of Institute of Physics

Prague - November 20th, 2025


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years

Brief history of Λ

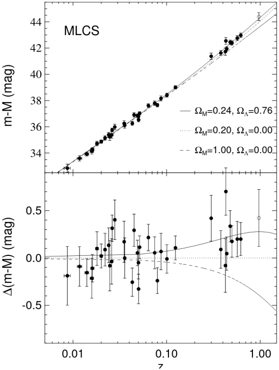


$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

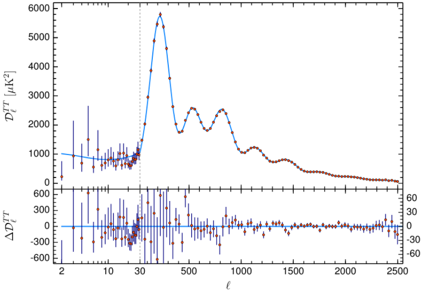
1915	Einstein's equations of General Relativity (without Λ)
1917	Einstein adds Λ to make the Universe static and eternal ("Biggest Blunder")
1927-29	Lemaître proposes an expanding Universe based on Hubble's observations. Confirmed by Hubble (so no Λ is needed)
1998	Riess, Perlmutter teams using measurements of supernovae find the expansion is accelerating (Λ again)

Nobel Prize 2011

ΛCDM cosmology



Riess et al. (1998), Perlmutter et al. (1999)

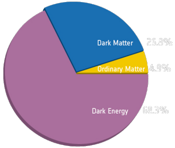


Planck (2013)

Cosmological constant as Dark Energy

$$T_{\mu\nu}^{\mathrm{DE}} = -\Lambda \frac{c^4}{8\pi G} g_{\mu\nu}$$

Perfect fluid: $\boxed{\rho = -p}$



68-73 %
Dark Energy

Cosmological constant problem

Origin of Λ?

Quantum Field Theory

Vacuum energy:

$$\langle T_{\mu\nu} \rangle \sim g_{\mu\nu} \sum_i m_i^4$$

Standard Model particles:

$$\Lambda_{\mathsf{QFT}} \sim 10^{50} \Lambda_{\mathsf{obs}}$$

"Worst predicition in the history of science"

Hierarchy problem similar to the Higgs mass

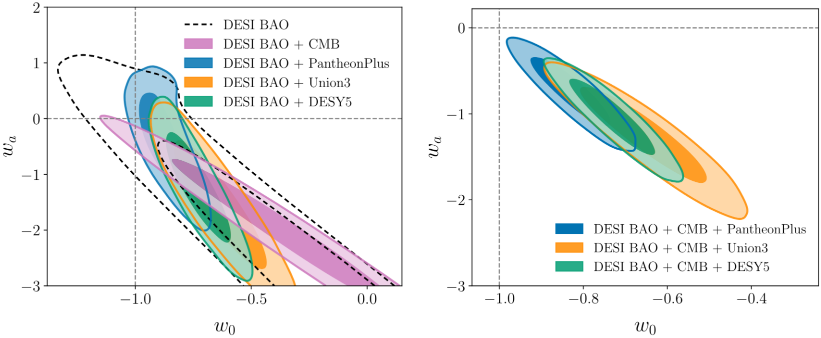
For this talk: We will assume this problem is resolved by some yet "unknown" physics, and that instead Dark Energy is not related to Λ

Dynamical Dark Energy?

DE equation of state:

$$\rho = \omega p$$

$$\omega(a) = \omega_0 + \omega_a(1-a)$$



DESI (2024)

Currently: $2.8 - 3.5\sigma$

Dynamical Dark Energy

We may consider the expansion to be driven by a single new light degree of freedom

With no single 'best- motivated' proposal at hand, it is useful to resort to the maximally model-independent EFT approach

Effective Field Theory of Dark Energy

Gubitosi, Piazza, Vernizzi (2012)

Universal description of Dark Energy and Modified Gravity that includes all single-field models. Up to quadratic order in cosmological perturbations

$$
\begin{aligned}
S \quad = \quad & \int d^4x\sqrt{-g}\Big[\frac{M_*^2}{2}f\,{}^{(4)}R - \Lambda - cg^{00} + \frac{m_2^4}{2}(\delta g^{00})^2 \\
& -\frac{m_3^3}{2}\,\delta K\delta g^{00} - m_4^2\delta\mathcal{K}_2 + \frac{\tilde{m}_4^2}{2}\,\delta g^{00}R - \frac{m_5^2}{2}\delta g^{00}\delta\mathcal{K}_2 \\
& -\frac{m_6}{3}\delta\mathcal{K}_3 - \tilde{m}_6\delta g^{00}\delta\mathcal{G}_2 - \frac{m_7}{3}\delta g^{00}\delta\mathcal{K}_3\Big]
\end{aligned}
$$

with M_*, Λ, c, m_2, m_3, m_4, $\tilde{m}_4$, m_5, m_6, $\tilde{m}_6$, m_7 arbitrary functions of time

- Good for making general statements about dynamics of cosmological perturbations

- Not good to study solutions in different contexts (e.g. black holes)

Covariant formulation (Scalar-Tensor theory)

Horndeski (1974)

In $d = 4$ dimensions:

$$\mathcal{L} = \sum_I c_I \mathcal{L}_I$$

Most general scalar-tensor lagrangian with 2-nd order EOM:

$$\begin{aligned} X &= -(\nabla\phi)^2 \\ \phi_\mu &= \partial_\mu \phi \\ \phi_{\mu\nu} &= \nabla_\mu \nabla_\nu \phi \end{aligned}$$

$$\begin{aligned}
\mathcal{L}_2 &= G_2(\phi, X) \\
\mathcal{L}_3 &= G_3(\phi, X)\Box\phi \\
\mathcal{L}_4 &= G_4(\phi, X)R - 2G_{4,X}(\phi, X)\left(\Box\phi^2 - \phi^{\mu\nu}\phi_{\mu\nu}\right) \\
\mathcal{L}_5 &= G_5(\phi, X)G_{\mu\nu}\phi^{\mu\nu} - \frac{1}{3}G_{5,X}(\phi, X)\left(\Box\phi^3 - 3\Box\phi\,\phi_{\mu\nu}\phi^{\mu\nu} + 2\phi_{\mu\nu}\phi^{\mu\sigma}\phi^{\nu}_{\sigma}\right)
\end{aligned}$$

Properties

- Second-order field equations
- Derivative interactions (EFT)
- Nonminimal coupling between ϕ and $g_{\mu\nu}$
- Nonrenormalization (shift-symmetric)

Phenomenology

- Self-accelerating cosmology
- Screening mechanisms
- Modified propagation
- ...

Modified propagation and screening mechanisms

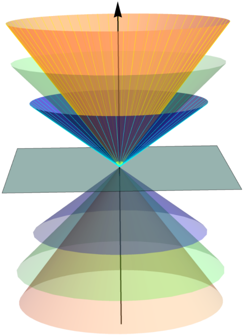
Perturbations $h_{\mu\nu}$ and π on top of nontrivial scalar backgrounds:

$$S_\pi = \int \sqrt{-S} Z^{\mu\nu}(\phi_0)\partial_\mu\pi\partial_\nu\pi$$

Similar for $h_{\mu\nu}$

In general:

- Modified propagation speed
- Kinetic mixing between π and $h_{\mu\nu}$
- Nonlinear regimes $Z \gg 1 \implies$ suppression of scalar interactions



Courtesy: G. Trenkler

Self-accelerating cosmology: Ghost condensate

K-essence:

$$S = M_P^2 \int d^4x \sqrt{-g} \left[\frac{R}{2} + K(X) \right]$$

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

Simple example:

$$K(X) = -X + \frac{c_2 X^2}{M^2} \qquad \text{“wrong” sign}$$

Homogeneous and isotropic Universe

$$ds^2 = -d\tau^2 + a(\tau)^2 \left(d\rho^2 + \rho^2 d\Omega^2 \right) \quad ; \quad \phi = \phi(\tau)$$

Scalar field equation (attractor)

$$\dot\phi \left(-1 + \frac{c_2 \dot\phi^2}{M^2} \right) = 0 \qquad \Longrightarrow \qquad \dot\phi^2 = \frac{M^2}{c_2} \quad \text{(nontrivial solution)}$$

Friedmann equation (without Λ)

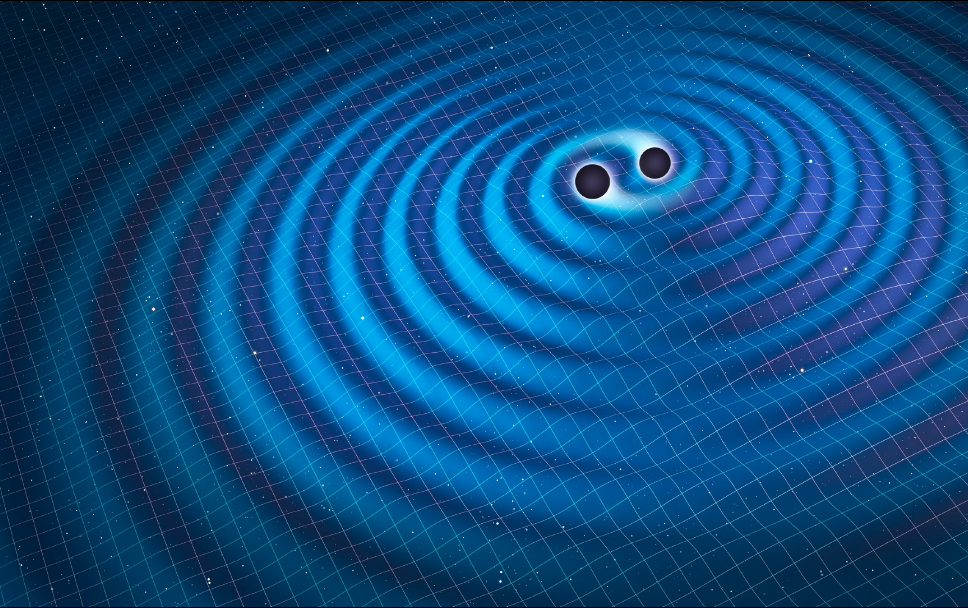
$$3H^2 = -\frac{\dot\phi^2}{2} + \frac{3}{4} \frac{c_2 \dot\phi^4}{M^2} \qquad \Longrightarrow \qquad 12 c_2 H^2 = M^2 \quad ✓$$

with $H = \dot a / a$ is the Hubble parameter

Comments:

- Minkowski (solution for trivial $\dot\phi = 0$) is unstable (ghost). Self accelerating solution is stable
- Full self-acceleration ($\Lambda = 0$) possible for $M \sim H$
- This simple model does not work (strong coupling), but it can be made more complex by including more operators

What can we learn about Dark Energy from observations at shorter scales?

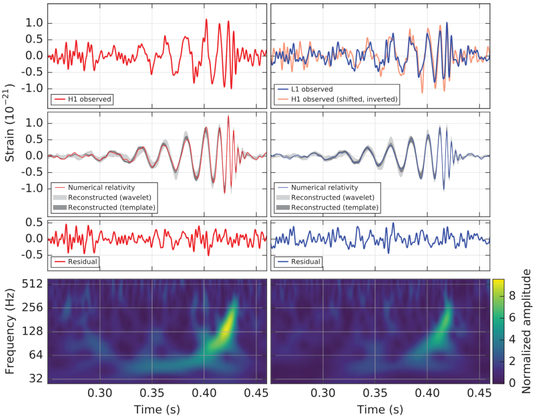


Gravitational waves

Current

LIGO/VIRGO $(10 - 10^2\ M_\odot)$

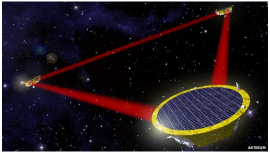
GW150914



LIGO (2016)

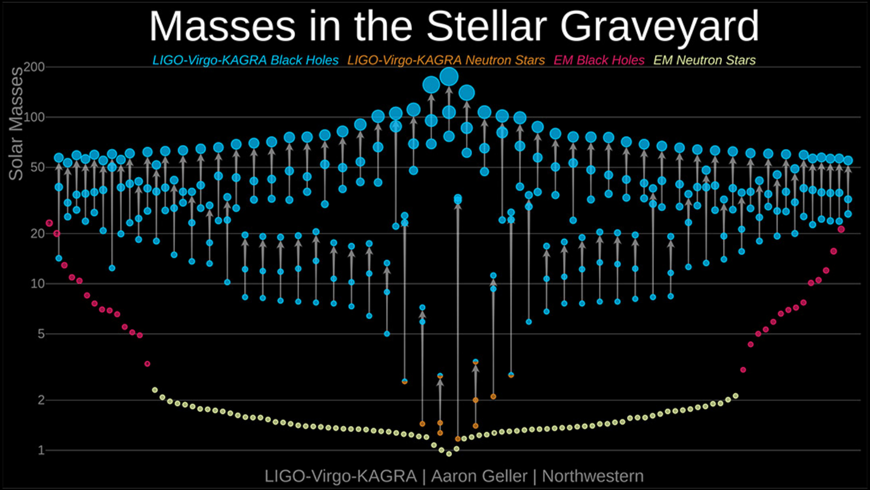
Future

LISA $(10^5 - 10^7\ M_\odot)$



Nobel Prize 2017

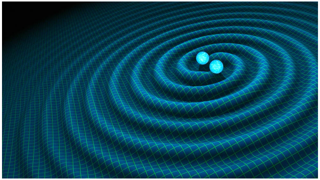
Einstein Telescope, Cosmic Explorer


Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

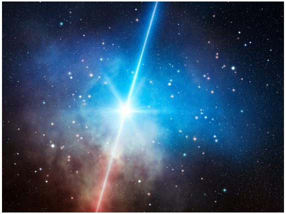
Measurement of the speed of GWs

Simultaneous observations of GWs and Gamma Rays origining from a Neutron Star merger

GW170817 (LIGO/VIRGO)



GRB170817A (Fermi)



- Delay between signals: $\Delta t \simeq 2 sec$
- Distance to the source: $d \sim 130 Mly$
- Main implication:

$$\left| \frac{c_T}{c} - 1 \right| \lesssim 10^{-15}$$

Luminal theories

Creminelli, Vernizzi (2017)
Ezquiaga, Zumalacárregui (2017)
Sakstein, Jain (2017)
Baker, Bellini, Ferreira, Lagos, Noller, Sawicki (2017)

$G_4(X)$ and $G_5(\phi, X)$ affect the speed of propagation of gravitational waves
Surving models:

$$S_{(c_T=1)} = \int d^4x\sqrt{-g}\,[G_4(\phi)R + G_2(X) + G_3(X)\Box\phi]$$

Caveat

- Scale of observations (LIGO frequency band) is very close to the cutoff of the EFT for cosmologically interesting theories ($M_P H^2 \sim 10^3$km^{-1})

Forbidden HD operators

$$\Lambda_2^4 \frac{(\partial\phi)^{2n}}{\Lambda_2^{4n}} \frac{(\nabla\nabla\phi)^m}{\Lambda_{sc}^{3m}}$$

with $m = 2, 3$

For $m = 3$ (G_5) sliding Λ_{sc} a factor 10^3 is enough to pass the constraint. Can still be relevant for physics at shorter scales!

HD operators at shorter scales

1. $\Lambda_{sc} \sim M_P H^2 \implies$ HD operators have $\mathcal{O}(1)$ effects in cosmology.

   Observations of GW speed strongly limit their structure *

2. $\Lambda_{sc} \gg M_P H^2 \implies$ HD operators have negligible effects in cosmology.

   If $\Lambda \gtrsim 10^3 M_P H^2$: Automatic pass of the cosmological constraints.

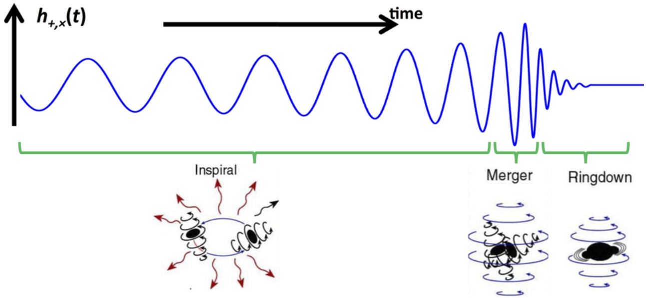
   Other ways to probe the HD operators in scalar-tensor theories of dark energy?

*caveat: $M_P H^2 \sim 10^2$Hz, LIGO band: $10 - 10^4$Hz

Probing HD operators with BHs

Binary black hole mergers

Gravitational waves: $h_{\mu\nu}$



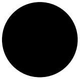
- Inspiral: Scalar wave emission $\implies$ Dephasing
- Merger: ?
- Ringdown: QNM Spectrum

Sensitive to HD operators only around a nontrivial ϕ background

- No-hair theorems severely restrict this possibility

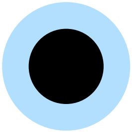
No-hair theorems

GR



M, J, Q

Scalar-Tensor



Q_s

No-hair theorems

Case by case basis

- Bekenstein (1972), Hawking
- Hui, Nicolis (2012): Shift-symmetric Scalar-Tensor theories

Exceptions

- Break shift-symmetry
- Time-dependence
- Special operator: "Scalar-Gauss-Bonnet"
- ...

Two cases

1. Scalar-Gauss-Bonnet

2. Cosmologically induced charges

Sotiriou and Zhou (2014)

1. Scalar-Gauss-Bonnet

$$S = \int d^4x \sqrt{-g} \left(M_P^2 R - \frac{1}{2}(\partial\phi)^2 + \alpha\phi\mathcal{G} \right)$$

$$\mathcal{G} = R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma} - 4R_{\mu\nu}R^{\mu\nu} + R^2$$

- Scalar-field equation:

$$\Box\phi + \alpha\mathcal{G} = 0$$

- Example: Test-field on Schwarzschild background

$$\Box\phi = -\frac{12\alpha\, r_s^2}{r^6}$$

Scalar charge

$$\phi \simeq \frac{Q_s}{r} \qquad \text{as} \quad r \to +\infty$$

Black holes

$$Q_s = \frac{4\alpha}{r_s} \sim \frac{1}{M_{\mathsf{BH}}}$$

Other sources (horizonless)

$$Q_s = 0$$

$\Longrightarrow$ Interesting phenomenological implications

1. Scalar-Gauss-Bonnet

Most studied model (astrophysics)

$$S = \int d^4x \sqrt{-g} \left(M_\mathsf{P}^2 R - \frac{1}{2}(\partial\phi)^2 + \alpha M_\mathsf{P} \phi \, \mathcal{G} \right)$$

- No HD operators
- No screening mechanism
- No direct relation with cosmology and dark energy
- Strongly inhomogeneous solutions in cosmology (Babichev, Sawicki, LT (2024))

More general models

$$S = \int d^4x \sqrt{-g} \left(M_\mathsf{P}^2 R + \Lambda_2^4 \frac{(\partial\phi)^{2n}}{\Lambda_2^{4n}} \frac{(\nabla\nabla\phi)^m}{\Lambda_{sc}^{3m}} + \ldots + \alpha M_\mathsf{P} \phi \, \mathcal{G} \right)$$

$m = 0, 1, 2, 3$

- EFT with cutoff Λ_{sc}
- Provides dark energy: $\Lambda_2 \equiv \sqrt{M_\mathsf{P} H_0}$
- HD operators
- Screening mechanism (Vainshtein)

1. Phenomenology

Noller, Santoni, Trincherini, LT (2019)

Background geometry

Deviations from GR:

$$\varepsilon_0(\phi_0) \sim \frac{\alpha \phi_0 \mathcal{G}}{M_\mathsf{P}^2 \mathcal{R}}$$

Kinetic mixing

$$Z_{mix}(\phi_0)\, \partial\pi\, \partial h$$

- Induces a direct coupling between matter and π: Fifth forces, scalar wave emission, ...

Vainshtein screening

$$Z_\pi(\phi_0)(\partial\pi)^2$$

- Couplings of the scalar are suppressed in regions where $Z_\pi(\phi_0) \gg 1$:

$$\varepsilon_{mix}(\phi_0) \sim \frac{Z_{mix}}{\sqrt{Z_\pi}}$$

<u>Result:</u>

$$\varepsilon_0 \sim \frac{r_s}{r} \varepsilon_{mix}^2 \ll 1$$

1. Phenomenology

Cosmological constraints

Speed of GWs and graviton decay:

$$\Lambda_{sc} \gtrsim 10^3 \Lambda_3$$

Inspiral

Dephasing due to scalar wave emission:

$$\frac{\alpha}{\sqrt{Z_\pi}} \lesssim (2.7\text{km})^2$$

Saturating this bound (optimistic case) $\implies \Lambda_{sc} = \Lambda_{sc}(\alpha, n, m)$

Local constraints

Solar system: Fifth forces (Lunar Laser Ranging):

$$\varepsilon_{mix}(E - M) \lesssim 10^{-10}$$

Estimate of relative correction to QNM frequencies $\varepsilon_{mix}(r \sim r_s)$

m	n	Operator	$\varepsilon_{mix}(r \sim r_s)$	$\varepsilon_{mix}(E - M)$	Λ^{obs}_{min} [km^{-1}]	Λ^{pos}_{min} [km^{-1}]	α [km^2]
0	1	X	10^{-1}	3×10^{-21}	3×10^3	10^2	10
0	2	X^2	10^{-3}	10^{-11}	10	10^2	10^9
1	1	XZ	10^{-3}	10^{-13}	10	10^2	3×10^9
1	2	X^2Z	3×10^{-4}	3×10^{-10}	1	10^2	3×10^{12}
2	1	XZ^2	3×10^{-4}	10^{-10}	1	10^2	3×10^{14}

$Z = \nabla\nabla\phi/\Lambda^3$

1. Explicit construction of solutions

Lara, Trenkler, LT (Work in progress)

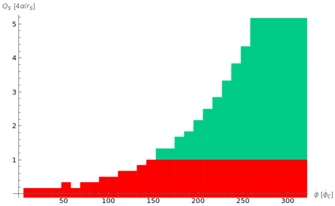
K-essence and Scalar-Gauss-Bonnet

$$S = M_P^2 \int d^4x \sqrt{-g} \left[\frac{R}{2} + K(X) + \alpha\phi\,\mathcal{G} \right]$$

$$K(X) = -X + \frac{c_2 X^2}{M^2}$$

Test-field approximation

Numerical solutions



(preliminary)

- Real stable solutions (no ghost) exist for large enough $\dot\phi$ and Q_s
- Q_s may now take a continuum of values
- Separation of scales increases strength of screening but also the minimal value of $\dot\phi$ for real solutions. Inhomogeneity problem?

1. Open questions

- More complete stability analysis (gradient instabilities)
- Beyond test-field approximation (backreaction)
- Confirm the order-of-magnitude estimates
- More general cosmologies ($G_3(X)$, $G_4(X)$)
- More general HD operators ($G_4(X)$, $G_5(X)$)

2. Cosmologically induced charges

Babichev, Esposito-Farèse, Sawicki, LT (2025)

Subclass of Horndeski

$$
\begin{aligned}
S \quad = \quad & M_{\mathsf{P}}^2 \int \sqrt{-g}\, d^4x \Big\{ \frac{R}{2} - \Lambda_{\mathsf{bare}} + G_2(X) + G_3(X)\Box\varphi + G_5(X) G^{\mu\nu}\varphi_{\mu\nu} \\
& - \frac{1}{3} G_5'(X) \Big[(\Box\varphi)^3 - 3\,\Box\varphi\,\varphi_{\mu\nu}\varphi^{\mu\nu} + 2\,\varphi_{\mu\nu}\varphi^{\nu\rho}\varphi_{\rho}{}^{\mu} \Big] \Big\}
\end{aligned}
$$

"Linear" $G_i(X)$ functions:

$$
\begin{aligned}
G_2(X) &= k_2 X \\
G_3(X) &= \frac{k_3}{M^2} X \\
G_5(X) &= \frac{k_5}{M^4} X
\end{aligned}
$$

Self-accelerating solutions: $k_2 < 0$

2. Cosmologically induced charges

Schwarzschild-de Sitter metric

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

where

$$f(r) = 1 - \frac{r_S}{r} - (Hr)^2.$$

Stationary solution for a test scalar field

$$\varphi = \dot{\varphi}_{\mathrm{BH}}\, t + \varphi(r)$$

with $\dot{\varphi}_{\mathrm{BH}} = \text{const.}$ Scalar-field equation:

$$\partial_r \left(r^2 J^r \right) = 0$$

with solution

$$\frac{J^r}{M_{\mathrm{Pl}}^2} = \frac{\alpha_{\mathrm{BH}} r_S}{r^2},$$

where α_{BH} is the black-hole scalar charge. For our model:

$$\begin{aligned}
\frac{J^r}{M_{\mathrm{Pl}}^2} &= A\varphi'^2 + B\varphi' + C, \\
A &= \frac{f}{M^2}\left[\left(\frac{4f}{r} + f'\right)k_3 + \frac{3f-1}{(Mr)^2} f' k_5\right], \\
B &= 2fk_2, \\
C &= -\left[k_3 + \frac{f-1}{(Mr)^2}k_5\right]\frac{f'\dot{\varphi}_{\mathrm{BH}}^2}{fM^2}. \qquad \Longrightarrow \text{source term!}
\end{aligned}$$

generalization to $k_5 \neq 0$ of Babichev & Esposito-Farèse (2012) for NS

2. Accretion

Energy-density flux [Babichev, Charmousis, Hassaine (2015)]

$$T^r{}_t = -\dot{\varphi}_{\mathsf{BH}}\, J^r|_{r=r_S}$$

Mass change

$$\frac{dm}{dt} = \frac{M_{\mathsf{Pl}}^2}{2}\frac{dr_S}{dt} = M_{\mathsf{Pl}}^2 r_S |\dot{\varphi}_{\mathsf{BH}}\alpha_{\mathsf{BH}}|$$

Characteristic time of the black hole mass change $\Gamma_{\mathsf{acc}}^{-1}$:

$$\Gamma_{\mathsf{acc}} \sim |\dot{\varphi}_{\mathsf{BH}}\, \alpha_{\mathsf{BH}}|$$

Possible scenarios

1. *Small accretion rate:* Accretion rate $\Gamma_{\mathsf{acc}} \lesssim H$ for

$$\dot{\varphi}_{\mathsf{BH}} \approx \dot{\varphi}_c$$

$\Longrightarrow$ The evolution of the black hole is effectively already frozen

- This is the scenario for the pure cubic Galileon model ($k_5 = 0$)

2. *Quenched accretion:* Large accretion rate $\Gamma_{\mathsf{acc}} \gg H$ for $\dot{\varphi}_{\mathsf{BH}} = \dot{\varphi}_c \Longrightarrow$ The black hole accretes scalar field until $\Gamma_{\mathsf{acc}} \sim H$, freezing at

$$\dot{\varphi}_{\mathsf{BH}} \ll \dot{\varphi}_c$$

- This is the scenario for sufficiently small black holes when a quintic Horndeski operator is present

2. Cosmologically induced charges

Pure cubic

$k_5 = 0$

$$\begin{aligned} \dot{\varphi}_{\mathrm{BH}} &= \dot{\varphi}_c \times \left[1 + \frac{3}{2}\sqrt{3}Hr_S + \mathcal{O}\left(H^2 r_S^2\right)\right] \\ \alpha_{\mathrm{BH}} &= \frac{1}{3k_3}\left(\frac{k_2 M}{H}\right)^2 \left[1 + \frac{15}{4}\sqrt{3}Hr_S + \mathcal{O}\left(H^2 r_S^2\right)\right] \end{aligned}$$

Pure quintic

$k_3 = 0$

$$\begin{aligned} |\dot{\varphi}_{\mathrm{local}}| &\gtrsim \left(\frac{9HM^4 r_S^2}{8|k_5|}\right)^{1/3} \\ |\alpha_{\mathrm{BH}}| &\gtrsim 2\left(\frac{|k_5|H^2}{9M^4 r_S^2}\right)^{1/3} \end{aligned}$$

Note: No self-acceleration

Cubic plus small quintic

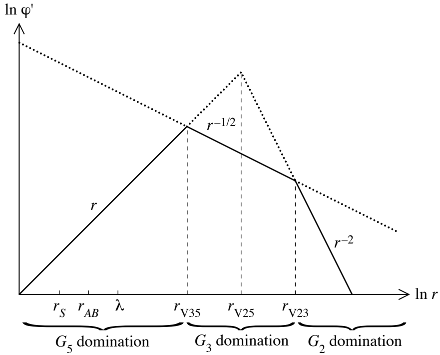
$(Hr_S)^2 \ll \left|\frac{k_5}{k_3}\right| \left(\frac{H}{M}\right)^2 \ll Hr_S$

$$\begin{aligned} |\dot{\varphi}_{\mathrm{local}}| &\gtrsim \left(\frac{9HM^4 r_S^2}{8|k_5|}\right)^{1/3} \\ |\alpha_{\mathrm{BH}}| &\gtrsim 2\left(\frac{|k_5|H^2}{9M^4 r_S^2}\right)^{1/3} \end{aligned}$$

Self-acceleration provided by k_3 (full for $M \sim H$)

2. Screening mechanism

Nonlinear regime where HD operators dominate at short distances



Vainshtein radii

$$r_{V35}^3 = \frac{|k_5| r_S}{2|k_3| M^2}$$

$$r_{V25}^3 = \frac{\sqrt{|k_5 \alpha_{\mathsf{BH}}|}\, r_S}{\sqrt{2}|k_2| M^2}$$

$$r_{V23}^3 = \frac{|k_3 \alpha_{\mathsf{BH}}| r_S}{k_2^2 M^2}$$

Effective metric

$$Z_3^{tt}(r) \sim |k_2| \left(\frac{r_{V23}}{r}\right)^{3/2}$$

$$Z_5^{tt}(r) \sim |k_2| \left(\frac{r_{V25}}{r}\right)^{3}$$

2. Observational consequences

Energy flux

$$F_{\text{scalar}} = \frac{F^{\text{dipole}}_{\text{scalar}}}{z_{\lambda,1}} + \frac{F^{\text{quadrupole}}_{\text{scalar}}}{z_{\lambda,2}}$$

$$F^{\text{dipole}}_{\text{scalar}} \approx \frac{1}{48G|k_2|}\left(\frac{r_S}{r_{AB}}\right)^4 \left(\alpha^{\text{eff}}_A - \alpha^{\text{eff}}_B\right)^2$$

$$F^{\text{quadrupole}}_{\text{scalar}} \approx \frac{1}{15G|k_2|}\left(\frac{r_S}{r_{AB}}\right)^5 \alpha^{\text{eff}}_A \alpha^{\text{eff}}_B$$

LIGO/Virgo

$$\frac{F^{\text{dipole}}_{\text{scalar}}/z_{\lambda,1}}{F_{\text{GR}}} < 10^{-3}$$

$$\frac{F^{\text{quadrupole}}_{\text{scalar}}/z_{\lambda,2}}{F_{\text{GR}}} < 5 \times 10^{-2}$$

LISA:

$$\frac{F_{\text{scalar}}}{F_{\text{GR}}} \lesssim 3 \times 10^{-7}$$

Screening suppression

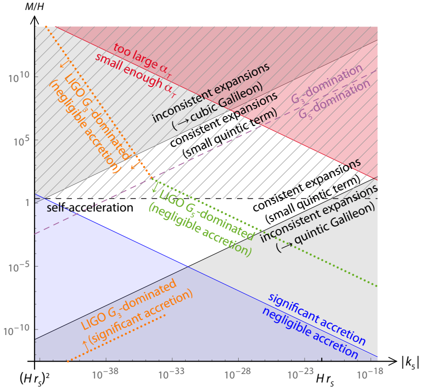
Dar, De Rham, Deskins, Giblin, Tolley (2018)

$$z^{\text{cubic}}_{\lambda,\ell} \approx \frac{1}{4}\left(\Omega_{\text{p}} r_{AB}\right)^{3-\ell}\left(\Omega_{\text{p}} r_{V23}\right)^{3/2}$$

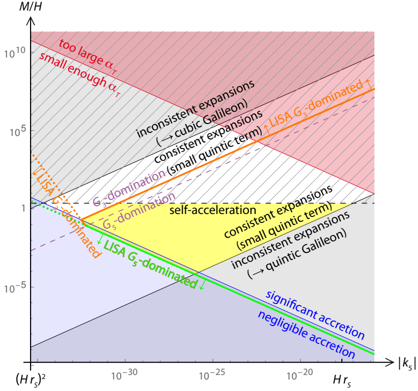
$$z^{\text{quintic}}_{\lambda} \sim \left(\Omega_{\text{p}} r_{V25}\right)^3$$

2. Observational consequences

LIGO/Virgo



LISA



LISA: improvement of the constraint on G_5 by 10^{16} w.r.t the one from $c_T = 1$

2. Open questions

- Stability analysis
- Beyond test-field approximation
- Quenched accretion: Numerical relativity simulations are required to validate assumption about the endstate of evolution (very hard)
- More general operators beyond "linear" class

Conclusions

- Dark Energy is a crucial ingredient for describing the observed Universe at cosmological scales. There are increasing hints to its dynamical nature
- Dark Energy can be effectively considered as a new light degree of freedom that couples non-minimally to gravity (modified gravity). It is better described as an Effective Field Theory
- Interesting phenomenological effects such as modified propagation, screening mechanisms and black-hole scalar charges, open the window for probing the physics of Dark Energy at shorter scales. Especially the rapidly growing field of gravitational-wave observations offers great promise
- Many challenges remain in producing robust predictions beyond the simplest models