Effective models for dynamical scalarization

Raissa F. P. Mendes

Universidade Federal Fluminense

Centro Brasileiro de Pesquisas Físicas

Based on:

M. Khalil, R. Mendes, N. Ortiz, J. Steinhoff, *PDR* ***106***, *104016 (2022)*

- Testing General Relativity
- Limitations of the pN expansion: the rise of nonperturbative effects
- Accommodating nonperturbative effects: pK, pD & all that
- Effective action approach to dynamical scalarization
- Going beyond the adiabatic approximation

- Testing General Relativity
- Limitations of the pN expansion: the rise of nonperturbative effects
- Accommodating nonperturbative effects: pK, pD & all that
- Effective action approach to dynamical scalarization
- Going beyond the adiabatic approximation

Testing General Relativity

Testing General Relativity

- Tests of basic principles of a (metric) theory of gravity
  - Universality of free fall
  - Local Lorentz invariance
  - Local position invariance

Testing General Relativity

- Tests of basic principles of a (metric) theory of gravity
  - Universality of free fall
  - Local Lorentz invariance
  - Local position invariance


PHYSICAL REVIEW LETTERS

Highlights Recent Accepted Collections Authors Referees Search Press

Featured in Physics Editors' Suggestion

MICROSCOPE Mission: First Results of a Space Test of the Equivalence Principle

Pierre Touboul et al.

Phys. Rev. Lett. **119**, 231101 – Published 4 December 2017

Physics See Synopsis: Space Tests of the Equivalence Principle

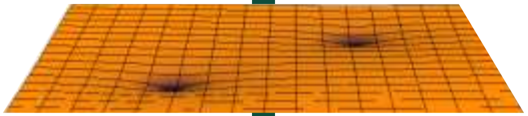
MicroSCOPE - CNES

Testing General Relativity

- Tests of basic principles of a (metric) theory of gravity
  - Universality of free fall
  - Local Lorentz invariance
  - Local position invariance

- Tests in the post-Newtonian regime
  - *Parametrized post-Newtonian (PPN) formalism*

$$\phi/c^2 = GM/Rc^2 \ll 1, \qquad v/c \ll 1$$



$$\begin{aligned} g_{00} = &-1 + 2U - 2\beta U^2 - 2\xi\Phi_W + (2\gamma + 2 + \alpha_3 + \zeta_1 - 2\xi)\Phi_1 + 2(3\gamma - 2\beta + 1 + \zeta_2 + \xi)\Phi_2 \\ &+ 2(1 + \zeta_3)\Phi_3 + 2(3\gamma + 3\zeta_4 - 2\xi)\Phi_4 - (\zeta_1 - 2\xi)A - (\alpha_1 - \alpha_2 - \alpha_3)w^2U - \alpha_2 w^i w^j U_{ij} \\ &+ (2\alpha_3 - \alpha_1)w^i V_i + O(\epsilon^3) \end{aligned}$$

$$g_{0i} = -\frac{1}{2}(4\gamma + 3 + \alpha_1 - \alpha_2 + \zeta_1 - 2\xi)V_i - \frac{1}{2}(1 + \alpha_2 - \zeta_1 + 2\xi)W_i - \frac{1}{2}(\alpha_1 - 2\alpha_2)w^i U - \alpha_2 w^j U_{ij} + O(\epsilon^{2.5})$$

$$g_{ij} = (1 + 2\gamma U)\delta_{ij} + O(\epsilon^2)$$

Testing General Relativity

- Tests of basic principles of a (metric) theory of gravity
  - Universality of free fall
  - Local Lorentz invariance
  - Local position invariance

- Tests in the post-Newtonian regime
  - *Parametrized post-Newtonian (PPN) formalism*

$$\phi/c^2 = GM/Rc^2 \ll 1, \qquad v/c \ll 1$$

Parameter	Effect	Limit	Remarks
$\gamma - 1$	time delay	2.3×10^{-5}	Cassini tracking
	light deflection	4×10^{-4}	VLBI
$\beta - 1$	perihelion shift	3×10^{-3}	$J_2 = 10^{-7}$ from helioseismology
	Nordtvedt effect	2.3×10^{-4}	$\eta_N = 4\beta - \gamma - 3$ assumed
ξ	Earth tides	10^{-3}	gravimeter data
α_1	orbital polarization	10^{-4}	Lunar laser ranging
		2×10^{-4}	PSR J2317+1439
α_2	spin precession	4×10^{-7}	solar alignment with ecliptic
α_3	pulsar acceleration	4×10^{-20}	pulsar $\dot{P}$ statistics
η_N	Nordtvedt effect	9×10^{-4}	lunar laser ranging
ζ_1	—	2×10^{-2}	combined PPN bounds
ζ_2	binary acceleration	4×10^{-5}	$\ddot{P}_p$ for PSR 1913+16
ζ_3	Newton's 3rd law	10^{-8}	lunar acceleration
ζ_4	—	—	not independent (see Equation (58))

Table 4: *Current limits on the PPN parameters. Here η_N is a combination of other parameters given by $\eta_N = 4\beta - \gamma - 3 - 10\xi/3 - \alpha_1 + 2\alpha_2/3 - 2\zeta_1/3 - \zeta_2/3$.*

Will (2006)

Testing General Relativity

- Tests of basic principles of a (metric) theory of gravity
  - Universality of free fall
  - Local Lorentz invariance
  - Local position invariance

- Tests in the post-Newtonian regime
  - *Parametrized post-Newtonian (PPN) formalism*

$$\phi/c^2 = GM/Rc^2 \ll 1, \qquad v/c \ll 1$$

BepiColombo
ESA/JAXA

Parameter	Effect	Limit	Remarks
$\gamma - 1$	time delay	2.3×10^{-5}	Cassini tracking
	light deflection	4×10^{-4}	VLBI
$\beta - 1$	perihelion shift	3×10^{-3}	$J_2 = 10^{-7}$ from helioseismology
	Nordtvedt effect	2.3×10^{-4}	$\eta_N = 4\beta - \gamma - 3$ assumed
ξ	Earth tides	10^{-3}	gravimeter data
α_1	orbital polarization	10^{-4}	Lunar laser ranging
		2×10^{-4}	PSR J2317+1439
α_2	spin precession	4×10^{-7}	solar alignment with ecliptic
α_3	pulsar acceleration	4×10^{-20}	pulsar $\dot{P}$ statistics
η_N	Nordtvedt effect	9×10^{-4}	lunar laser ranging
ζ_1	—	2×10^{-2}	combined PPN bounds
ζ_2	binary acceleration	4×10^{-5}	$\ddot{P}_p$ for PSR 1913+16
ζ_3	Newton's 3rd law	10^{-8}	lunar acceleration
ζ_4	—	—	not independent (see Equation (58))

Table 4: *Current limits on the PPN parameters. Here η_N is a combination of other parameters given by $\eta_N = 4\beta - \gamma - 3 - 10\xi/3 - \alpha_1 + 2\alpha_2/3 - 2\zeta_1/3 - \zeta_2/3$.*

Will (2006)

Testing General Relativity

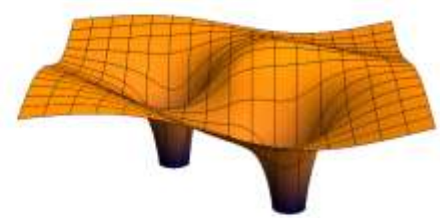
- Tests of basic principles of a (metric) theory of gravity
  - Universality of free fall
  - Local Lorentz invariance
  - Local position invariance

- Tests in the post-Newtonian regime
  - *Parametrized post-Newtonian (PPN) formalism*

$\phi/c^2 = GM/Rc^2 \ll 1, \qquad v/c \ll 1$

- Tests in the "strong gravity" regime
  - Black holes $\phi/c^2 \sim 0.5$
  - Neutron stars $\phi/c^2 \sim 0.2 - 0.3$

$v/c \ll 1$



$v/c \lesssim 1$

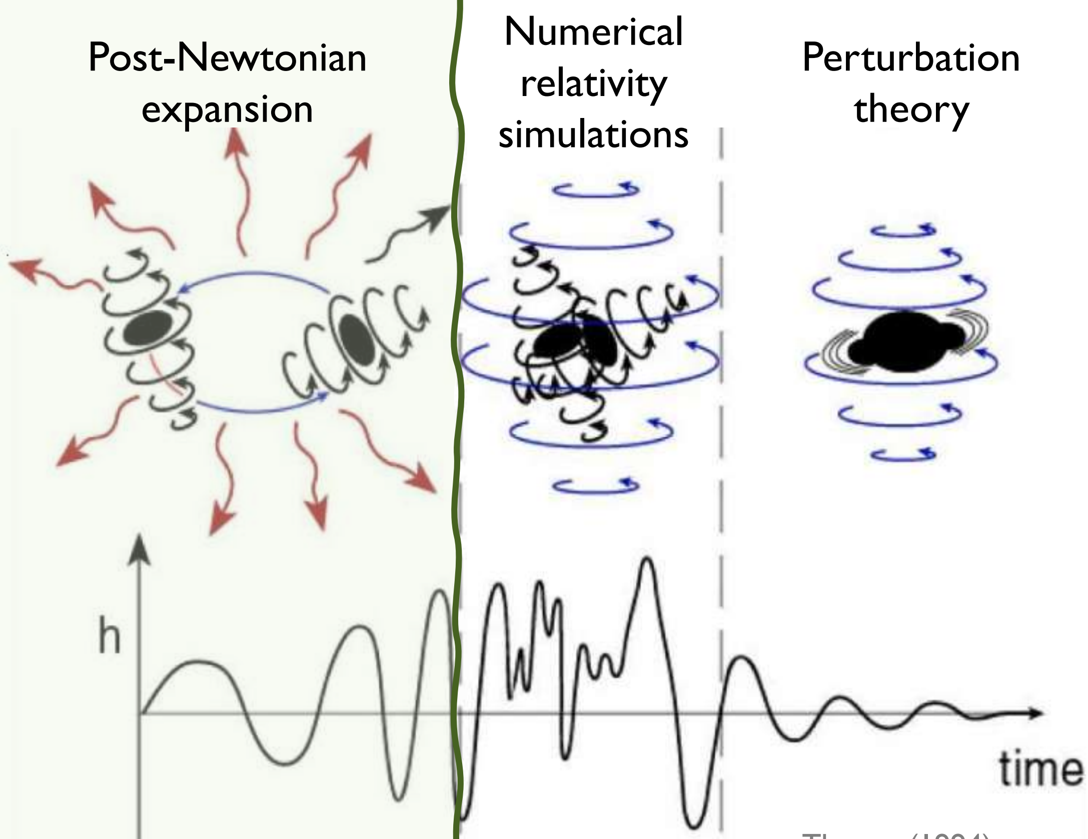
- Tests in the radiative regime

- Testing General Relativity
- Limitations of the pN expansion: the rise of nonperturbative effects
- Accommodating nonperturbative effects: pK, pD & all that
- Effective action approach to dynamical scalarization
- Going beyond the adiabatic approximation

Post-Newtonian expansion

Small parameters:

$$\underbrace{\frac{v^2}{c^2}, \frac{GM}{rc^2}}_{\text{slowly moving}} \ll 1 \qquad \underbrace{\frac{v_{int}^2}{c^2}, \frac{GM}{Rc^2}}_{\text{weakly gravitating}} \ll 1$$



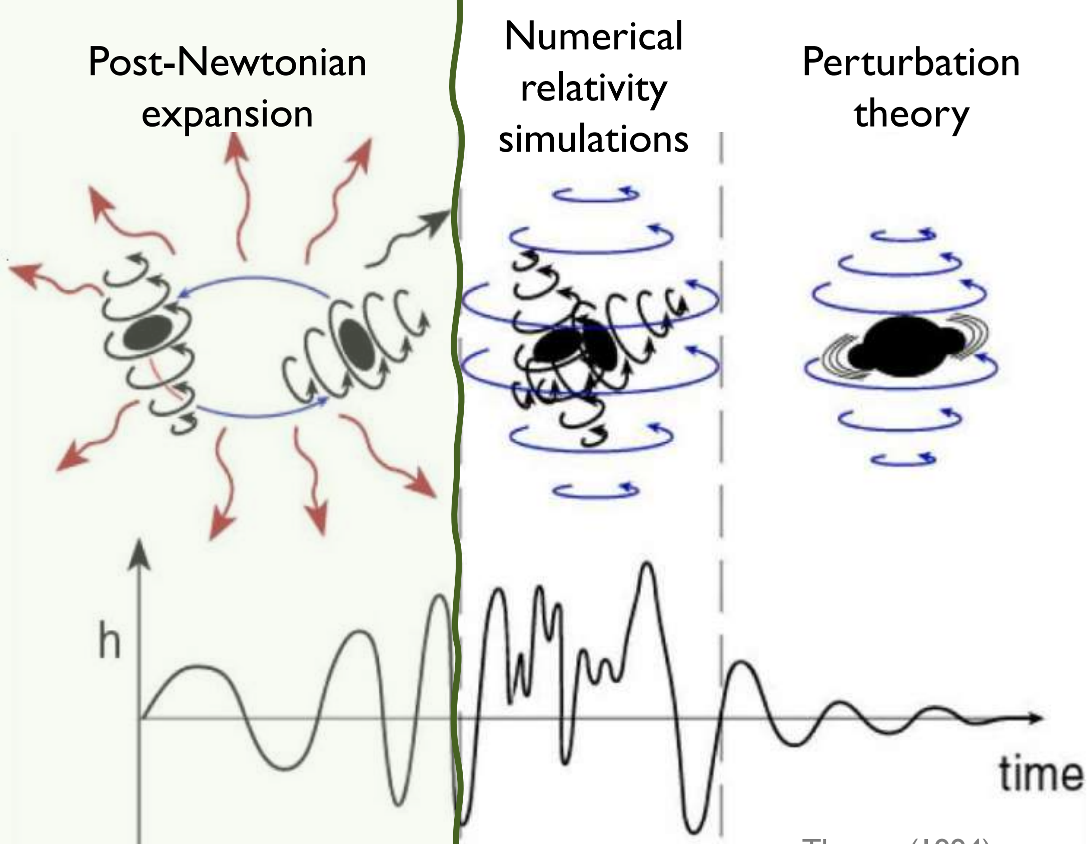
Thorne (1994)

Post-Newtonian expansion

Small parameters:

$$\underbrace{\frac{v^2}{c^2}, \frac{GM}{rc^2}}_{\text{slowly moving}} \ll 1 \qquad \underbrace{\frac{v_{int}^2}{c^2}, \frac{GM}{Rc^2}}_{\text{weakly gravitating}} \ll 1$$

- Wider applicability in GR due to the Strong Equivalence Principle!



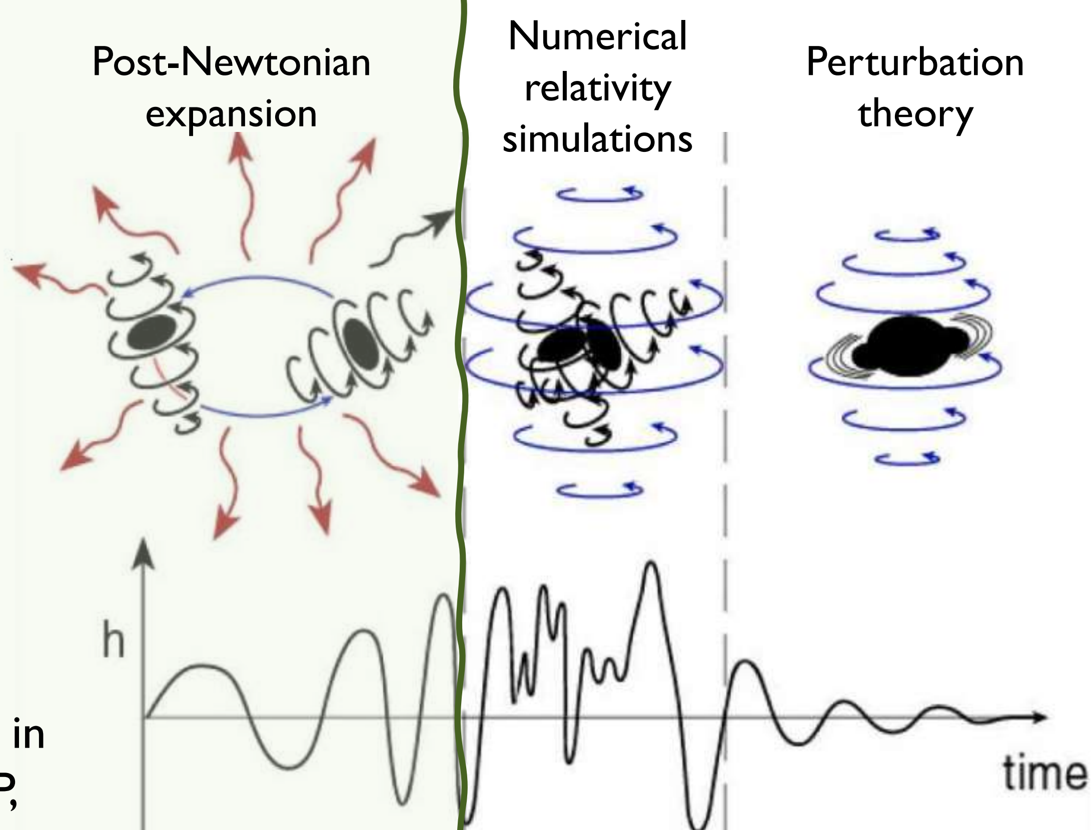
Thorne (1994)

Post-Newtonian expansion

Small parameters:

$$\underbrace{\frac{v^2}{c^2}, \frac{GM}{rc^2} \ll 1}_{\text{slowly moving}} \qquad \underbrace{\frac{v_{int}^2}{c^2}, \frac{GM}{Rc^2} \ll 1}_{\text{weakly gravitating}}$$

- Wider applicability in GR due to the Strong Equivalence Principle!
- Modified theories of gravity in general do not obey the SEP, even allowing for non-perturbative strong field effects!



Thorne (1994)

Case study: Scalar-tensor theories

$$S = \frac{1}{16\pi G}\int d^4x\,\sqrt{-g}\left[R - 2g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi\right] + S_m[\Psi_m; \underbrace{a(\phi)^2 g_{\mu\nu}}]$$

Universal coupling to
"physical" metric
$\tilde{g}_{\mu\nu} = a(\phi)^2 g_{\mu\nu}$

See also: Doneva et al. (2022), "Scalarization"

Case study: Scalar-tensor theories

$$S = \frac{1}{16\pi G}\int d^4x\,\sqrt{-g}\left[R - 2g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi\right] + S_m\Big[\Psi_m;\underbrace{a(\phi)^2 g_{\mu\nu}}\Big]$$

Universal coupling to "physical" metric $\tilde{g}_{\mu\nu} = a(\phi)^2 g_{\mu\nu}$

- For a system of N non-self-gravitating point particles:

$$S_m = -\sum_{A=1}^{N}\int \tilde{m}_A d\tilde{s}_A = -\sum_{A=1}^{N}\int \tilde{m}_A\sqrt{-\tilde{g}_{\mu\nu}(x_A)dx_A^\mu x_A^\nu}$$

$$S_m = -\sum_{A=1}^{N}\int \underbrace{\tilde{m}_A a(\phi(x^A))}_{m_A(\phi(x^A))} ds_A = -\sum_{A=1}^{N}\int m_A(\phi(x^A))ds_A$$

Effective coupling:

$$\alpha(\phi) = \frac{d\ln a(\phi)}{d\phi} = \frac{d\ln m(\phi)}{d\phi}$$

Case study: Scalar-tensor theories

$$S = \frac{1}{16\pi G}\int d^4x\,\sqrt{-g}\left[R - 2g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi\right] + S_m\left[\Psi_m; \underbrace{a(\phi)^2 g_{\mu\nu}}\right]$$

Universal coupling to "physical" metric
$\tilde{g}_{\mu\nu} = a(\phi)^2 g_{\mu\nu}$

- For a system of N self-gravitating point particles, Eardley (1975) suggests skeletonizing the action as

$$S_m = -\sum_{A=1}^{N}\int \tilde{m}_A(\phi)d\tilde{s}_A = -\sum_{A=1}^{N}\int m_A(\phi)ds_A$$

field dependent binding energy

Body-dependent effective coupling:

$$\alpha_A(\phi) = \frac{d\ln m_A(\phi)}{d\phi}$$

* See also Damour and Esposito-Farèse (1992)

Case study: Scalar-tensor theories

- Let: $\Phi = \left(g_{\mu\nu} - f_{\mu\nu}, \phi - \phi_0\right)$

  σ : matter variables

- Total action: $S_{tot}^{GF}[\sigma, \Phi] = \underbrace{S_{\Phi}^{GF}[\Phi]}_{S_{\Phi}[\Phi] + \text{GF terms}} + S_m[\sigma, \Phi]$

$$\boxed{\begin{gathered} \frac{\delta S_{tot}^{GF}}{\delta \Phi} = \frac{\delta S_{\Phi}}{\delta \Phi} + \frac{\delta S_m}{\delta \Phi} = 0 \\ \frac{\delta S_{tot}^{GF}}{\delta \sigma} = \frac{\delta S_m}{\delta \sigma} = 0 \end{gathered}}$$

Following Damour & Esposito-Farèse (1996)

Case study: Scalar-tensor theories

- Let: $\Phi = \left(g_{\mu\nu} - f_{\mu\nu}, \phi - \phi_0\right)$

  σ : matter variables

- Total action: $S_{tot}^{GF}[\sigma, \Phi] = \underbrace{S_{\Phi}^{GF}}_{S_\Phi[\Phi] + \text{GF terms}}[\Phi] + S_m[\sigma, \Phi]$

- Strategy:

$$\frac{\delta S_{tot}^{GF}}{\delta \Phi} = 0 \quad \Longrightarrow \quad \bar{\Phi}[\sigma]$$

solve perturbatively!

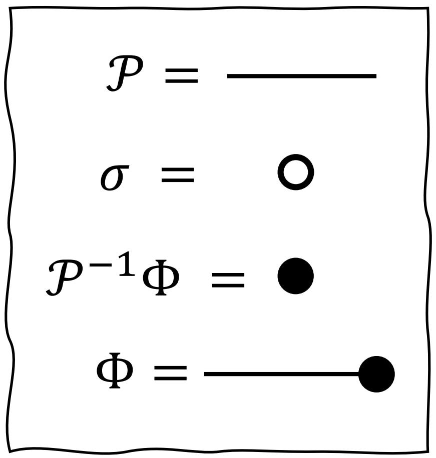
- Fokker action:

$$\boxed{S_{\mathrm{F}}[\sigma] = S_{tot}^{GF}[\sigma, \bar{\Phi}[\sigma]]}$$

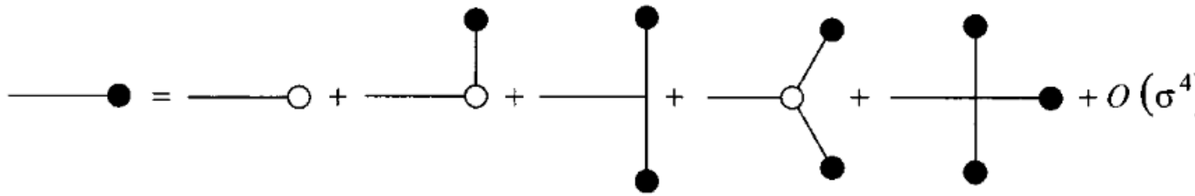
Following Damour & Esposito-Farèse (1996)

Case study: Scalar-tensor theories

Following Damour & Esposito-Farèse (1996)

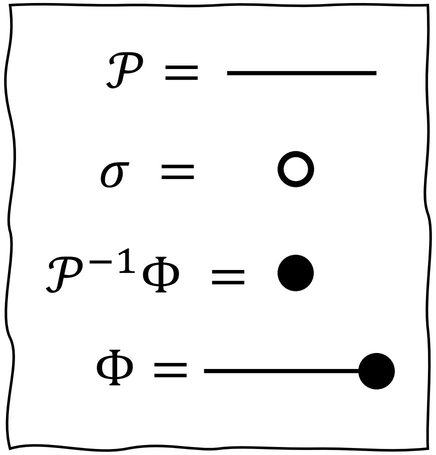


$$1. \quad \frac{\delta S_{tot}^{GF}}{\delta \Phi} = 0 \quad \Longrightarrow \quad \bar{\Phi}[\sigma]$$

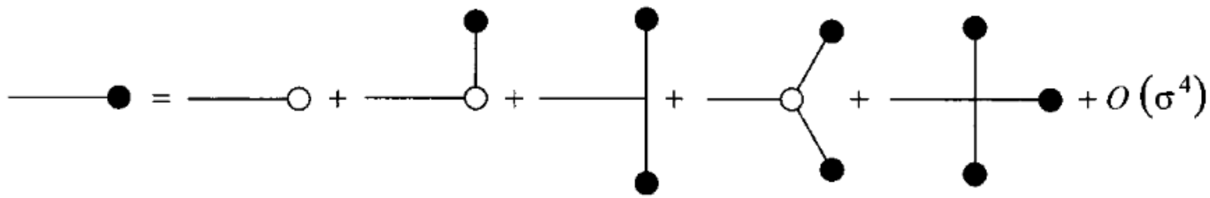


Case study: Scalar-tensor theories

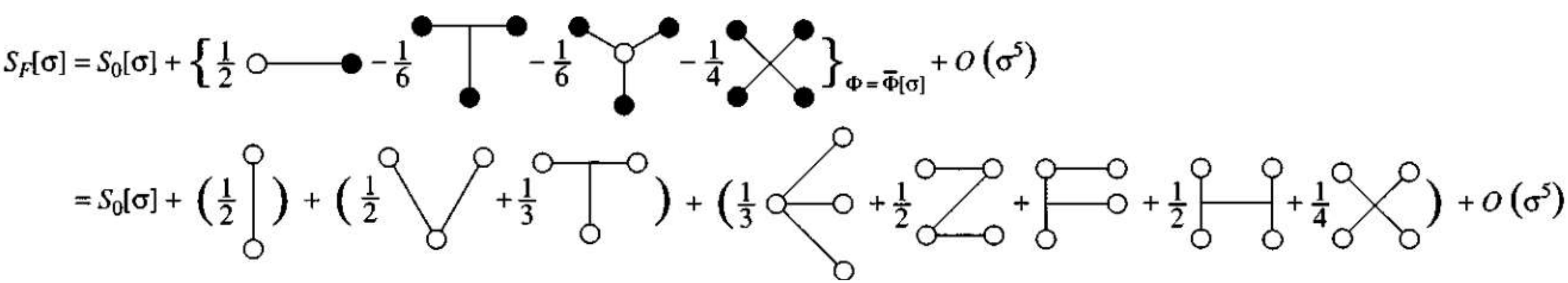
Following Damour & Esposito-Farèse (1996)



1. $\dfrac{\delta S^{GF}_{tot}}{\delta \Phi} = 0 \quad \Longrightarrow \quad \bar{\Phi}[\sigma]$



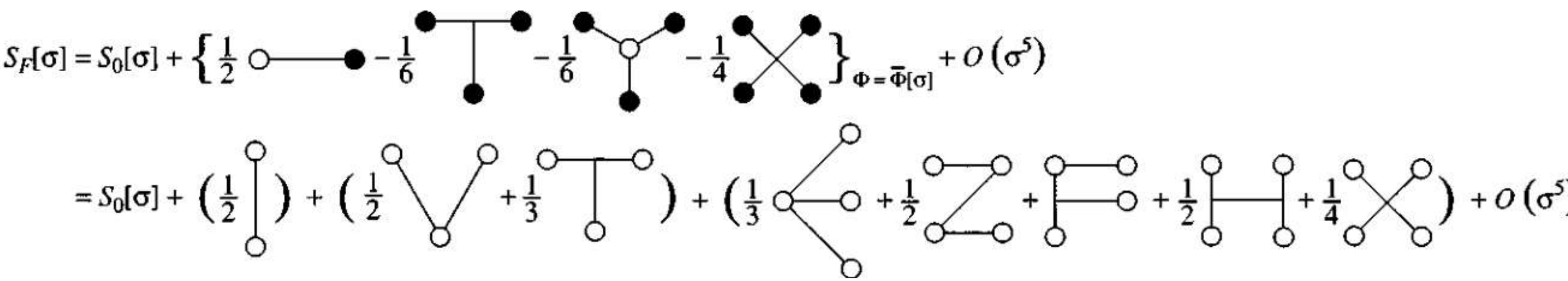
2. $S_{\mathrm{F}}[\sigma] = S^{GF}_{tot}[\sigma, \bar{\Phi}[\sigma]]$



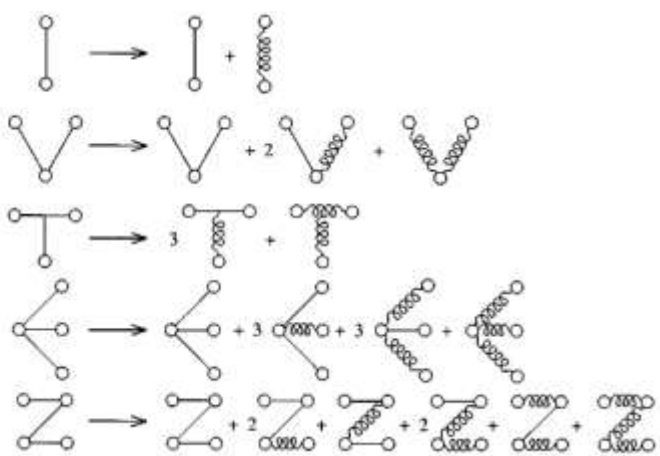
Case study: Scalar-tensor theories

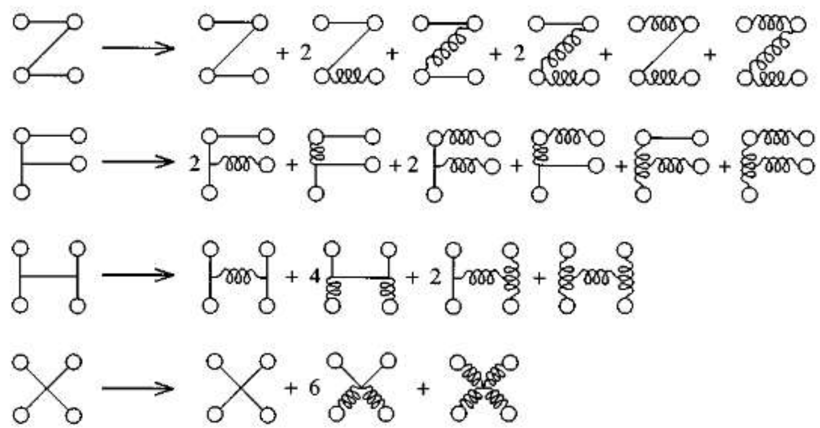
Following Damour & Esposito-Farèse (1996)

2. $S_{\mathrm{F}}[\sigma] = S^{GF}_{tot}[\sigma, \bar{\Phi}[\sigma]]$



3. Spin-0,2 propagators:



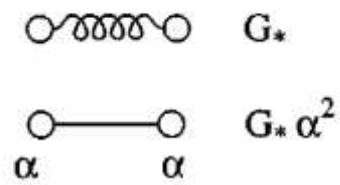


4. Expansion in $v/c, GM/Rc^2$

Case study: Scalar-tensor theories

- Newtonian limit:

$$G_{AB} = G[1 + (\alpha_A \alpha_B)_0]$$

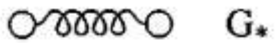


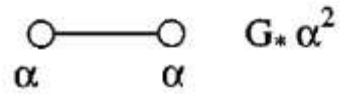
$$\alpha_{A0} = \alpha_A(\phi_0) = \frac{d \ln m_A(\phi)}{d\phi}\Big|_{\phi=\phi_0}$$

Case study: Scalar-tensor theories

- Newtonian limit:

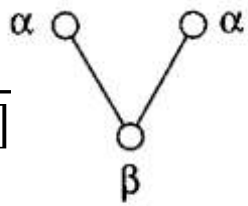
$$G_{AB} = G[1 + (\alpha_A \alpha_B)_0]$$





- 1PN parameters:

$$\bar{\gamma}_{AB} = -\frac{2(\alpha_A \alpha_B)_0}{1 + (\alpha_A \alpha_B)_0}, \qquad \bar{\beta}^A_{BC} = \frac{1}{2} \frac{(\alpha_B \beta_A \alpha_C)_0}{[1 + (\alpha_A \alpha_B)_0][1 + (\alpha_A \alpha_C)_0]}$$

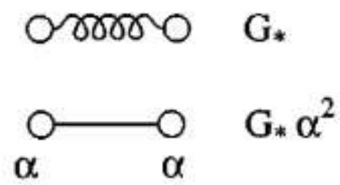


$$\beta_{A0} = \frac{d\alpha_A}{d\phi}\Big|_{\phi_0}$$

Case study: Scalar-tensor theories

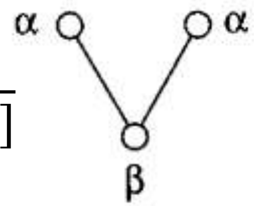
- Newtonian limit:

$$G_{AB} = G[1 + (\alpha_A \alpha_B)_0]$$



- 1PN parameters:

$$\bar{\gamma}_{AB} = -\frac{2(\alpha_A \alpha_B)_0}{1 + (\alpha_A \alpha_B)_0}, \qquad \bar{\beta}^A_{BC} = \frac{1}{2}\frac{(\alpha_B \beta_A \alpha_C)_0}{[1 + (\alpha_A \alpha_B)_0][1 + (\alpha_A \alpha_C)_0]}$$

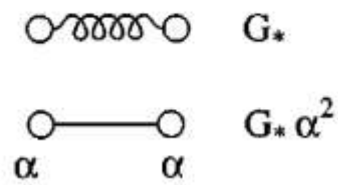


- 2PN parameters: $\epsilon^A_{BCD}, \zeta_{ABCD}$

Case study: Scalar-tensor theories

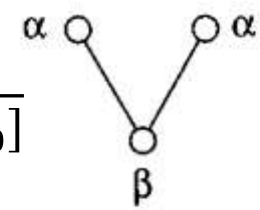
- Newtonian limit:

$$G_{AB} = G[1 + (\alpha_A \alpha_B)_0]$$



- 1PN parameters:

$$\bar{\gamma}_{AB} = -\frac{2(\alpha_A\alpha_B)_0}{1 + (\alpha_A\alpha_B)_0}, \qquad \bar{\beta}^A_{BC} = \frac{1}{2}\frac{(\alpha_B\beta_A\alpha_C)_0}{[1 + (\alpha_A\alpha_B)_0][1 + (\alpha_A\alpha_C)_0]}$$



- 2PN parameters: $\epsilon^A_{BCD}, \zeta_{ABCD}$
- For any PN order: corrections proportional to α_{A0}^2.

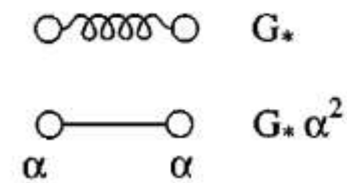
constant if non-self-gravitating

$$\alpha_{A0} = \alpha_A(\phi_0) = \frac{d\ln m_A(\phi)}{d\phi}\bigg|_{\phi=\phi_0} = \frac{d\ln[\widetilde{m_A}(\phi)a(\phi)]}{d\phi}\bigg|_{\phi=\phi_0}$$

Case study: Scalar-tensor theories

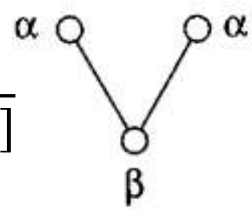
- Newtonian limit:

$$G_{AB} = G[1 + (\alpha_A \alpha_B)_0]$$



- 1PN parameters:

$$\bar{\gamma}_{AB} = -\frac{2(\alpha_A \alpha_B)_0}{1 + (\alpha_A \alpha_B)_0}, \qquad \bar{\beta}^A_{BC} = \frac{1}{2}\frac{(\alpha_B \beta_A \alpha_C)_0}{[1 + (\alpha_A \alpha_B)_0][1 + (\alpha_A \alpha_C)_0]}$$



- 2PN parameters: $\epsilon^A_{BCD}, \zeta_{ABCD}$
- For any PN order: corrections proportional to α_{A0}^2.

constant if non-self-gravitating

$$\alpha_{A0} = \alpha_A(\phi_0) = \frac{d \ln m_A(\phi)}{d\phi}\bigg|_{\phi=\phi_0} = \frac{d \ln[\widetilde{m_A}(\phi) a(\phi)]}{d\phi}\bigg|_{\phi=\phi_0}$$

Expand in $C_A = \frac{G m_A}{R_A c^2}$:

$$\alpha_{A0} = \alpha_0[1 + A_1 C_A + A_2 C_A^2 + \cdots]$$

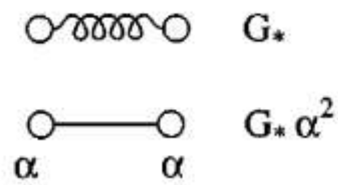
$$\alpha_0 = d \ln a(\phi) / d\phi \Big|_{\phi_0}$$

(Damour & Esposito-Farèse, 1992)

Case study: Scalar-tensor theories

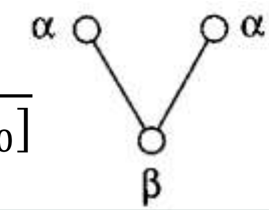
- Newtonian limit:

$$G_{AB} = G[1 + (\alpha_A \alpha_B)_0]$$



- 1PN parameters:

$$\bar{\gamma}_{AB} = -\frac{2(\alpha_A \alpha_B)_0}{1 + (\alpha_A \alpha_B)_0}, \qquad \bar{\beta}^A_{BC} = \frac{1}{2}\frac{(\alpha_B \beta_A \alpha_C)_0}{[1 + (\alpha_A \alpha_B)_0][1 + (\alpha_A \alpha_C)_0]}$$



- 2PN parameters: $\epsilon^A_{BCD}, \zeta_{ABCD}$
- For any PN order: corrections proportional to α_{A0}^2.

This seems to imply that a theory with $\alpha_0 = 0$ would be indistinguishable from GR to any PN order.

$$\alpha_{A0} = \alpha_A(\phi_0) = \frac{d \ln m_A(\phi)}{d\phi}\bigg|_{\phi=\phi_0} = \frac{d \ln[\widetilde{m_A}(\phi) a(\phi)]}{d\phi}\bigg|_{\phi=\phi_0}$$

Expand in $C_A = \frac{G m_A}{R_A c^2}$: $\qquad \alpha_{A0} = \alpha_0[1 + A_1 C_A + A_2 C_A^2 + \cdots]$

$$\alpha_0 = d \ln a(\phi) / d\phi \Big|_{\phi_0}$$

(Damour & Esposito-Farèse, 1992)

Case study: Scalar-tensor theories

- Limitation of the post-Newtonian expansion:

  Non-perturbative effects make it inappropriate to expand

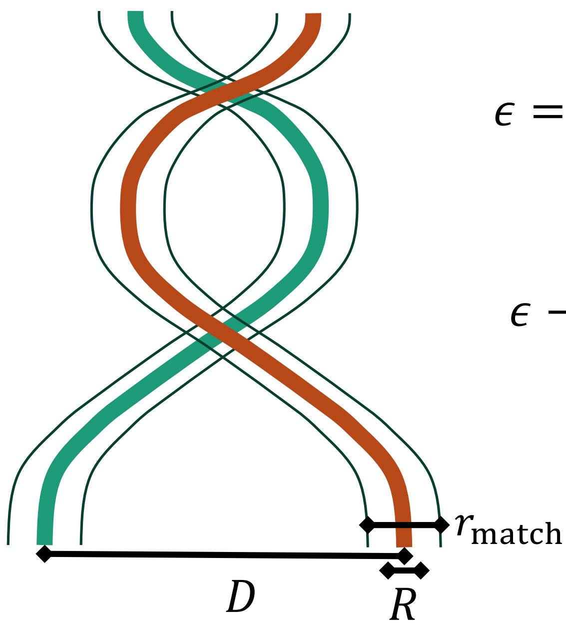
$$\alpha_{A0} = \alpha_0[1 + A_1 C_A + A_2 C_A^2 + \cdots]$$

Case study: Scalar-tensor theories

- Limitation of the post-Newtonian expansion:

  Non-perturbative effects make it inappropriate to expand

$$\alpha_{A0} = \alpha_0[1 + A_1 C_A + A_2 C_A^2 + \cdots]$$



$$\epsilon = \frac{R}{r_{\text{match}}} = \frac{r_{\text{match}}}{D} \ll 1$$

inner problem

$$\epsilon \to 0: \begin{cases} r_{\text{match}} \to \infty \text{ when measured in units of } R \\ r_{\text{match}} \to 0 \text{ when measured in units of } D \end{cases}$$

outer problem

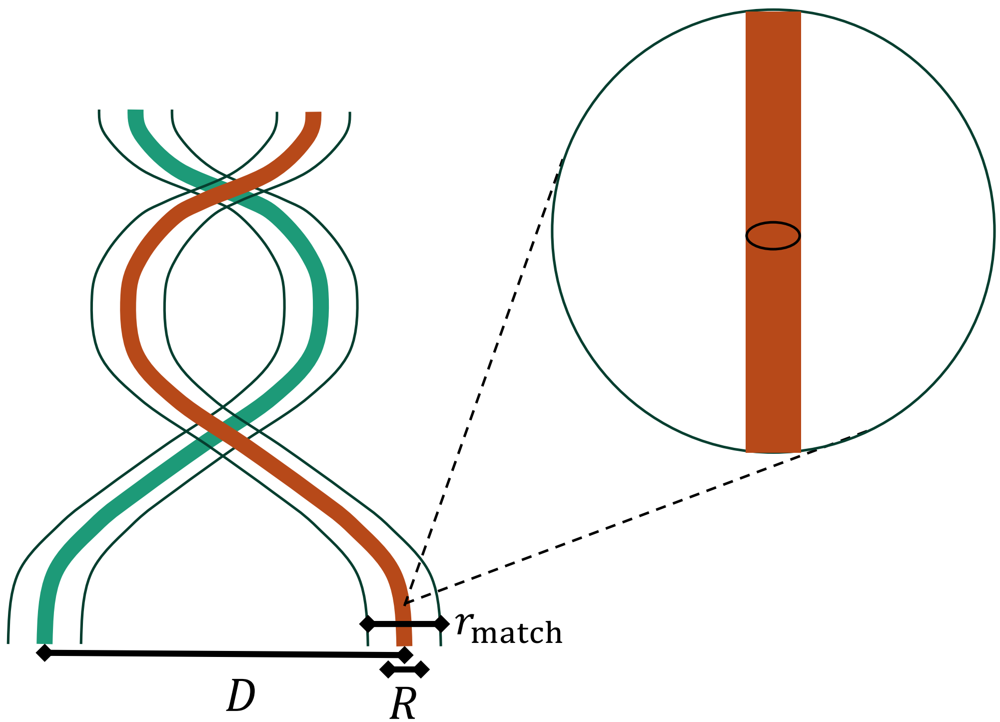
[Damour & Esposito-Farèse (1992)]

Case study: Scalar-tensor theories

- Limitation of the post-Newtonian expansion:

  Non-perturbative effects make it inappropriate to expand

$$\alpha_{A0} = \alpha_0[1 + A_1 C_A + A_2 C_A^2 + \cdots]$$



<u>Inner problem:</u>

Solve the TOV-like equations of hydrostatic equilibrium with BC

$$g_{\mu\nu} \xrightarrow{r \to r_{\text{match}}} \hat{g}_{\mu\nu} = f_{\mu\nu}$$

$$\phi \xrightarrow{r \to r_{\text{match}}} \hat{\phi}$$

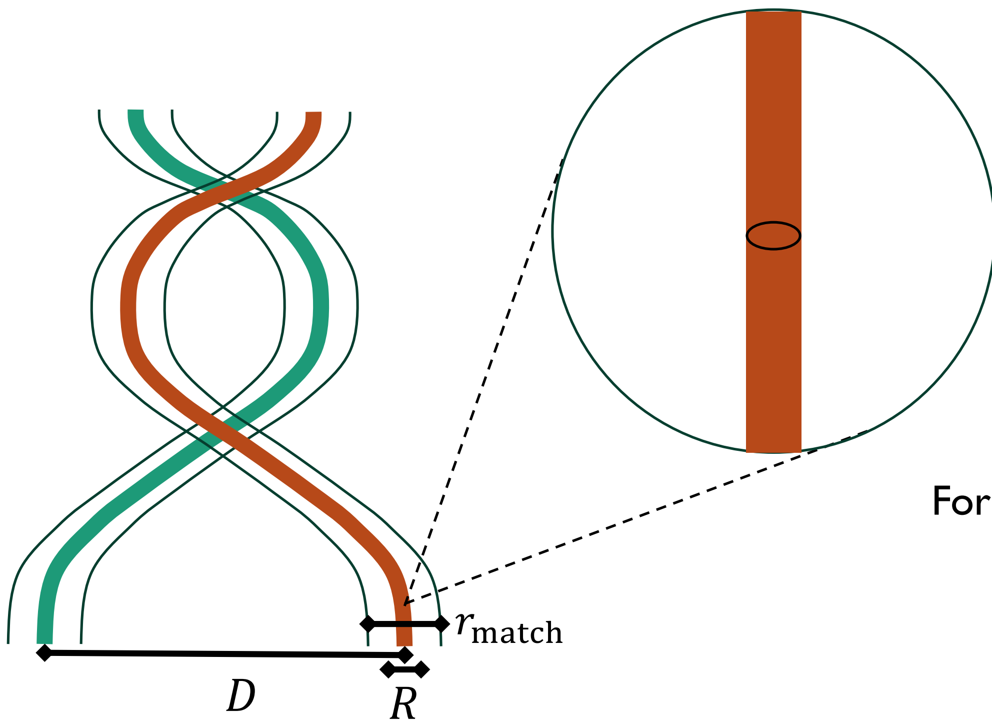
[Damour & Esposito-Farèse (1992)]

Case study: Scalar-tensor theories

- Limitation of the post-Newtonian expansion:

  Non-perturbative effects make it inappropriate to expand

$$\alpha_{A0} = \alpha_0[1 + A_1 C_A + A_2 C_A^2 + \cdots]$$



Inner problem:
Solve the TOV-like equations of hydrostatic equilibrium with BC

$$g_{\mu\nu} \xrightarrow{r\to r_{\text{match}}} \hat{g}_{\mu\nu} = f_{\mu\nu}$$
$$\phi \xrightarrow{r\to r_{\text{match}}} \hat{\phi}$$

For $r/R \gg 1$:

$$g_{\mu\nu} = f_{\mu\nu} + \frac{2Gm_A(\hat{\phi})}{rc^2}\delta_{\mu\nu} + \cdots$$
$$\phi = \hat{\phi} - \frac{Gm_A(\hat{\phi})\alpha_A(\hat{\phi})}{rc^2} + \cdots$$

[Damour & Esposito-Farèse (1992)]

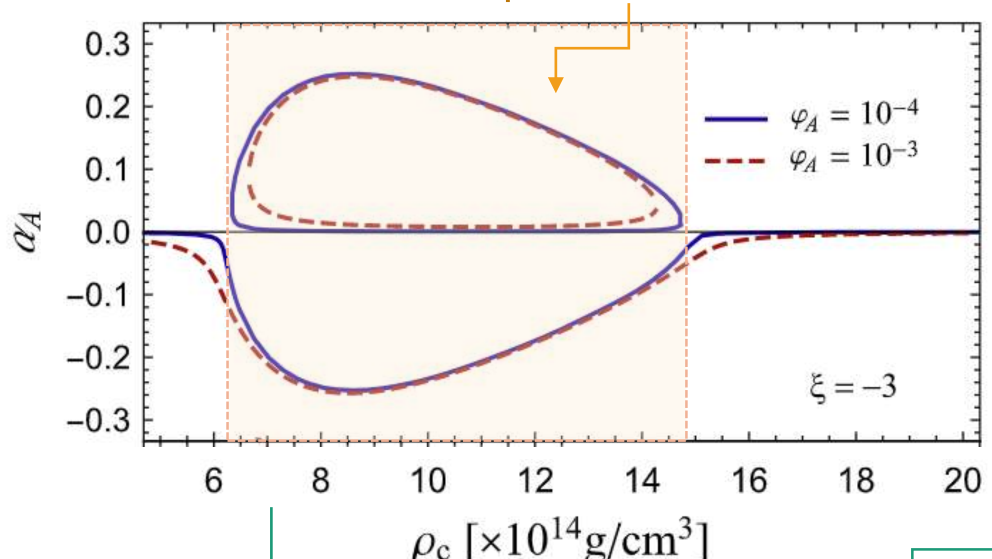
Case study: Scalar-tensor theories

- Limitation of the post-Newtonian expansion:

  Non-perturbative effects make it inappropriate to expand

$$\alpha_{A0} = \alpha_0[1 + A_1 C_A + A_2 C_A^2 + \cdots]$$

spontaneous scalarization



$$\boxed{\alpha_0 = 2\xi\phi_0 + O(\phi_0)^2}$$

For a nonminimally coupled scalar field, with coupling $\xi R \Phi^2$

[R. Mendes & T. Ottoni (2019)]

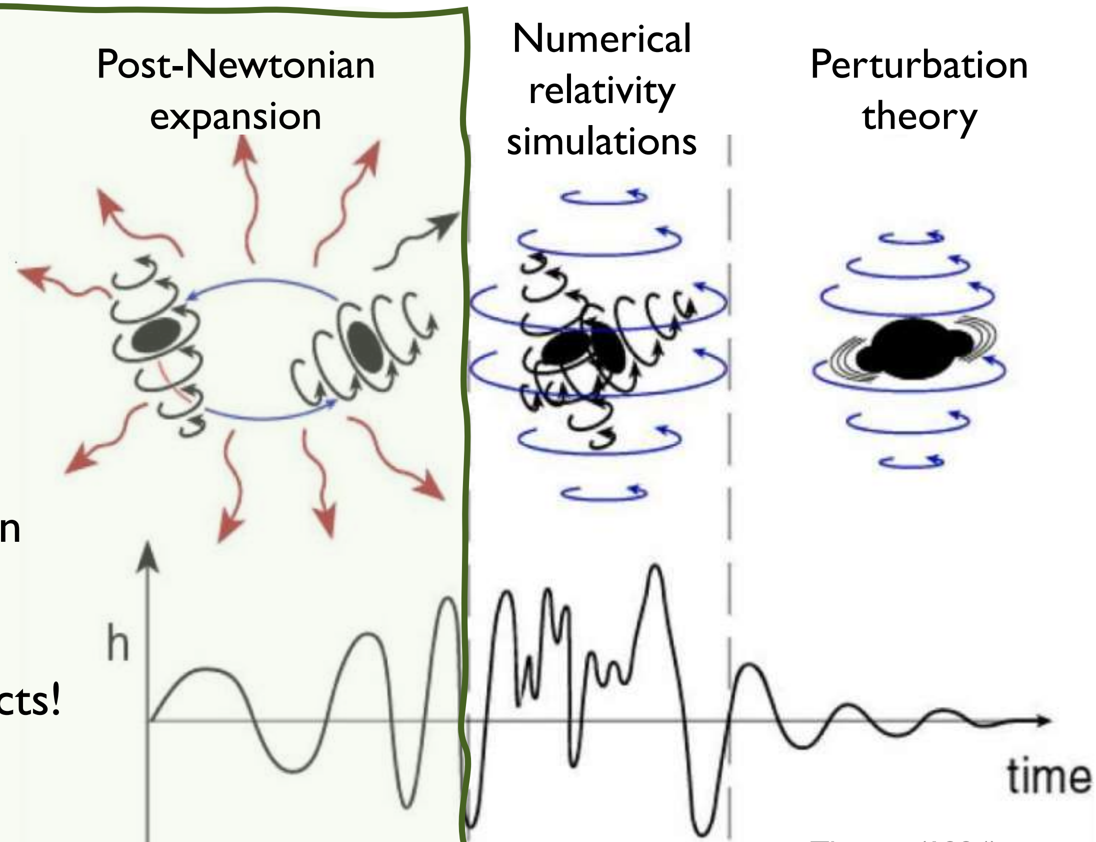
- Testing General Relativity
- Limitations of the pN expansion: the rise of nonperturbative effects
- Accommodating nonperturbative effects: pK, pD & all that
- Effective action approach to dynamical scalarization
- Going beyond the adiabatic approximation

Post-Keplerian expansion

PN: Small parameters:

$$\underbrace{\frac{v}{c}, \frac{GM}{rc^2} \ll 1}_{\text{slowly moving}} \qquad \underbrace{\frac{v_{int}}{c}, \frac{GM}{Rc^2} \ll 1}_{\text{weakly gravitating}}$$

- Modified theories of gravity in general do not obey the SEP, even allowing for non-perturbative strong field effects!



Thorne (1994)

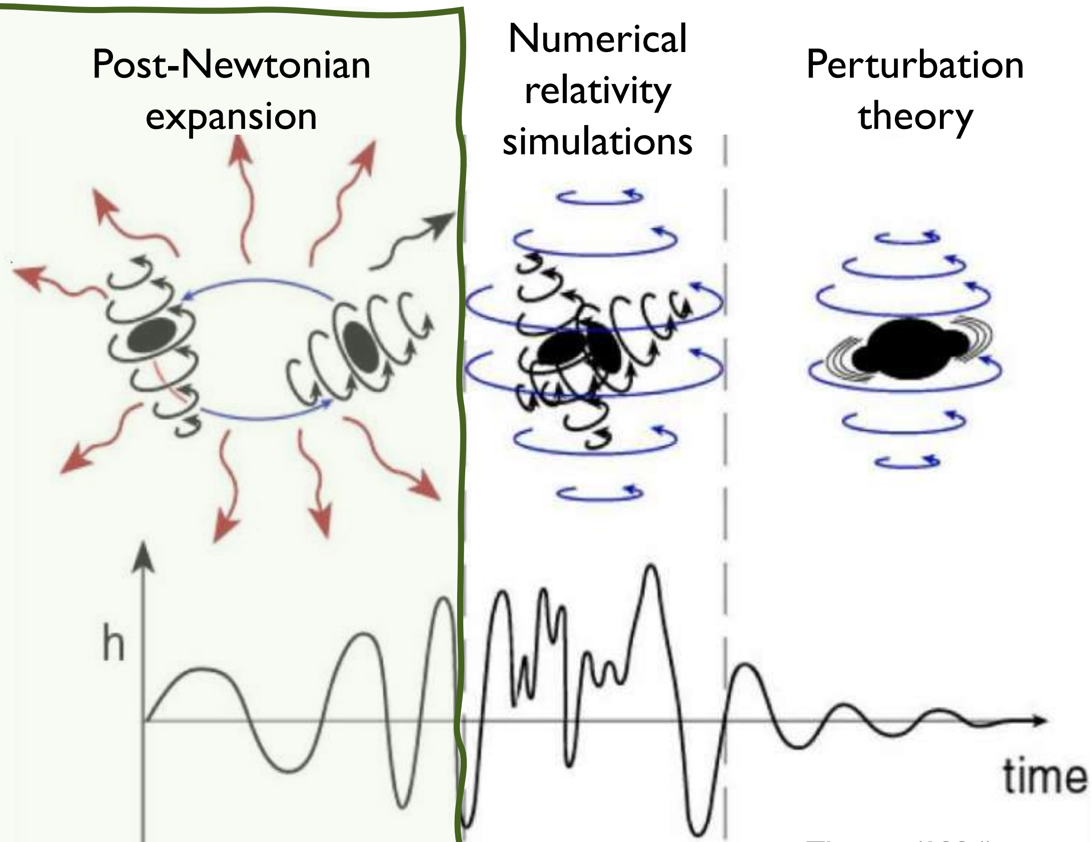
Post-Keplerian expansion

PN: Small parameters:

$$\underbrace{\frac{v}{c}, \frac{GM}{rc^2} \ll 1}_{\text{slowly moving}} \qquad \underbrace{\cancel{\frac{v_{int}}{c}, \frac{GM}{Rc^2}} \ll 1}_{\text{weakly gravitating}}$$

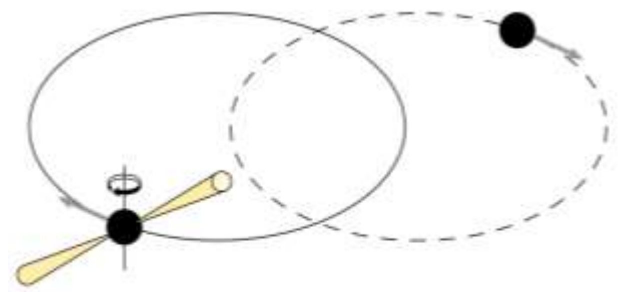
PK (Post-Keplerian): Small parameters:

$$\underbrace{\frac{v}{c}, \frac{GM}{rc^2} \ll 1}_{\text{slowly moving}}$$



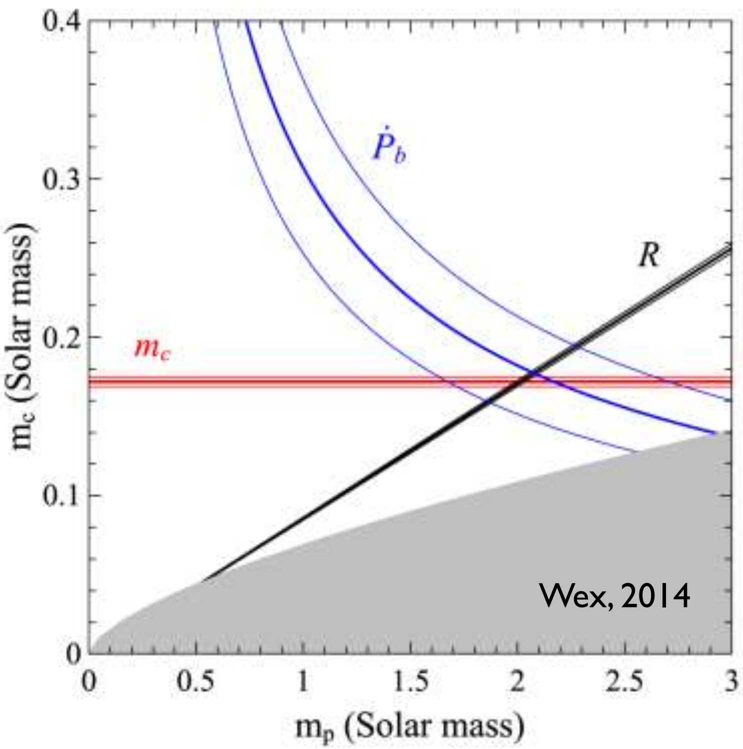
Thorne (1994)

Post-Keplerian expansion

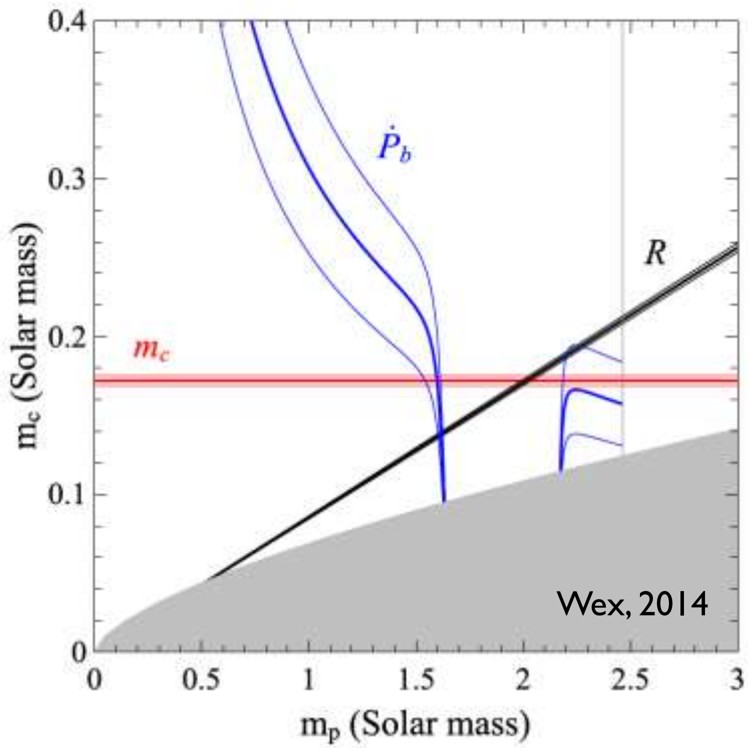


PSR J0348+0432

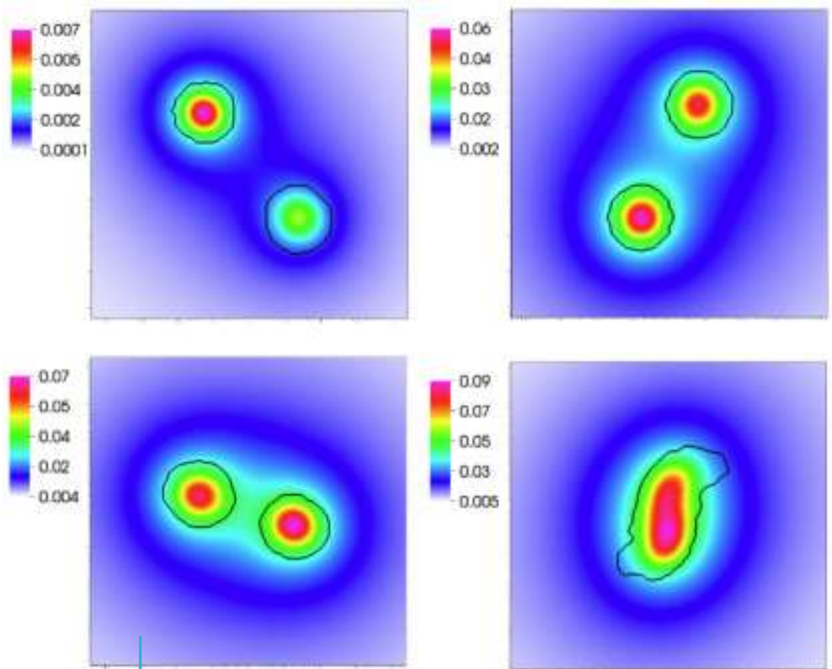
- General Relativity



- Scalar-tensor theory of Damour and Esposito-Farèse



Dynamical scalarization



color coding: scalar field amplitude

RAPID COMMUNICATIONS

PHYSICAL REVIEW D **87**, 081506(R) (2013)

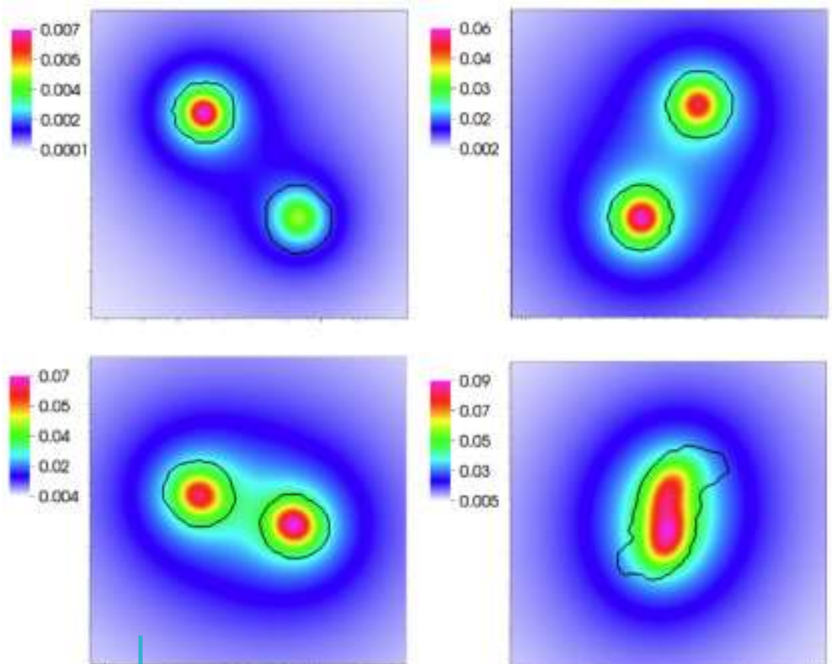
Neutron-star mergers in scalar-tensor theories of gravity

Enrico Barausse,[1,2] Carlos Palenzuela,[3] Marcelo Ponce,[2] and Luis Lehner[4,5]
[1]*Institut d'Astrophysique de Paris/CNRS, 98bis boulevard Arago, 75014 Paris, France*
[2]*Department of Physics, University of Guelph, Guelph, Ontario N1G 2W1, Canada*
[3]*Canadian Institute for Theoretical Astrophysics, Toronto, Ontario M5S 3H8, Canada*
[4]*Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada*
[5]*Canadian Institute for Advanced Research, Cosmology & Gravity Program, Canada*
(Received 21 December 2012; published 25 April 2013)

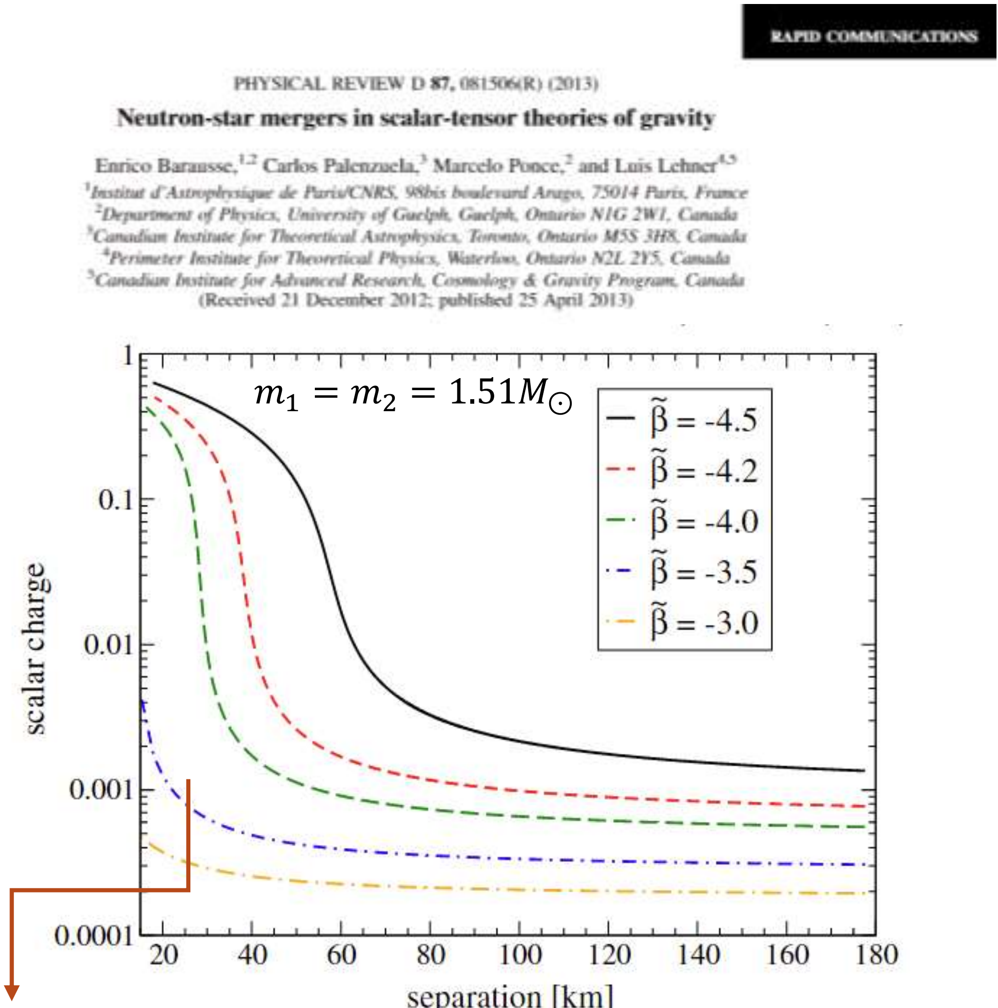
Scalar-tensor theories of gravity are natural phenomenological alternatives to General Relativity, where the gravitational interaction is mediated by a scalar degree of freedom, besides the usual tensor gravitons. In regions of the parameter space of these theories where constraints from both solar system experiments and binary-pulsar observations are satisfied, we show that binaries of neutron stars present marked differences from General Relativity in both the late-inspiral and merger phases. In particular, phenomena related to the spontaneous scalarization of isolated neutron stars take place in the late stages of the evolution of binary systems, with important effects in the ensuing dynamics. We comment on the relevance of our results for the upcoming Advanced LIGO/Virgo detectors.

DOI: 10.1103/PhysRevD.87.081506 PACS numbers: 04.30.−w, 04.25.D−, 97.60.Jd

Dynamical scalarization



color coding: scalar field amplitude


RAPID COMMUNICATIONS

PHYSICAL REVIEW D 87, 081506(R) (2013)

Neutron-star mergers in scalar-tensor theories of gravity

Enrico Barausse,[1,2] Carlos Palenzuela,[3] Marcelo Ponce,[2] and Luis Lehner[4,5]
[1]*Institut d'Astrophysique de Paris/CNRS, 98bis boulevard Arago, 75014 Paris, France*
[2]*Department of Physics, University of Guelph, Guelph, Ontario N1G 2W1, Canada*
[3]*Canadian Institute for Theoretical Astrophysics, Toronto, Ontario M5S 3H8, Canada*
[4]*Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada*
[5]*Canadian Institute for Advanced Research, Cosmology & Gravity Program, Canada*
(Received 21 December 2012; published 25 April 2013)

In these models, spontaneous scalarization of isolated stars only possible if $\tilde{\beta} \lesssim -4.5$

Palenzuela, Barausse, Ponce, Lehner (2014)

Dynamical scalarization

capturing spontaneous scalarization

- The PK formalism avoids expanding

$$m_A(\phi_0) = \tilde{m}_A a(\phi_0)\left[1 + A_1\left(\frac{Gm_A}{R_A c^2}\right) + A_2\left(\frac{Gm_A}{R_A c^2}\right)^2 + \cdots\right]$$

but still expands

$$m_A(\phi) = m_A(\phi_0)\left[1 + C_1\left(\frac{\phi - \phi_0}{\phi_0}\right) + C_2\left(\frac{\phi - \phi_0}{\phi_0}\right)^2 + \cdots\right]$$

missing dynamical scalarization

Dynamical scalarization

capturing spontaneous scalarization

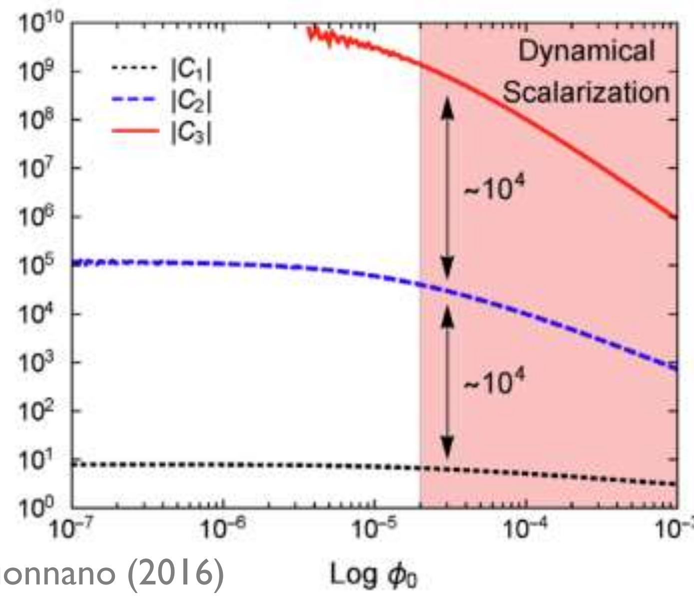
- The PK formalism avoids expanding

$$m_A(\phi_0) = \tilde{m}_A a(\phi_0)\left[1 + A_1\left(\frac{Gm_A}{R_A c^2}\right) + A_2\left(\frac{Gm_A}{R_A c^2}\right)^2 + \cdots\right]$$

but still expands

$$m_A(\phi) = m_A(\phi_0)\left[1 + C_1\left(\frac{\phi - \phi_0}{\phi_0}\right) + C_2\left(\frac{\phi - \phi_0}{\phi_0}\right)^2 + \cdots\right]$$

missing dynamical scalarization



Sennet & Buonnano (2016)

Dynamical scalarization

capturing spontaneous scalarization

- The PK formalism avoids expanding

$$m_A(\phi_0) = \tilde{m}_A a(\phi_0)\left[1 + A_1\left(\frac{Gm_A}{R_A c^2}\right) + A_2\left(\frac{Gm_A}{R_A c^2}\right)^2 + \cdots\right]$$

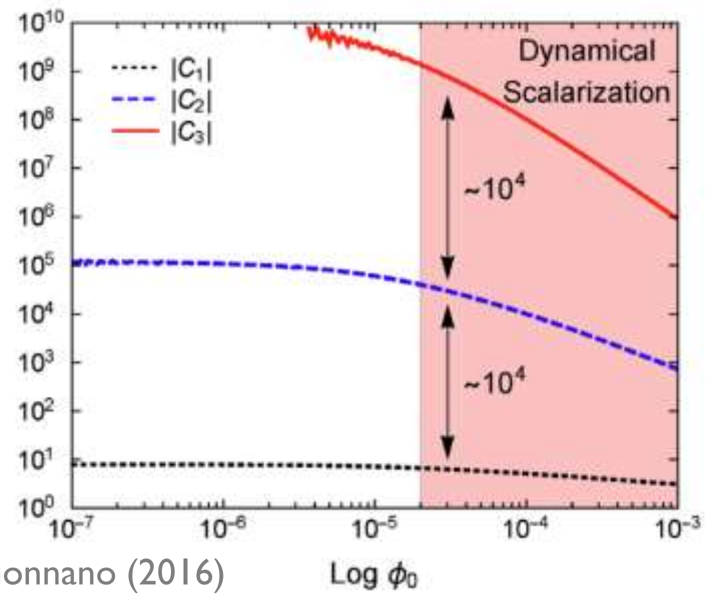
but still expands

$$m_A(\phi) = m_A(\phi_0)\left[1 + C_1\left(\frac{\phi-\phi_0}{\phi_0}\right) + C_2\left(\frac{\phi-\phi_0}{\phi_0}\right)^2 + \cdots\right]$$

$\propto \frac{Gm}{rc^2}$

missing dynamical scalarization

partial resummation:
"post-Dickean formalism"



Sennet & Buonnano (2016)

- Testing General Relativity
- Limitations of the pN expansion: the rise of nonperturbative effects
- Accommodating nonperturbative effects: pK, pD & all that
- Effective action approach to dynamical scalarization
- Going beyond the adiabatic approximation

Effective action model for DS

- Sennet, Shao, Steinhoff (2017)
- Khalil, Sennett, Steinhoff, Buonanno (2019)

- Same starting point

$$S_m = -\sum_{A=1}^{2} \int m_A(\phi)\sqrt{-u^\mu u_\mu}\, d\sigma$$

- 1st step: Reparametrizing in terms of the scalar charge/monopole:

$$\boxed{Q_A = -\frac{dm_A}{d\phi} = -m_A \alpha_A}$$

$$\phi = \phi_0 + \frac{Q}{r} + O\left(\frac{1}{r^2}\right)$$

Effective action model for DS

- Sennet, Shao, Steinhoff (2017)
- Khalil, Sennett, Steinhoff, Buonanno (2019)

- Same starting point

$$S_m = -\sum_{A=1}^{2} \int m_A(\phi)\sqrt{-u^\mu u_\mu}\,d\sigma$$

- 1st step: Reparametrizing in terms of the scalar charge/monopole…

$$Q_A = -\frac{dm_A}{d\phi} = -m_A\alpha_A$$

… using a Legendre transformation

$$\boxed{\bar{m}_A(Q) = m_A(\phi) + Q\phi}$$

$$S_m = -\sum_{A=1}^{2} \int (\bar{m}_A(Q) - Q\phi)\sqrt{-u^\mu u_\mu}\,d\sigma$$

Effective action model for DS

- Sennet, Shao, Steinhoff (2017)
- Khalil, Sennett, Steinhoff, Buonanno (2019)

- Same starting point

$$S_m = -\sum_{A=1}^{2} \int m_A(\phi) \sqrt{-u^\mu u_\mu} d\sigma$$

- 1st step: Reparametrizing in terms of the scalar charge/monopole using a Legendre transformation:

$$\bar{m}_A(Q) = m_A(\phi) + Q\phi$$

- 2nd step: Promote Q to an independent degree of freedom.
- 3rd step: Power-series expansion

$$\boxed{\bar{m}_A(Q) = c^{(0)} + c^{(1)}Q + \frac{c^{(2)}}{2!}Q^2 + \frac{c^{(3)}}{3!}Q^3 + \frac{c^{(4)}}{4!}Q^4 + O(Q^5)}$$

Effective action model for DS

- Sennet, Shao, Steinhoff (2017)
- Khalil, Sennett, Steinhoff, Buonanno (2019)

- Same starting point

$$S_m = -\sum_{A=1}^{2} \int m_A(\phi)\sqrt{-u^\mu u_\mu}\, d\sigma$$

- 1st step: Reparametrizing in terms of the scalar charge/monopole using a Legendre transformation:

$$\bar{m}_A(Q) = m_A(\phi) + Q\phi$$

- 2nd step: Promote Q to an independent degree of freedom.
- 3rd step: Power-series expansion

$$\boxed{\bar{m}_A(Q) = c^{(0)} + \cancel{c^{(1)}}Q + \frac{c^{(2)}}{2!}Q^2 + \cancel{\frac{c^{(3)}}{3!}}Q^3 + \frac{c^{(4)}}{4!}Q^4 + O(Q^5)}$$

Often, S_{tot} is invariant under $\phi \to -\phi$ (or $Q \to -Q$): keep only even terms

Effective action model for DS

- Sennet, Shao, Steinhoff (2017)
- Khalil, Sennett, Steinhoff, Buonanno (2019)

- Same starting point

$$S_m = -\sum_{A=1}^{2} \int m_A(\phi)\sqrt{-u^\mu u_\mu}\, d\sigma$$

- 1st step: Reparametrizing in terms of the scalar charge/monopole using a Legendre transformation:

$$\bar{m}_A(Q) = m_A(\phi) + Q\hat{\phi} \qquad \hat{\phi} = \phi - \phi_0$$

- 2nd step: Promote Q to an independent degree of freedom.
- 3rd step: Power-series expansion

$$\boxed{\bar{m}_A(Q) = m^{(0)} - \phi_0 Q + \frac{c^{(2)}}{2!}Q^2 + \frac{c^{(4)}}{4!}Q^4 + O(Q^5)}$$

Often, S_{tot} is invariant under $\phi \to -\phi$ (or $Q \to -Q$): keep only even terms

If $\phi_0 \neq 0$: $c^{(1)} = -\phi_0$.

Effective action model for DS

- Sennet, Shao, Steinhoff (2017)
- Khalil, Sennett, Steinhoff, Buonanno (2019)

- Newtonian-order solution:

$$\boxed{\begin{gathered} g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} + O(c^{-3}) \\ \hat{\phi} = \psi + O(c^{-4}) \end{gathered}}$$

$$h_{00}(\vec{x},t) = \frac{\overline{m}_A(Q_A)}{|\vec{x} - \vec{y}_A(t)|} + \frac{\overline{m}_B(Q_B)}{|\vec{x} - \vec{y}_B(t)|} + O(c^{-4})$$

$$h_{0i}(\vec{x},t) = O(c^{-3})$$

$$h_{ij}(\vec{x},t) = O(c^{-4})$$

$$\psi(\vec{x},t) = \frac{Q_A}{|\vec{x} - \vec{y}_A(t)|} + \frac{Q_B}{|\vec{x} - \vec{y}_B(t)|} + O(c^{-4})$$

Effective action model for DS

- Sennet, Shao, Steinhoff (2017)
- Khalil, Sennett, Steinhoff, Buonanno (2019)

- Newtonian-order solution:

$$\boxed{\begin{gathered} g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} + O(c^{-3}) \\ \hat{\phi} = \psi + O(c^{-4}) \end{gathered}}$$

$$h_{00}(\vec{x},t) = \frac{\bar{m}_A(Q_A)}{|\vec{x}-\vec{y}_A(t)|} + \frac{\bar{m}_B(Q_B)}{|\vec{x}-\vec{y}_B(t)|} + O(c^{-4})$$

$$h_{0i}(\vec{x},t) = O(c^{-3})$$

$$h_{ij}(\vec{x},t) = O(c^{-4})$$

$$\psi(\vec{x},t) = \frac{Q_A}{|\vec{x}-\vec{y}_A(t)|} + \frac{Q_B}{|\vec{x}-\vec{y}_B(t)|} + O(c^{-4})$$

- Inserting in the matter action one gets:

$$\boxed{S \sim \int dt \left[-\bar{m}_A - \bar{m}_B + \frac{\bar{m}_A}{2}\vec{v}_A^2 + \frac{\bar{m}_B}{2}\vec{v}_B^2 + \frac{\bar{m}_A\bar{m}_B}{r} + \frac{Q_A Q_B}{r} \right]}$$

$$v^i = \frac{dy^i}{dt} \qquad r = |\vec{y}_A - \vec{y}_B|$$

Effective action model for DS

- Sennet, Shao, Steinhoff (2017)
- Khalil, Sennett, Steinhoff, Buonanno (2019)

- Newtonian-order Hamiltonian:

$$\boxed{H = \bar{m}_A + \bar{m}_B + \frac{\vec{p}_A^{\,2}}{2\bar{m}_A} + \frac{\vec{p}_B^{\,2}}{2\bar{m}_B} - \frac{\bar{m}_A \bar{m}_B}{r} - \frac{Q_A Q_B}{r}}$$

Effective action model for DS

- Sennet, Shao, Steinhoff (2017)
- Khalil, Sennett, Steinhoff, Buonanno (2019)

- Newtonian-order Hamiltonian:

$$H = \bar{m}_A + \bar{m}_B + \frac{\vec{p}_A^{\,2}}{2\bar{m}_A} + \frac{\vec{p}_B^{\,2}}{2\bar{m}_B} - \frac{\bar{m}_A \bar{m}_B}{r} - \frac{Q_A Q_B}{r}$$

- Equation of motion for Q_A:

$$\boxed{0 = \frac{\partial H}{\partial Q_A} = z_A \left(-\phi_0 + c_A^{(2)} Q_A + \frac{c_A^{(4)}}{6} Q_A^3 \right) - \frac{Q_B}{r} + O(Q_A^4)}$$

$$z_A = \frac{\partial H}{\partial \bar{m}_A} = 1 - \frac{\vec{p}_A^{\,2}}{2\bar{m}_A^2} - \frac{\bar{m}_B}{r}$$

Effective action model for DS

- Sennet, Shao, Steinhoff (2017)
- Khalil, Sennett, Steinhoff, Buonanno (2019)

- Equation of motion for Q_A:

$$\boxed{0 = \frac{\partial H}{\partial Q_A} = z_A\left(-\phi_0 + c_A^{(2)} Q_A + \frac{c_A^{(4)}}{6} Q_A^3\right) - \frac{Q_B}{r} + O(Q_A^4)}$$

To get an approximate solution:

- $z_A \approx 1$
- $\phi_0 = 0$
- $\bar{m}_A = \bar{m}_B$

$$0 = \frac{\partial H}{\partial Q} = -2Q\left[\frac{1}{r} - c^{(2)} - \frac{c^{(4)}}{6} Q^2\right]$$

Effective action model for DS

- Sennet, Shao, Steinhoff (2017)
- Khalil, Sennett, Steinhoff, Buonanno (2019)

- Equation of motion for Q_A:

$$\boxed{0 = \frac{\partial H}{\partial Q_A} = z_A\left(-\phi_0 + c_A^{(2)} Q_A + \frac{c_A^{(4)}}{6} Q_A^3\right) - \frac{Q_B}{r} + O(Q_A^4)}$$

To get an approximate solution:

- $z_A \approx 1$
- $\phi_0 = 0$
- $\bar{m}_A = \bar{m}_B$

$$0 = \frac{\partial H}{\partial Q} = -2Q\left[\frac{1}{r} - c^{(2)} - \frac{c^{(4)}}{6} Q^2\right]$$

Stability criterion

$$0 \leq \frac{\partial^2 H}{\partial Q^2} = 2c^{(2)} - \frac{2}{r} + c^{(4)} Q^2$$

violated by $Q = 0$ if $c^{(2)} < 1/r$

Effective action model for DS

- Sennet, Shao, Steinhoff (2017)
- Khalil, Sennett, Steinhoff, Buonanno (2019)

- Equation of motion for Q_A:

$$\boxed{0 = \frac{\partial H}{\partial Q_A} = z_A\left(-\phi_0 + c_A^{(2)} Q_A + \frac{c_A^{(4)}}{6} Q_A^3\right) - \frac{Q_B}{r} + O(Q_A^4)}$$

To get an approximate solution:
- $z_A \approx 1$
- $\phi_0 = 0$
- $\bar{m}_A = \bar{m}_B$

$$0 = \frac{\partial H}{\partial Q} = -2Q\left[\frac{1}{r} - c^{(2)} - \frac{c^{(4)}}{6} Q^2\right]$$

Stability criterion

$$0 \leq \frac{\partial^2 H}{\partial Q^2} = 2c^{(2)} - \frac{2}{r} + c^{(4)} Q^2$$

violated by $Q = 0$ if $c^{(2)} < 1/r$

- If $c^{(2)} < 0$, $Q = 0$ is always unstable: spontaneous scalarization!
- Even if $c^{(2)} > 0$, scalarization can occur at small orbital separations: $c^{(2)} < 1/r$: dynamical scalarization!

Effective action model for DS

- Sennet, Shao, Steinhoff (2017)
- Khalil, Sennett, Steinhoff, Buonanno (2019)

- Equation of motion for Q_A:

$$\boxed{0 = \frac{\partial H}{\partial Q_A} = z_A\left(-\phi_0 + c_A^{(2)} Q_A + \frac{c_A^{(4)}}{6} Q_A^3\right) - \frac{Q_B}{r} + O(Q_A^4)}$$

To get an approximate solution:

- $z_A \approx 1$
- $\phi_0 = 0$
- $\bar{m}_A = \bar{m}_B$

$$0 = \frac{\partial H}{\partial Q} = -2Q\left[\frac{1}{r} - c^{(2)} - \frac{c^{(4)}}{6} Q^2\right]$$

Stability criterion

$$0 \leq \frac{\partial^2 H}{\partial Q^2} = 2c^{(2)} - \frac{2}{r} + c^{(4)} Q^2$$

violated by $Q = 0$ if $c^{(2)} < 1/r$

Stable solutions:

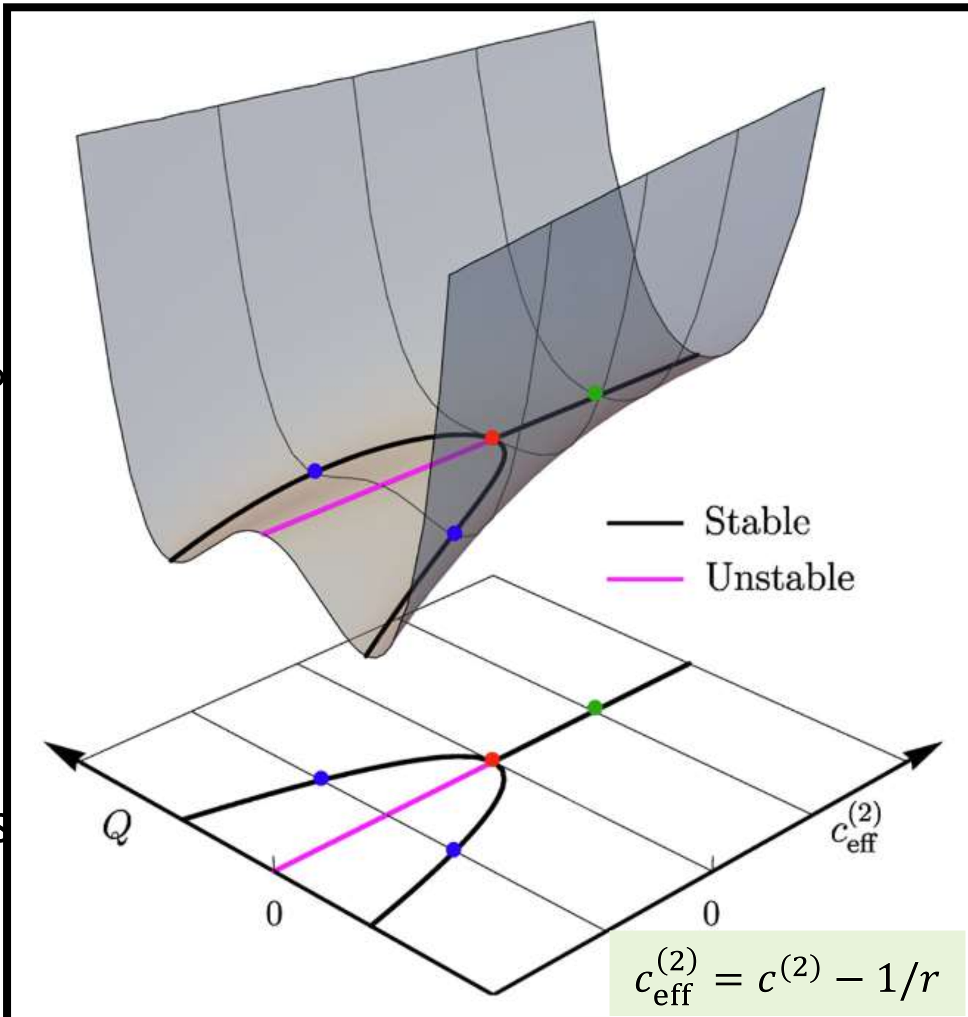
$$Q = \begin{cases} 0 & \text{for } 1/r \leq c^{(2)} \\ \pm\sqrt{\dfrac{6}{c^{(4)}}}\sqrt{\dfrac{1}{r} - c^{(2)}} & \text{for } 1/r \geq c^{(2)} \end{cases}$$

- If $c^{(2)} < 0$, $Q = 0$ is always unstable: spontaneous scalarization!
- Even if $c^{(2)} > 0$, scalarization can occur at small orbital separations: $c^{(2)} < 1/r$: dynamical scalarization!

Effective action model for DS

- Sennet, Shao, Steinhoff (2017)
- Khalil, Sennett, Steinhoff, Buonanno (2019)

To



$\left. \frac{{}^{(4)}_{A}}{6} Q_A^3 \right) - \frac{Q_B}{r} + O(Q_A^4)$

tability criterion

$$0 \leq \frac{\partial^2 H}{\partial Q^2} = 2c^{(2)} - \frac{2}{r} + c^{(4)} Q^2$$

iolated by $Q = 0$ if $c^{(2)} < 1/r$

$\left. Q^2 \right]$

S

$\left(\sqrt{c^{(4)}} \sqrt{r} \right.$

If $c^{(2)} < 0$, $Q = 0$ is always unstable: spontaneous scalarization!
Even if $c^{(2)} > 0$, scalarization can occur at small orbital separations: $c^{(2)} < 1/r$: dynamical scalarization!

- Testing General Relativity
- Limitations of the pN expansion: the rise of nonperturbative effects
- Accommodating nonperturbative effects: pK, pD & all that
- Effective action approach to dynamical scalarization
- Going beyond the adiabatic approximation

Effective action beyond adiabatic approx.

- Alternative interpretation as a coarse-grained description:

$$\phi = \phi^{IR} + \phi^{UV}$$

$$\lambda_{UV} \lesssim R$$

$$\lambda_{IR} \gtrsim R$$

Effective action beyond adiabatic approx.

- Alternative interpretation as a coarse-grained description:

$$\phi = \phi^{IR} + \phi^{UV}$$

$\lambda_{UV} \lesssim R$

$\lambda_{IR} \gtrsim R$

spatially average

Dynamical short-length processes represented by dynamical variables on the worldline

Effective action beyond adiabatic approx.

- Alternative interpretation as a coarse-grained description:

$$\phi = \phi^{IR} + \phi^{UV}$$

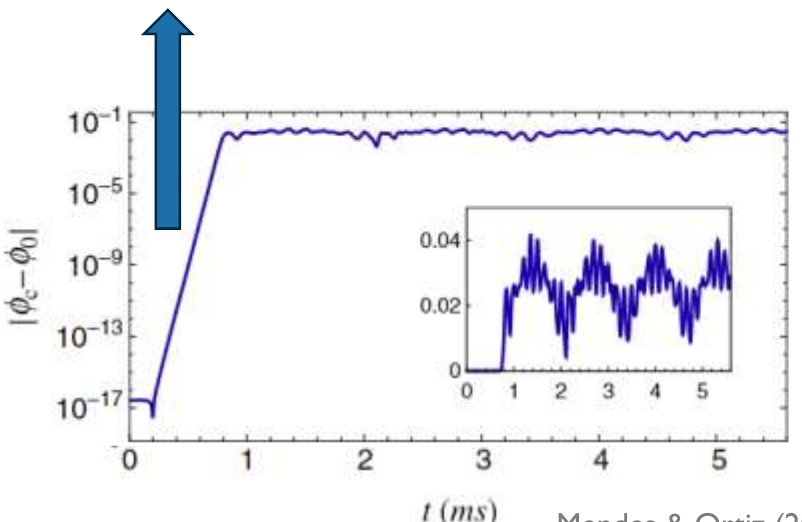
$\lambda_{UV} \lesssim R$

$\lambda_{IR} \gtrsim R$

spatially average

Dynamical short-length processes represented by dynamical variables on the worldline

Spontaneous scalarization is triggered by the instability of the fundamental (monopolar) scalar mode (ϕ-mode)



Mendes & Ortiz (2016)

Effective action beyond adiabatic approx.

- Alternative interpretation as a coarse-grained description:

$$\phi = \phi^{IR} + \phi^{UV}$$

$\lambda_{UV} \lesssim R$

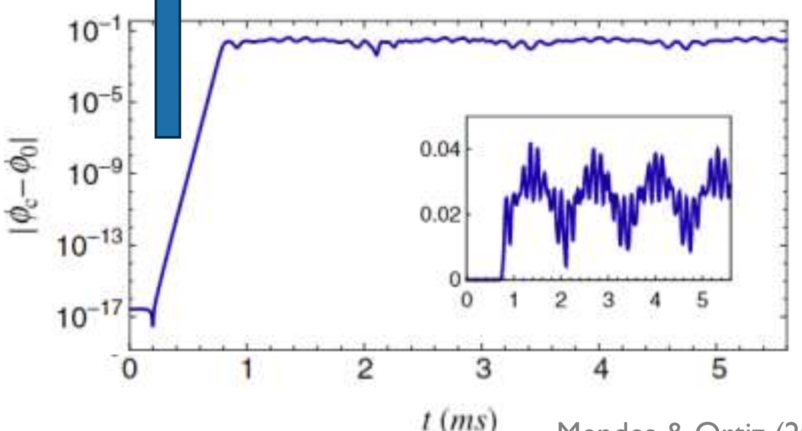
$\lambda_{IR} \gtrsim R$

spatially average

Dynamical short-length processes represented by dynamical variables on the worldline

(+) At the onset of spontaneous scalarization, the ϕ-mode has zero frequency

Spontaneous scalarization is triggered by the instability of the fundamental (monopolar) scalar mode (ϕ-mode)



Mendes & Ortiz (2016)

Effective action beyond adiabatic approx.

- Alternative interpretation as a coarse-grained description:

$$\phi = \phi^{IR} + \phi^{UV}$$

$\lambda_{UV} \lesssim R$

$\lambda_{IR} \gtrsim R$

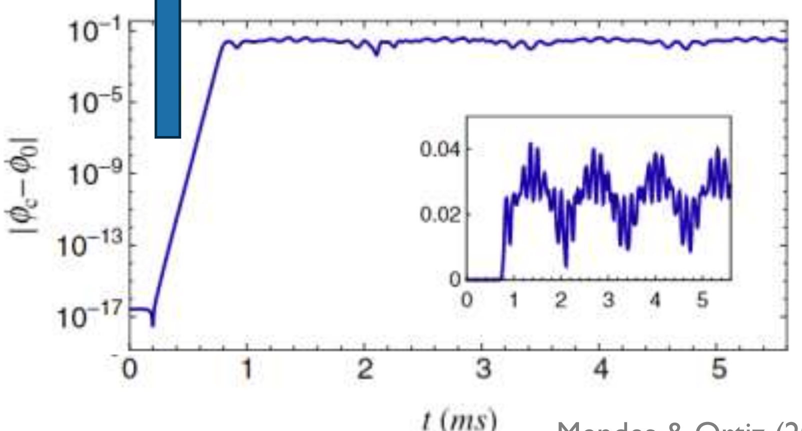
spatially average

Dynamical short-length processes represented by dynamical variables on the worldline

Introduce the ϕ mode as a new dynamical variable on the worldline: $q(\tau)$

(+) At the onset of spontaneous scalarization, the ϕ-mode has zero frequency

Spontaneous scalarization is triggered by the instability of the fundamental (monopolar) scalar mode (ϕ-mode)



Mendes & Ortiz (2016)

Effective action beyond adiabatic approx.

- Alternative interpretation as a coarse-grained description:

$$\phi = \phi^{IR} + \phi^{UV}$$

$\lambda_{UV} \lesssim R$

$\lambda_{IR} \gtrsim R$

spatially average

Dynamical short-length processes represented by dynamical variables on the worldline

- Expected dynamics of the scalar mode:

$$c_{\dot{q}^2}\ddot{q} + V'(q) = \phi^{IR}(y)$$

$$V(q) = \frac{c_{(2)}}{2}q^2 + \frac{c_{(4)}}{4!}q^4 + \cdots$$

Effective action beyond adiabatic approx.

- Alternative interpretation as a coarse-grained description:

$$\phi = \phi^{IR} + \phi^{UV}$$

$\lambda_{UV} \lesssim R$

$\lambda_{IR} \gtrsim R$

spatially average

Dynamical short-length processes represented by dynamical variables on the worldline

- Expected dynamics of the scalar mode:

$$c_{\dot{q}^2}\ddot{q} + V'(q) = \phi^{IR}(y) \quad \Longleftrightarrow \quad S_{NS}^{\text{crit}} = \int d\tau \left[\frac{c_{\dot{q}^2}}{2}\dot{q}^2 + \phi(y)q - m(q) + \cdots\right]$$

$$V(q) = \frac{c_{(2)}}{2}q^2 + \frac{c_{(4)}}{4!}q^4 + \cdots$$

$$m(q) = c_{(0)} + V(q)$$

Effective action beyond adiabatic approx.

- Before: adiabatic approximation

$$\cancel{c_{\dot{q}^2}}\ddot{q} + V'(q) = \phi^{IR}(y) \Longleftrightarrow S_{NS}^{\text{crit}} = \int d\tau \left[\cancel{\frac{c_{\dot{q}^2}}{2}} \dot{q}^2 + \phi(y) q - m(q) + \cdots \right]$$

$$V(q) = \frac{c_{(2)}}{2} q^2 + \frac{c_{(4)}}{4!} q^4 + \cdots$$

$$m(q) = c_{(0)} + V(q)$$

- In Khalil, Mendes, Ortiz, Steinhoff (PRD 2022) we:
  - Includes the scalar mode dynamics;
  - Considers generic (eccentric) orbits;
  - Include radiation-reaction effects at the EOM level.

Effective action beyond adiabatic approx.

- Before: adiabatic approximation

$$c_{\dot{q}^2}\ddot{q} + V'(q) = \phi^{IR}(y) \quad \Longleftrightarrow \quad S_{NS}^{\text{crit}} = \int d\tau \left[\frac{c_{\dot{q}^2}}{2}\dot{q}^2 + \phi(y)q - m(q) + \cdots\right]$$

$$V(q) = \frac{c_{(2)}}{2}q^2 + \frac{c_{(4)}}{4!}q^4 + \cdots$$

$$m(q) = c_{(0)} + V(q)$$

- In Khalil, Mendes, Ortiz, Steinhoff (PRD 2022) we:
  - Includes the scalar mode dynamics;
  - Considers generic (eccentric) orbits;
  - Include radiation-reaction effects at the EOM level.

Effective action beyond adiabatic approx.

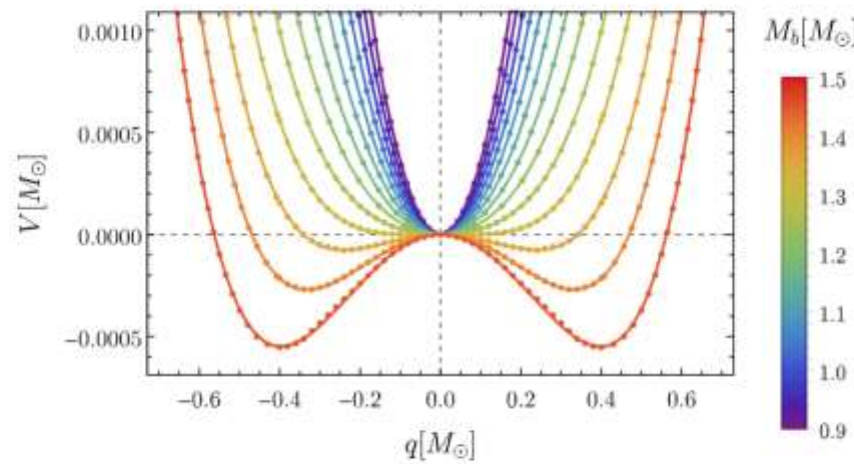
- Computing the UV coefficients

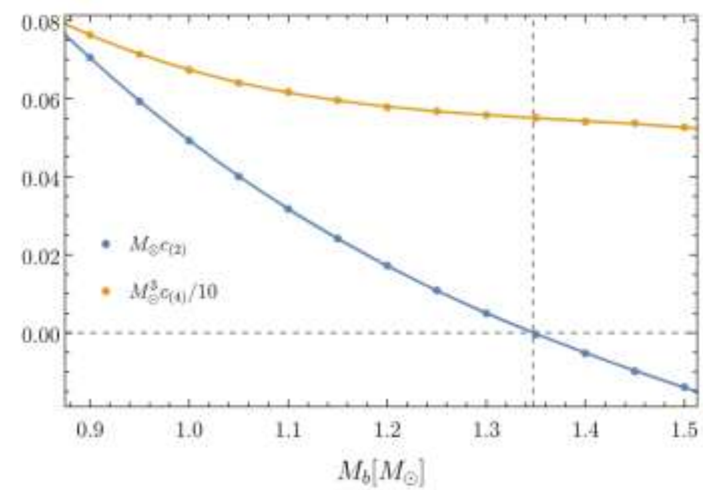
$c_{(2)}$ and $c_{(4)}$

(i) Solve numerically the structure equations in the full theory, for a fixed baryon mass M_b and different values of ϕ_∞

(ii) Compute $m(q) = m(\phi_\infty) - \phi_\infty q(\phi_\infty)$

(iii) Fit a polynomial to $m(q) - c_{(0)}$ and extract the quadratic ($c_{(2)}$) and quartic ($c_{(4)}$) coefficients.





Effective action beyond adiabatic approx.

- Computing the UV coefficients

$c_{\dot{q}^2}$:

(i) Compute the quasinormal mode frequency of the ϕ-mode using NS perturbation theory.

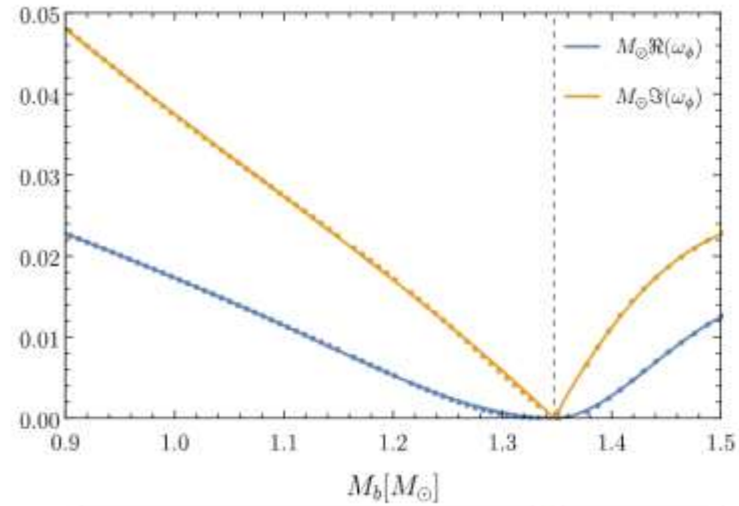
(ii) Contrast with the solution for a damped harmonic oscillator,

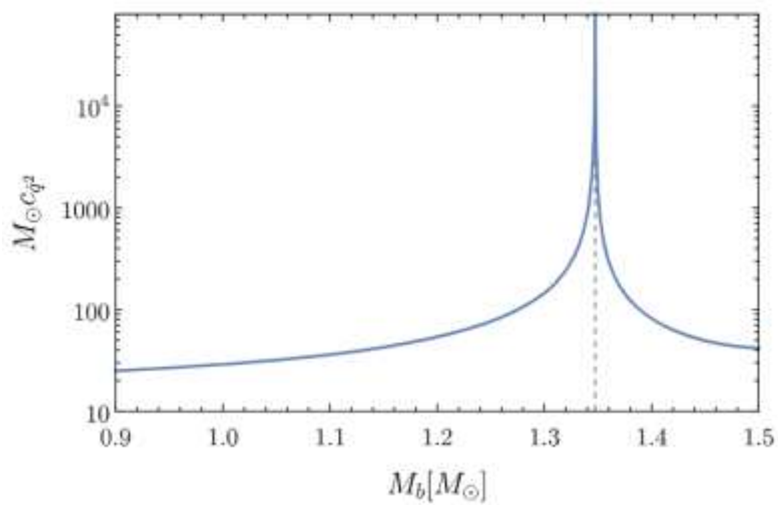
$$c_{\dot{q}^2}\ddot{q} + \dot{q} + c_{(2)}q = 0$$

$$\Updownarrow$$

$$q(t) = e^{-\omega_I t}[a\cos(\omega_R t) + b\sin(\omega_R t)]$$

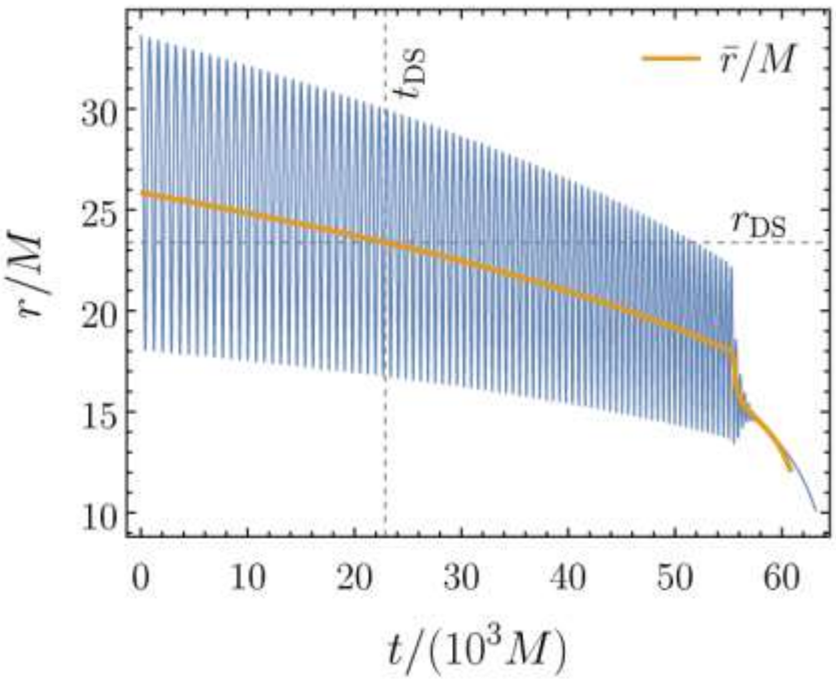
$$\omega_R^2 + \omega_I^2 = \frac{c_{(2)}}{c_{\dot{q}^2}}$$

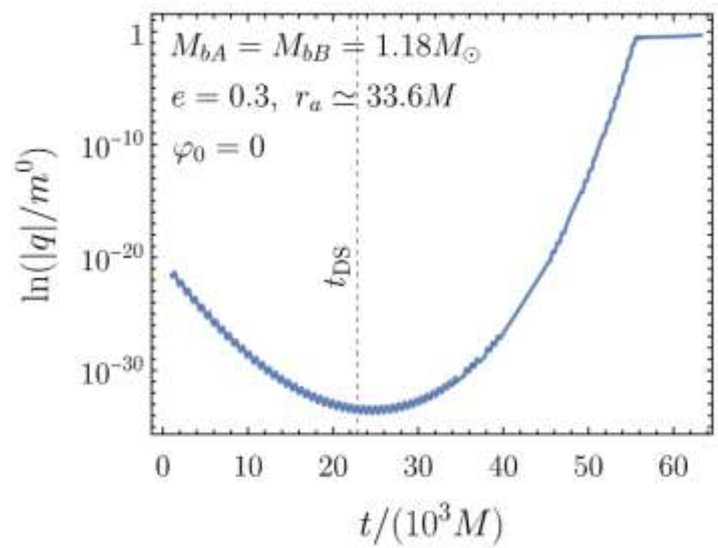


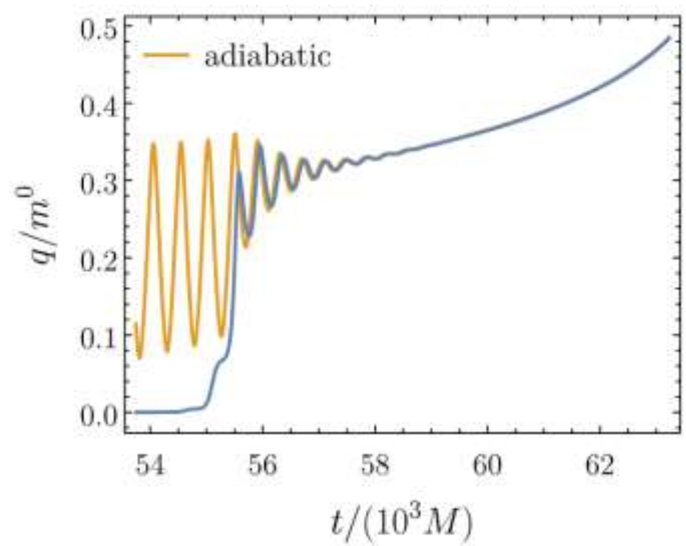


Effective action beyond adiabatic approx.

$r_{DS} = 1/c_{(2)}$







Separation and scalar charge for an equal-mass binary with initial eccentricity $e = 0.3$ and $\phi_0 = 0$.

- Testing General Relativity
- Limitations of the pN expansion: the rise of nonperturbative effects
- Accommodating nonperturbative effects: pK, pD & all that
- Effective action approach to dynamical scalarization
- Going beyond the adiabatic approximation

A final recap!

Thank you!