Signatures of alternative models of gravity in the gravitational waves: the quasi-normal modes of black holes and neutron stars

Jose Luis Blázquez-Salcedo

JLBS, Daniela D. Doneva, Jutta Kunz, Stoytcho S. Yazadjiev [arXiv:1805.05755]

JLBS, Daniela D. Doneva, Jutta Kunz, Kalin V. Staykov, Stoytcho S. Yazadjiev [arXiv:1804.04060]

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JLBS, Caio Macedo, Vitor Cardoso, Valeria Ferrari, Leonardo Gualtieri, Fech Scen Khoo, Jutta Kunz, Paolo Pani
PRD94 (2016) 104024 [arxiv:1609.01286 gr-qc]

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RESEARCH TRAINING GROUP
Models of Gravity

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Prismošten 19/6/2018

CARL VON OSSIETZKY universität OLDENBURG

Signatures of alternative models of gravity in the gravitational waves: the quasi-normal modes of black holes and neutron stars

1. Introduction

2. Black holes in scalar-Einstein-Gauss-Bonnet theory

   a) Perturbation theory and quasinormal modes
   b) Spectrum of the dilatonic black holes
   c) Stability: dilatonic vs scalarized
   d) Implications for astrophysical black holes

3. Neutron stars in scalar-tensor theory

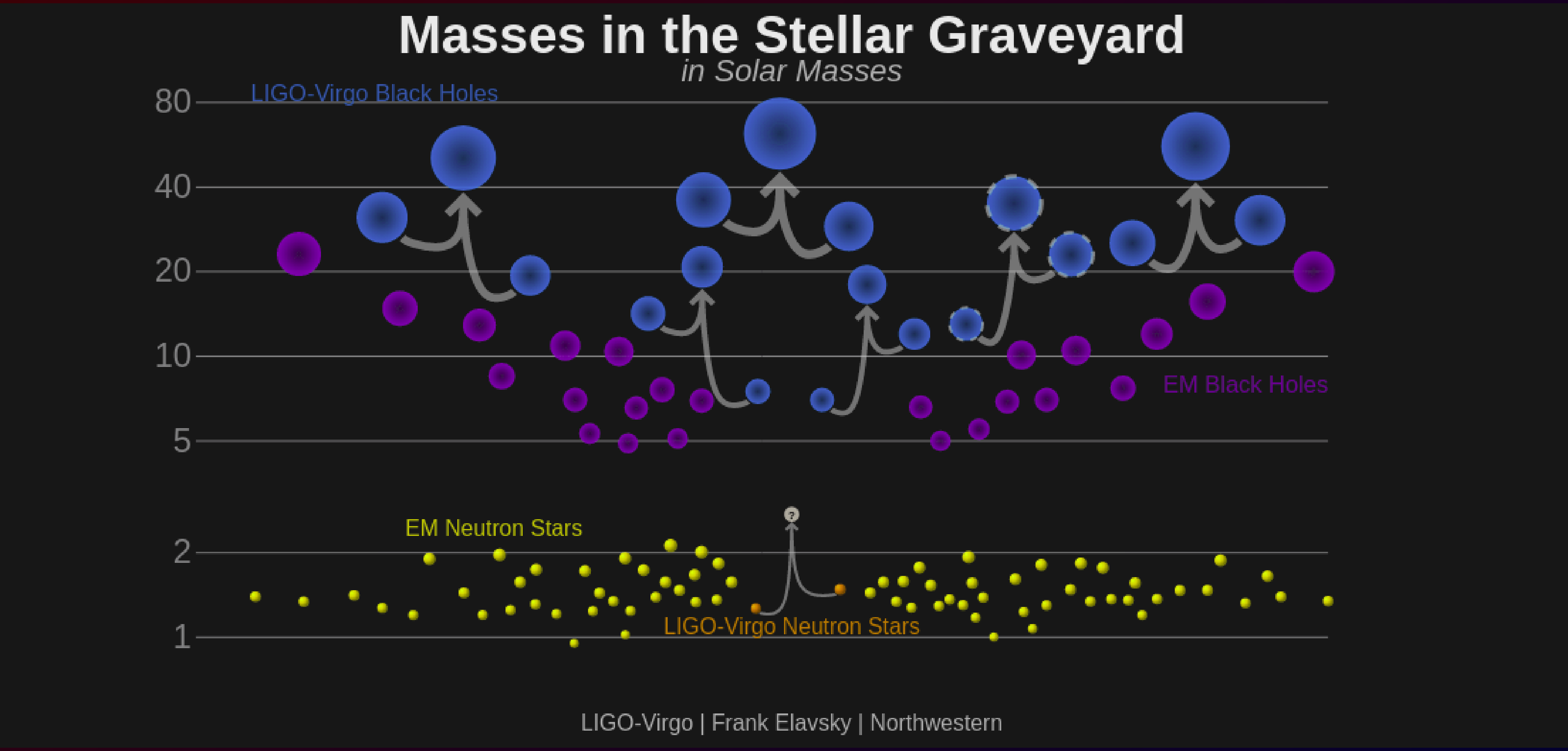
   a) Matter and equation of state
   b) Universal relations

4. Conclusions and Outlook

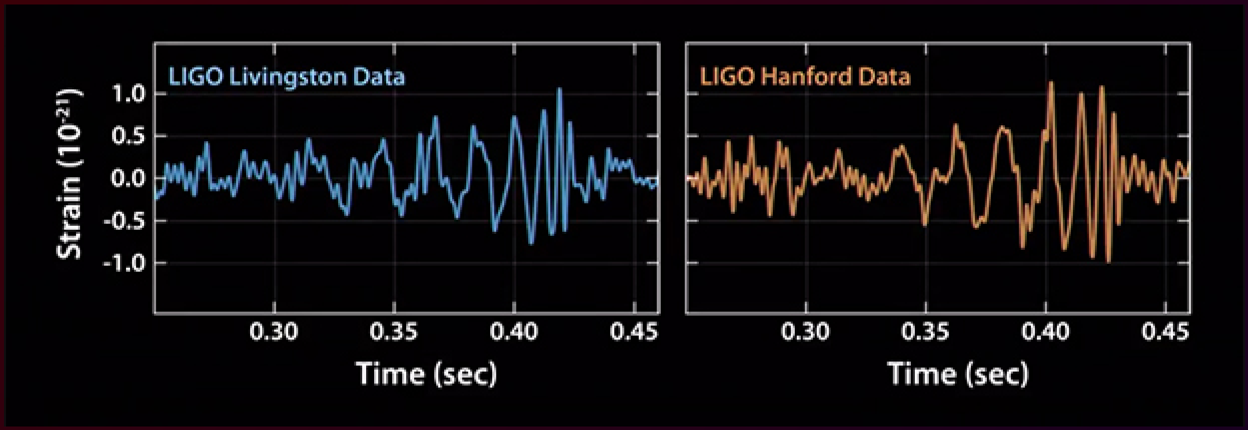
1. Introduction

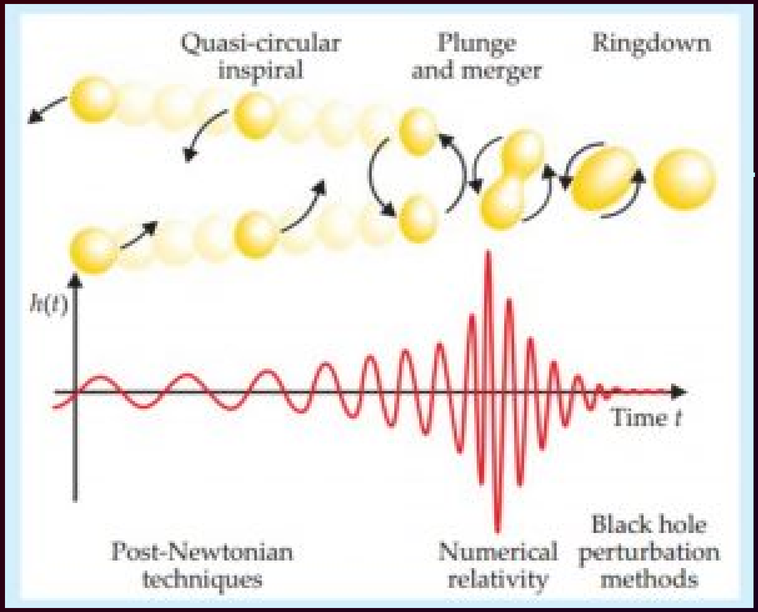
1. Introduction

Observations of gravitational waves emitted from BH and NS mergers



1. Introduction





Ringdown phase: resonant frequencies and exponential damping

Spectrum of quasinormal modes

GR: Mass, angular momentum, matter composition

Alternative theories: it may depend also on the parameters of the theory // extra charges (scalar fields)

1. Introduction

Why modified gravity?

- Dark energy and dark matter
- Quantum gravity

Compatible with experimental tests and theoretical requirements

- Horndeski gravity
- Scalar-tensor theory
- f(R)
- …

Einstein theory expected to break down
at high energies / strong gravity regimes:

Black holes, neutron stars, ...

1. Introduction

In this talk:

1. Introduction

In this talk:

- Black holes in scalar-Einstein-Gauss-Bonnet theory

$$S = \frac{1}{16\pi} \int d^4x \sqrt{-g} \Big[R - 2\nabla_\mu \varphi \nabla^\mu \varphi - V(\varphi) + \lambda^2 f(\varphi) \mathcal{R}^2_{GB} \Big]$$

$$R^2_{\rm GB} = R_{\mu\nu\rho\sigma} R^{\mu\nu\rho\sigma} - 4 R_{\mu\nu} R^{\mu\nu} + R^2$$

1. Introduction

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- Black holes in scalar-Einstein-Gauss-Bonnet theory

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- Neutron stars in scalar-tensor theory (R^2)

$$S=\frac{1}{16\pi G}\int d^4x\sqrt{-g}\,[R-2g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi-V(\varphi)]+S_{\rm matter}$$

$$V(\varphi)=\frac{1}{4a}\left(1-e^{-\frac{2\varphi}{\sqrt{3}}}\right)^2$$

1. Introduction

In this talk:

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- Neutron stars in nonminimal derivative coupling (Horndeski theory)

$$S=\int d^4x\sqrt{-g}\left[R+\eta G^{\mu\nu}\nabla_\mu\phi\nabla_\nu\phi\right]+S_{\rm matter}$$

2. Black holes in sEGB theory

2. Black holes in sEGB theory

Einstein-Gauss-Bonnet-dilaton gravity

- Higher order curvature corrections to Einstein theory are predicted by string theory

- Low energy limit of heterotic string theory
  Gauss-Bonnet term + scalar field

- Quadratic in curvature ⇒ second order differential equations (ghost free)

$$S_{\rm EGBd}(g,\Phi) = \frac{1}{16\pi}\int d^4x\sqrt{-g}\left(R - \frac{1}{2}\partial_\mu\Phi\,\partial^\mu\Phi + \frac{1}{4}\alpha e^{\gamma\Phi}R^2_{\rm GB}\right)$$

$$R^2_{\rm GB} = R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma} - 4R_{\mu\nu}R^{\mu\nu} + R^2$$

2. Black holes sEGB theory

$$S_{\mathrm{EGBd}}(g,\Phi)=\frac{1}{16\pi}\int d^4x\sqrt{-g}\left(R-\frac{1}{2}\partial_\mu\Phi\,\partial^\mu\Phi+\frac{1}{4}\alpha e^{\gamma\Phi}R^2_{\mathrm{GB}}\right)$$

Field equations of Einstein-Gauss-Bonnet-dilaton gravity

$$G_{\mu\nu}=\frac{1}{2}\,T_{\mu\nu}$$

$$\nabla^2\Phi=\frac{1}{4}\alpha\gamma e^{\gamma\Phi}R^2_{\mathrm{GB}}$$

$$T_{\mu\nu}=T^{(\phi)}_{\mu\nu}+\frac{1}{4}\alpha e^{\gamma\Phi}T^{(\mathrm{GBd})}_{\mu\nu}$$

$$T^{(\phi)}_{\mu\nu}=\partial_\mu\Phi\,\partial_\nu\Phi-\frac{1}{2}g_{\mu\nu}\partial_\rho\Phi\,\partial^\rho\Phi$$

$$T^{(\mathrm{GBd})}_{\mu\nu}=H_{\mu\nu}+4(\partial^\rho\Phi\,\partial^\sigma\Phi+\partial^\rho\partial^\sigma\Phi)P_{\mu\rho\nu\sigma}$$

$$H_{\mu\nu}=2(RR_{\mu\nu}-2R_{\mu\alpha}R^\alpha_{\ \nu}-2R_{\mu\alpha\beta\nu}R^{\alpha\beta}+R_{\mu\alpha\beta\delta}R_\nu^{\ \alpha\beta\delta})-\frac{1}{2}g_{\mu\nu}R^2_{GB}$$

$$P_{\alpha\beta\gamma\delta}=R_{\alpha\beta\delta\gamma}+g_{\alpha\gamma}R_{\delta\beta}-g_{\alpha\delta}R_{\gamma\beta}+g_{\beta\delta}R_{\gamma\alpha}-g_{\beta\gamma}R_{\delta\alpha}+\frac{1}{2}Rg_{\alpha\delta}g_{\gamma\beta}-\frac{1}{2}Rg_{\alpha\gamma}g_{\delta\beta}$$

2. Black holes in sEGB theory

Static and spherically symmetric black holes with scalar field:

Mignemi, Stewart, PRD47 5259 (1993)
Mignemi. PRD51 934 (1995)
Kanti et al, PRD54 5049 (1996)
Torii, Yajima, Maeda. PRD55 739 (1997)

$$ds^2 = g^{(0)}_{\mu\nu} dx^\mu dx^\nu = -F(r)dt^2 + K(r)dr^2 + r^2(d\theta^2 + \sin^2\theta\, d\varphi^2)$$

$$\Phi = \Phi_0(r)$$

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$$\Phi = \Phi_0(r)$$

Near-horizon expansion:

$$K(r) \approx \frac{1}{1-2m_1} \cdot \frac{r_H}{r - r_H},$$

$$F(r) \approx f_1(r - r_H)$$

$$\Phi_0(r) \approx \Phi_{00} + \Phi_{01}(r - r_H),$$

$$m_1 = \frac{\alpha\gamma\Phi_{01}}{2\alpha\gamma\Phi_{01} + 4 r_H e^{\gamma\Phi_{00}}}$$

Regularity implies:

$$\alpha\gamma r_H^2 \Phi_{01}^2 + 2e^{\gamma\Phi_{00}} r_H^3 \Phi_{01} + 6\alpha\gamma = 0$$

$$e^{2\gamma\Phi_{00}} r_H^4 - 6\alpha^2\gamma^2 > 0$$

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Static and spherically symmetric black holes with scalar field:

$$ds^2 = g^{(0)}_{\mu\nu} dx^\mu dx^\nu = -F(r)dt^2 + K(r)dr^2 + r^2(d\theta^2 + \sin^2\theta\, d\varphi^2)$$

$$\Phi = \Phi_0(r)$$

Asymptotically flat:

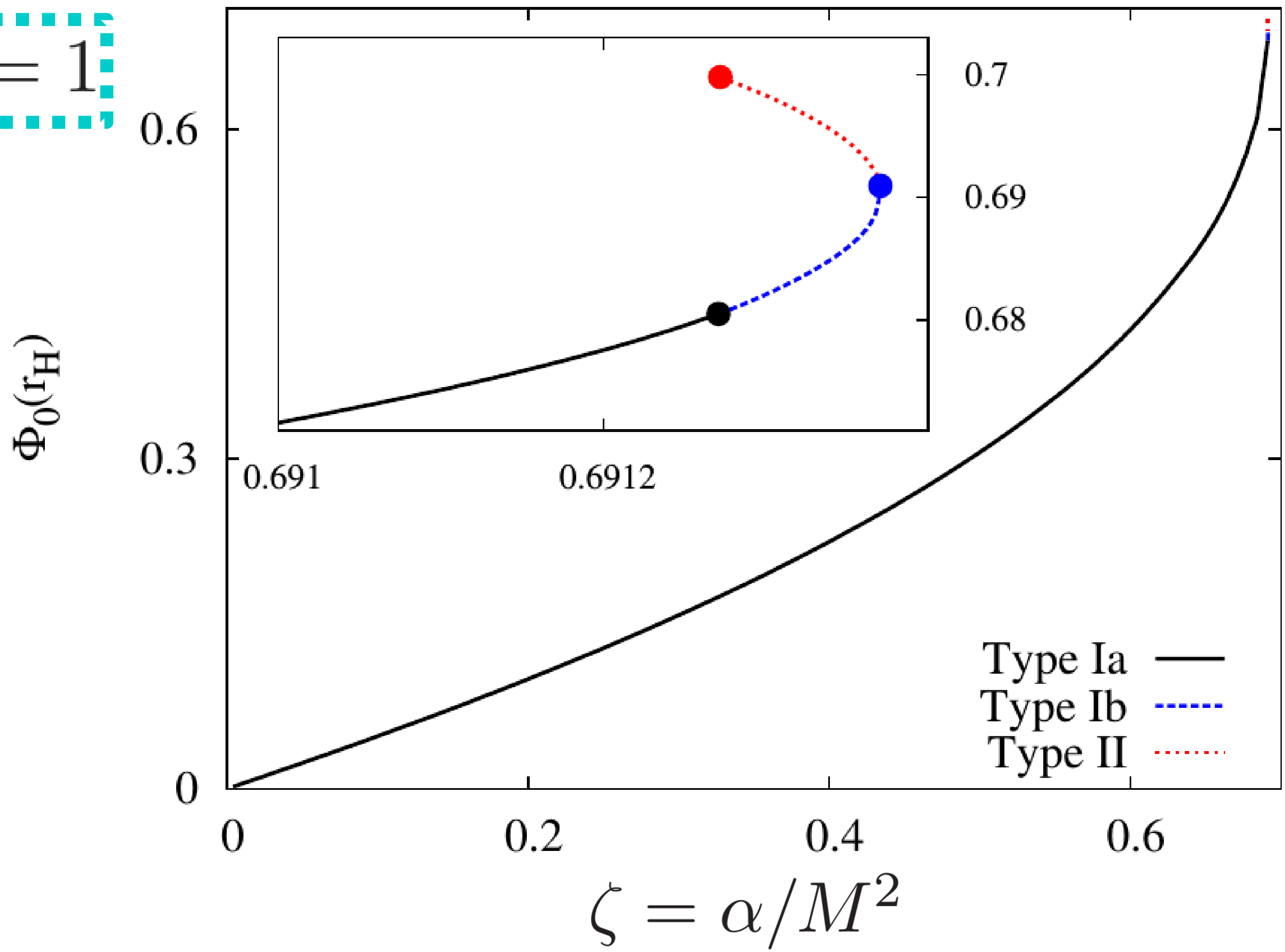
$$K(r) \approx 1 + 2M/r$$

$$F(r) \approx 1 - 2M/r + f_2/r^2$$

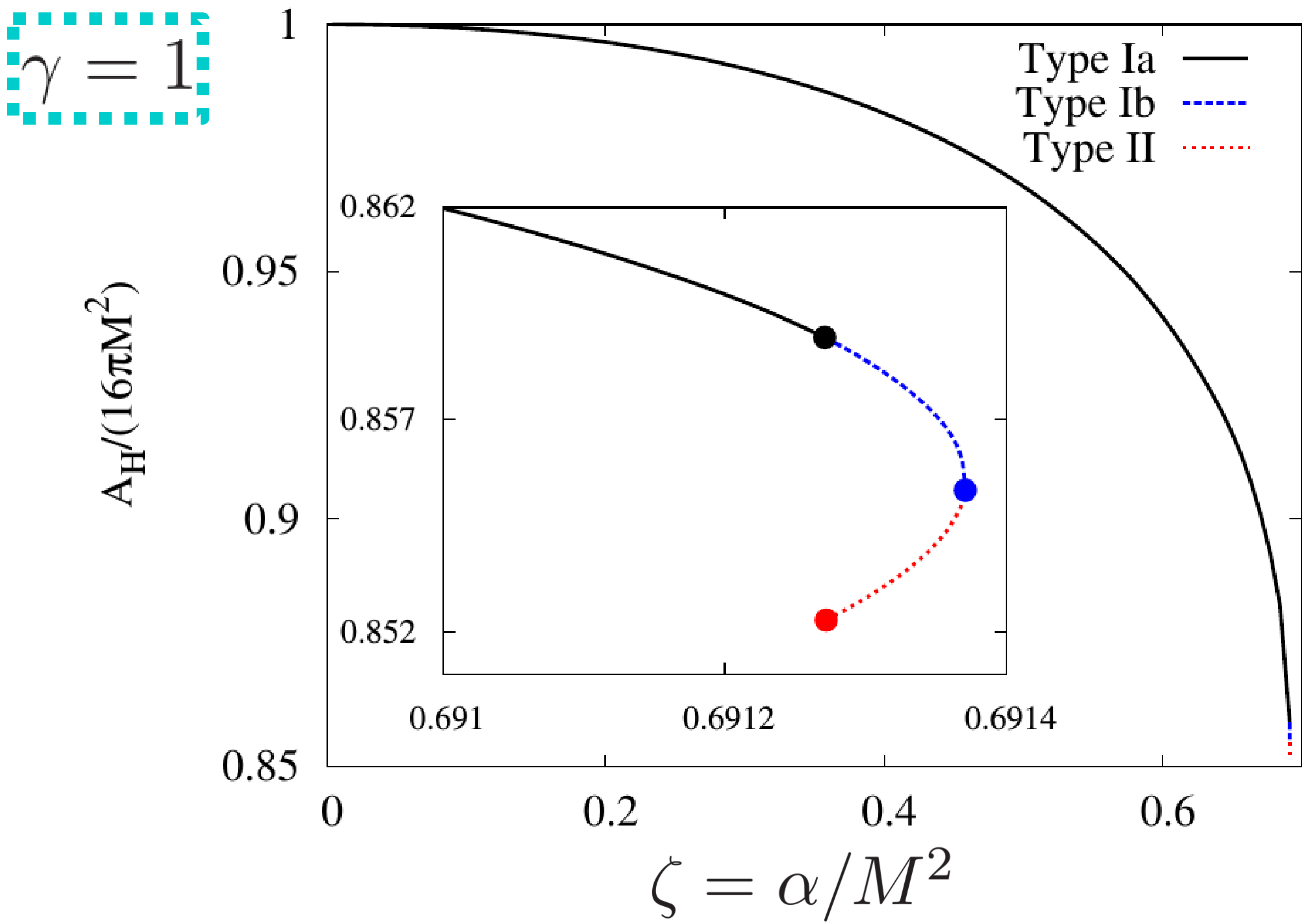
$$\Phi_0(r) = Q/r$$

2. Black holes in sEGB theory

$\gamma = 1$



2. Black holes in sEGB theory



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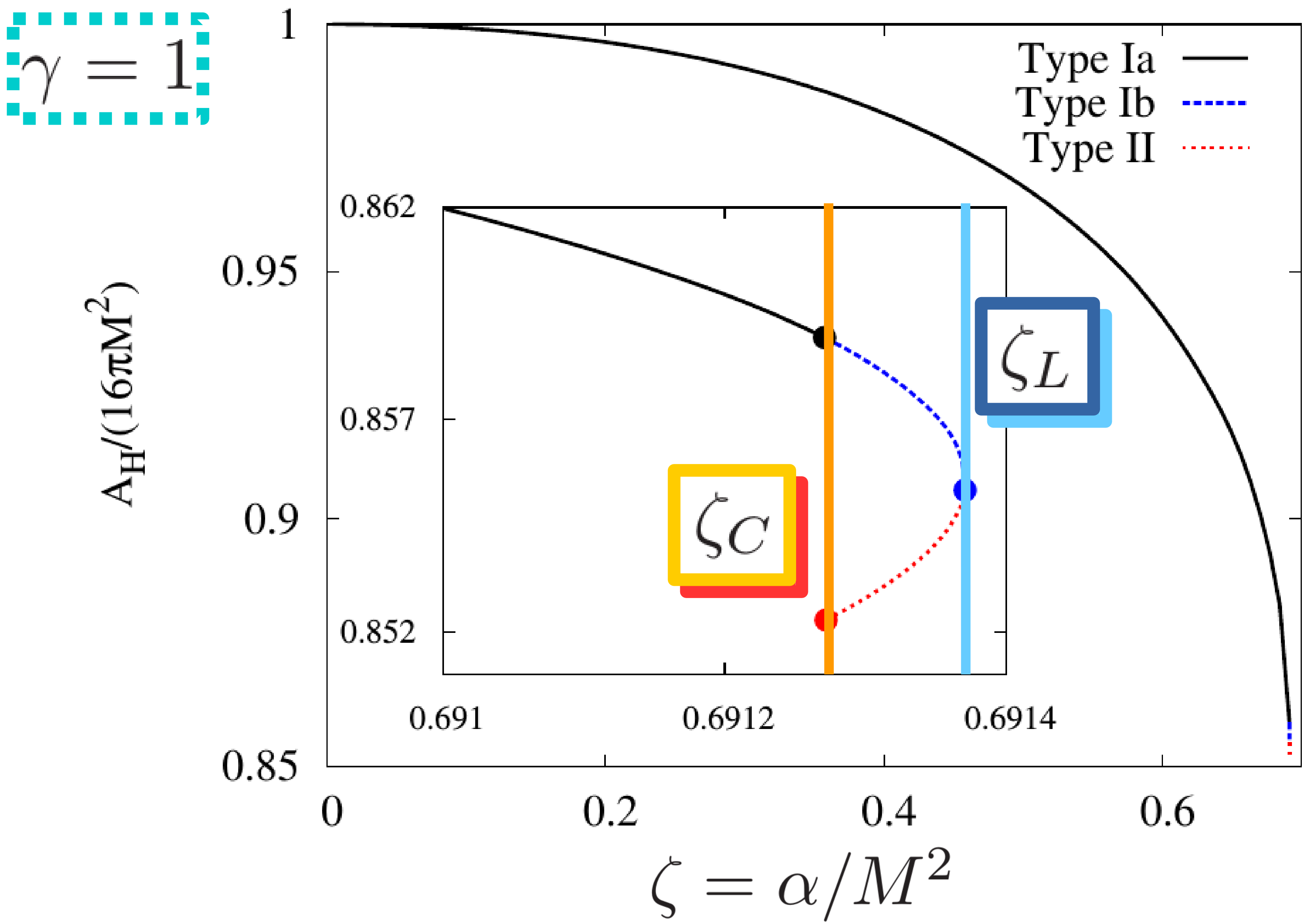

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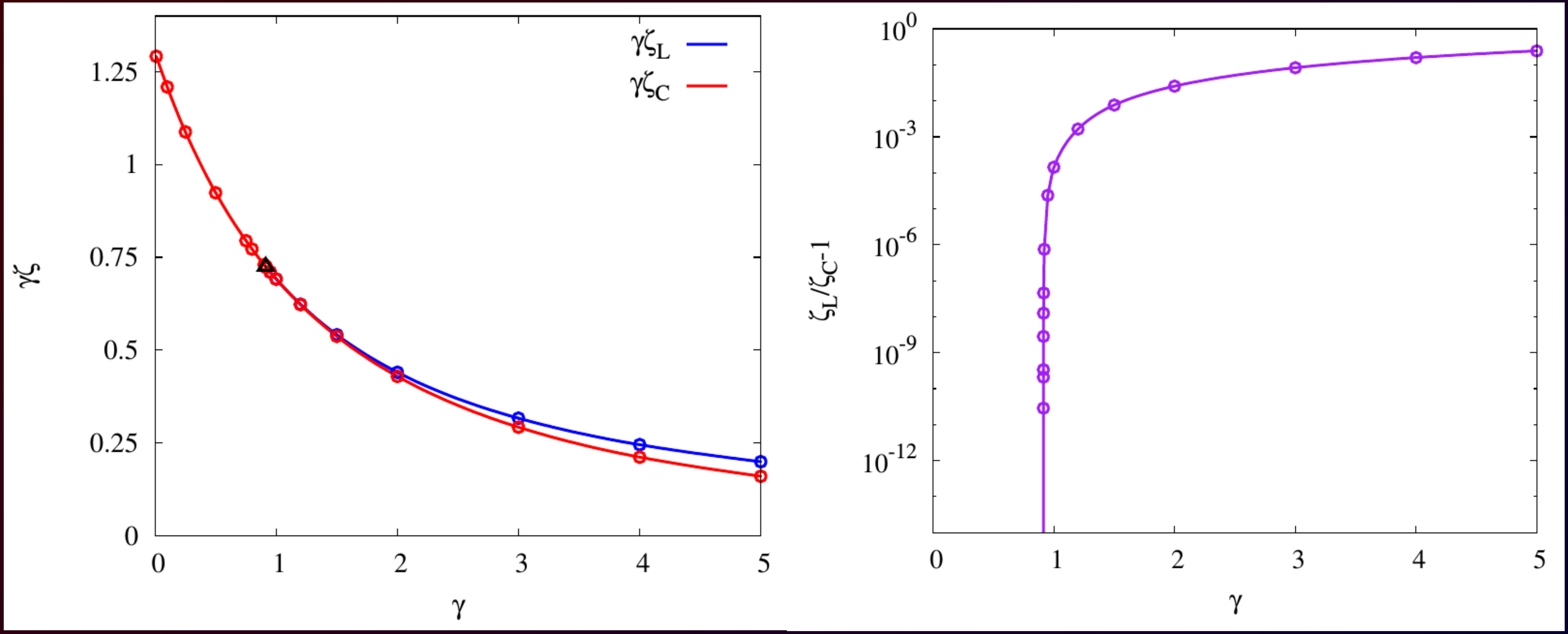

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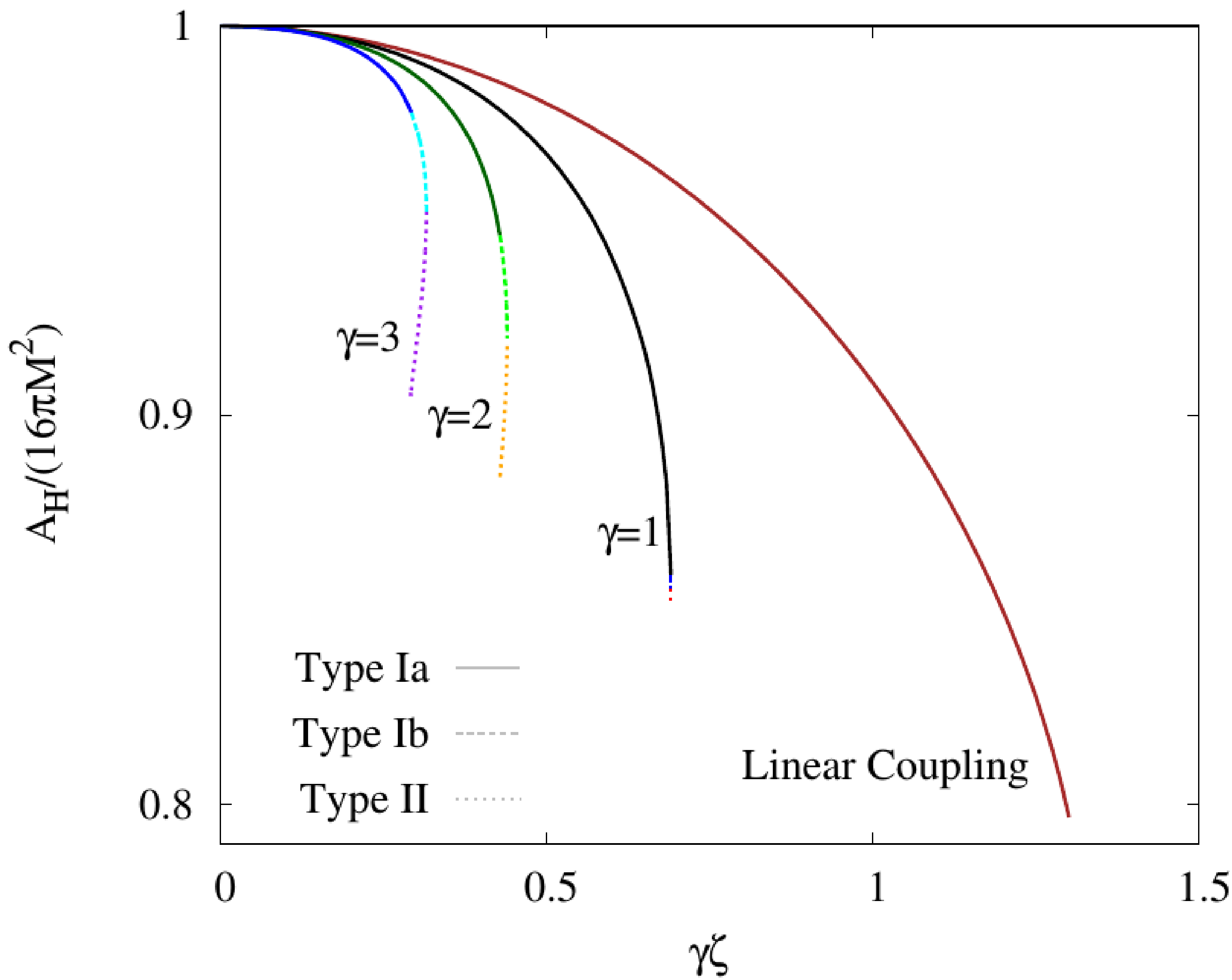

2. Black holes in sEGB theory

a) Perturbations theory and quasinormal modes

2. a) Perturbation theory and quasinormal modes

Non-radial perturbations of the static configuration:

$$g_{\mu\nu} = g_{\mu\nu}^{(0)}(r) + \epsilon h_{\mu\nu}(t, r, \theta, \varphi)$$
$$\Phi = \Phi_0(r) + \epsilon \delta\Phi(t, r, \theta, \varphi)$$

The perturbation depends in principle on all the coordinates (t,r,θ,φ)

Simplification:
- Expansion of the angular dependence in tensor harmonics (l,m)

Decoupling into axial $Y_{lm}(\theta,\varphi) \rightarrow Y_{lm}(\pi-\theta,\pi+\varphi) = (-1)^{l+1} Y_{lm}(\theta,\varphi)$

– polar $Y_{lm}(\theta,\varphi) \rightarrow Y_{lm}(\pi-\theta,\pi+\varphi) = (-1)^{l} Y_{lm}(\theta,\varphi)$

- Laplace transformation of the temporal dependence ($\omega=\omega_R+i\omega_I$)

2. a) Perturbation theory and quasinormal modes

Ansatz for axial perturbations:

$$h_{\mu\nu}^{(\text{axial})} = \int d\omega\, e^{-i\omega t} \sum_{l,m} \begin{bmatrix} 0 & 0 & -h_0 \frac{1}{\sin\theta}\frac{\partial}{\partial\varphi} Y_{lm} & h_0 \sin\theta \frac{\partial}{\partial\theta} Y_{lm} \\ 0 & 0 & -h_1 \frac{1}{\sin\theta}\frac{\partial}{\partial\varphi} Y_{lm} & h_1 \sin\theta \frac{\partial}{\partial\theta} Y_{lm} \\ -h_0 \frac{1}{\sin\theta}\frac{\partial}{\partial\varphi} Y_{lm} & -h_1 \frac{1}{\sin\theta}\frac{\partial}{\partial\varphi} Y_{lm} & h_2 \frac{1}{2\sin\theta} X_{lm} & -\frac{1}{2} h_2 \sin\theta\, W_{lm} \\ h_0 \sin\theta \frac{\partial}{\partial\theta} Y_{lm} & h_1 \sin\theta \frac{\partial}{\partial\theta} Y_{lm} & -\frac{1}{2} h_2 \sin\theta\, W_{lm} & -\frac{1}{2} h_2 \sin\theta\, X_{lm} \end{bmatrix}$$

$$W_{lm} = \frac{\partial^2}{\partial\theta^2} Y_{lm} - \cot\theta \frac{\partial}{\partial\theta} Y_{lm} - \frac{1}{\sin^2\theta} \frac{\partial^2}{\partial\varphi^2} Y_{lm} \,, \qquad X_{lm} = 2 \frac{\partial^2}{\partial\theta\,\partial\varphi} Y_{lm} - 2\cot\theta \frac{\partial}{\partial\varphi} Y_{lm}$$

We use the Regge-Wheler gauge: $h_2 = 0$

Axial perturbations do not couple to dilaton perturbations

2. a) Perturbation theory and quasinormal modes

Ansatz for polar perturbations:

$$h_{\mu\nu}^{(\text{polar})} = \int d\omega\, e^{-i\omega t} \sum_{l,m} \begin{bmatrix} 2NF(r)Y_{lm} & -H_1 Y_{lm} & -h_{0p}\frac{\partial}{\partial\theta}Y_{lm} & -h_{0p}\frac{\partial}{\partial\varphi}Y_{lm} \\ -H_1 Y_{lm} & -2K(r)LY_{lm} & h_{1p}\frac{\partial}{\partial\theta}Y_{lm} & h_{1p}\frac{\partial}{\partial\varphi}Y_{lm} \\ -h_{0p}\frac{\partial}{\partial\theta}Y_{lm} & h_{1p}\frac{\partial}{\partial\theta}Y_{lm} & B & -r^2 V X_{lm} \\ -h_{0p}\frac{\partial}{\partial\varphi}Y_{lm} & h_{1p}\frac{\partial}{\partial\varphi}Y_{lm} & -r^2 V X_{lm} & A \end{bmatrix}$$

$$A = (l(l+1)V - 2T)r^2 \sin^2\theta\, Y_{lm} + r^2 V \sin^2\theta\, W_{lm}$$
$$B = (l(l+1)V - 2T)r^2 Y_{lm} - r^2 V W_{lm}$$

Gauge fixing: $h_{0p} = h_{1p} = V = 0.$

Scalar polar perturbations:

$$\delta\Phi = \int d\omega\, e^{-i\omega t} \sum_{l,m} \Phi_1\, Y_{lm}$$

2. a) Perturbation theory and quasinormal modes

Axial equations:

$$\frac{d}{dr}\Psi_{(i)} + U_{(i)}\Psi_{(i)} = 0$$

$$\Psi_{axial} = (h_0, h_1)$$

Outgoing wave at infinity:

$$h_0(r) \approx e^{i\omega r_*} \cdot [h_{00} + \frac{h_{01}}{r} + O(r^{-2})] \,,$$

$$h_1(r) \approx e^{i\omega r_*} \cdot [-h_{00} + \frac{i}{\omega}((2iM\omega - 1)h_{01} + i\omega h_{00})\frac{1}{r} + O(r^{-2})] \,,$$

$$h_{01} = \frac{ih_{00}}{8\omega}(\omega^2(4f_2 + Q^2) + 4(l+2)(l-1))$$

2. a) Perturbation theory and quasinormal modes

Axial equations:

$$\frac{d}{dr}\Psi_{(i)} + U_{(i)}\Psi_{(i)} = 0$$

$$\Psi_{axial} = (h_0, h_1)$$

Ingoing wave at the horizon:

$$h_0(r) \approx \frac{e^{-i\omega r_*}}{r - r_H} \cdot [\hat{h}_{00} + O(r - r_H)] \ ,$$

$$h_1(r) \approx -\frac{e^{-i\omega r_*}}{r_H} \cdot [\hat{h}_{10} + O(r - r_H)] \ .$$

$$\hat{h}_{10} = -\hat{h}_{00}\sqrt{\frac{\alpha\gamma\Phi_{01} + 2e^{\gamma\Phi_{00}} r_H}{2r_H^2 f_1 e^{\gamma\Phi_{00}}}}$$

2. a) Perturbation theory and quasinormal modes

Polar equations:

$$\frac{d}{dr}\Psi_{(i)} + U_{(i)}\Psi_{(i)} = 0$$

$$\Psi_{polar} = (H_1, T, \Phi_1, \tfrac{d}{dr}\Phi_1)$$

Outgoing wave at infinity:

$$\begin{aligned}
T(r) &\approx e^{i\omega r_*} \cdot [T_0 + O(r^{-2})] \ , \\
H_1(r) &\approx \omega r e^{i\omega r_*} \cdot [-T_0 - \frac{1}{2\omega r}(4M\omega + i(l^2 + l - 2))T_0 + O(r^{-2})] \ , \\
\Phi_1(r) &\approx e^{i\omega r_*} \cdot \frac{1}{r} \cdot [\Phi_{10} - \frac{i}{2\omega r}(2iM\omega Q T_0 - l(l+1)\Phi_{10}) + O(r^{-2})]
\end{aligned}$$

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Ingoing wave at the horizon:

$$T(r) \approx e^{-i\omega r_*}\cdot[\hat{T}_0 + O(r-r_H)]\ ,$$

$$H_1(r) \approx e^{-i\omega r_*}\cdot\frac{\omega}{r-r_H}\cdot[\hat{H}_{10} + O(r-r_H)]\ ,$$

$$\Phi_1(r) \approx e^{-i\omega r_*}\cdot[\hat{\Phi}_{10} + O(r-r_H)]\ .$$

$$\hat{H}_{10} = \frac{D_2}{D_1}(e^{-\gamma\Phi_{00}}\alpha\gamma\hat{\Phi}_{10} - r_H^3\hat{T}_0)$$

$$D_2 := (4e^{\gamma\Phi_{00}}r_H + 2\alpha\gamma\Phi_{01})\omega^2 + e^{\gamma\Phi_{00}}f_1\ ,$$

$$D_1 := 2r_H[\alpha\gamma\Phi_{01} + 2e^{\gamma\Phi_{00}}r_H]\omega^2 - r_H f_1 e^{\gamma\Phi_{00}}l(l+1) + i\omega r_H e^{\gamma\Phi_{00}}(l^2+l+1)\sqrt{2\alpha\gamma e^{-\gamma\Phi_{00}}\Phi_{01}f_1 + 4r_H f_1}\ .$$

2. a) Perturbation theory and quasinormal modes

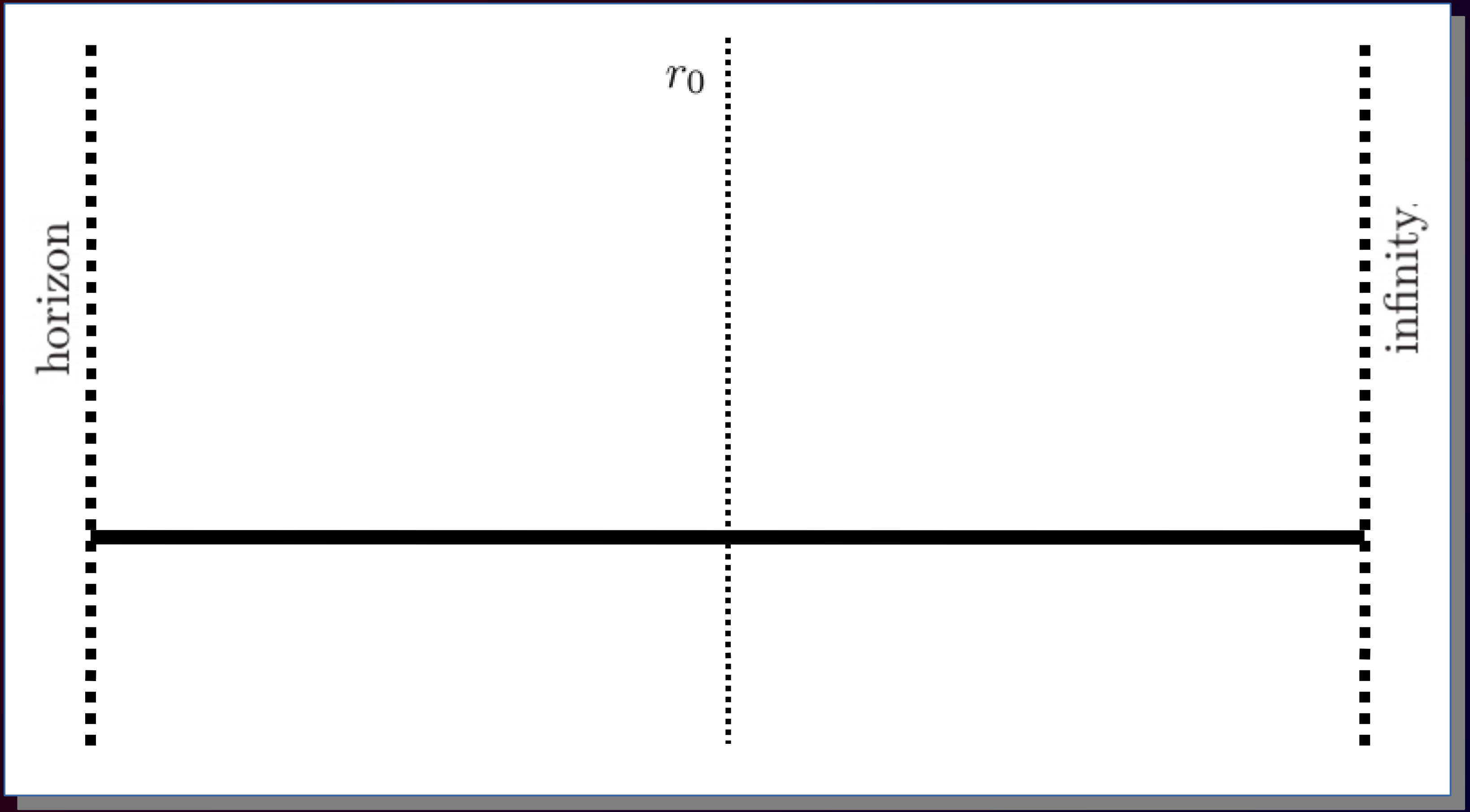
Numerical implementation:

Static back ground solution for a fixed mass, coupling constant, etc

2. a) Perturbation theory and quasinormal modes

Numerical implementation:

Divide background solution in two pieces



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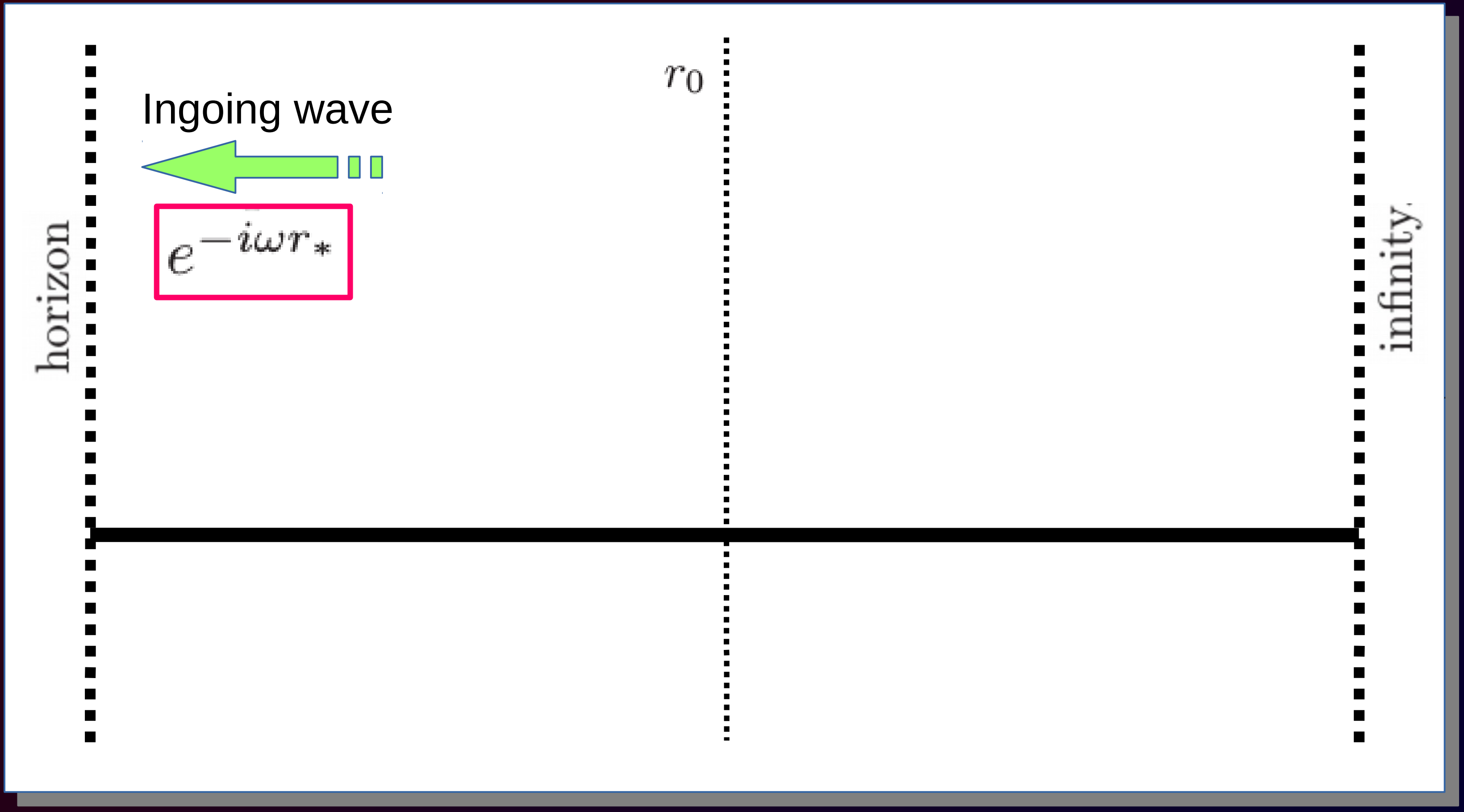
Numerical implementation:

Asymptotic behavior of the perturbation



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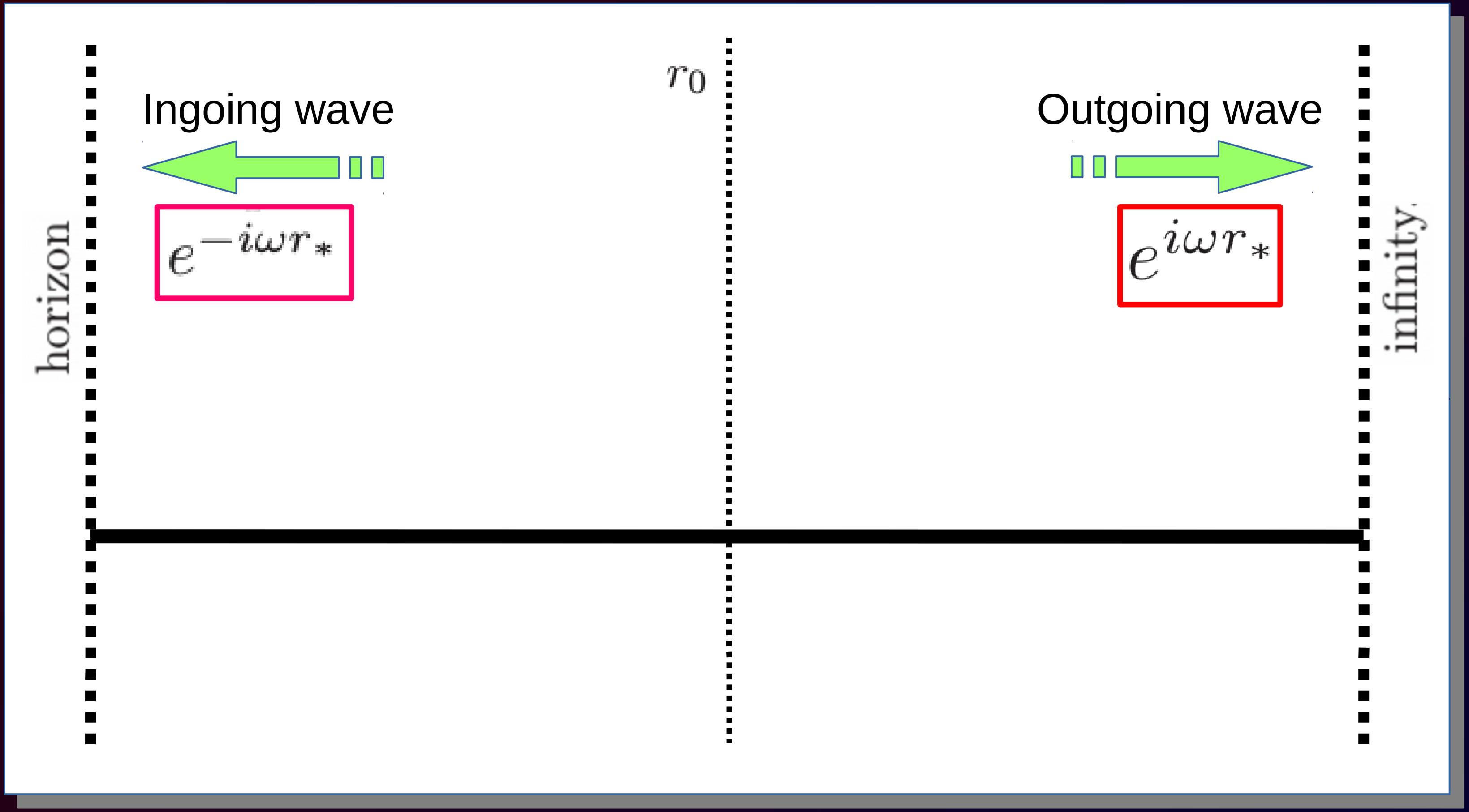

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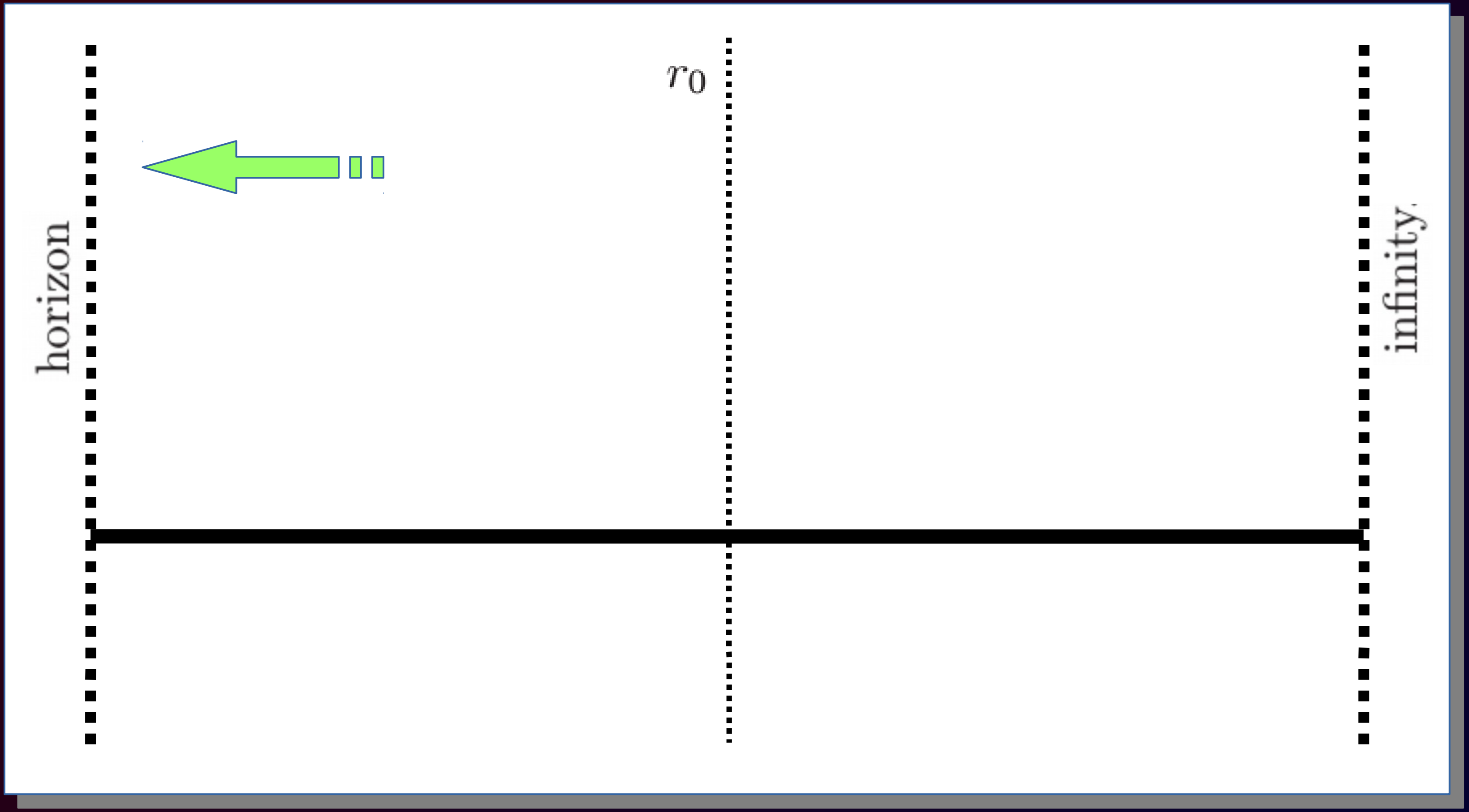
Numerical implementation:

Approximate perturbation close to the boundaries (analytical)



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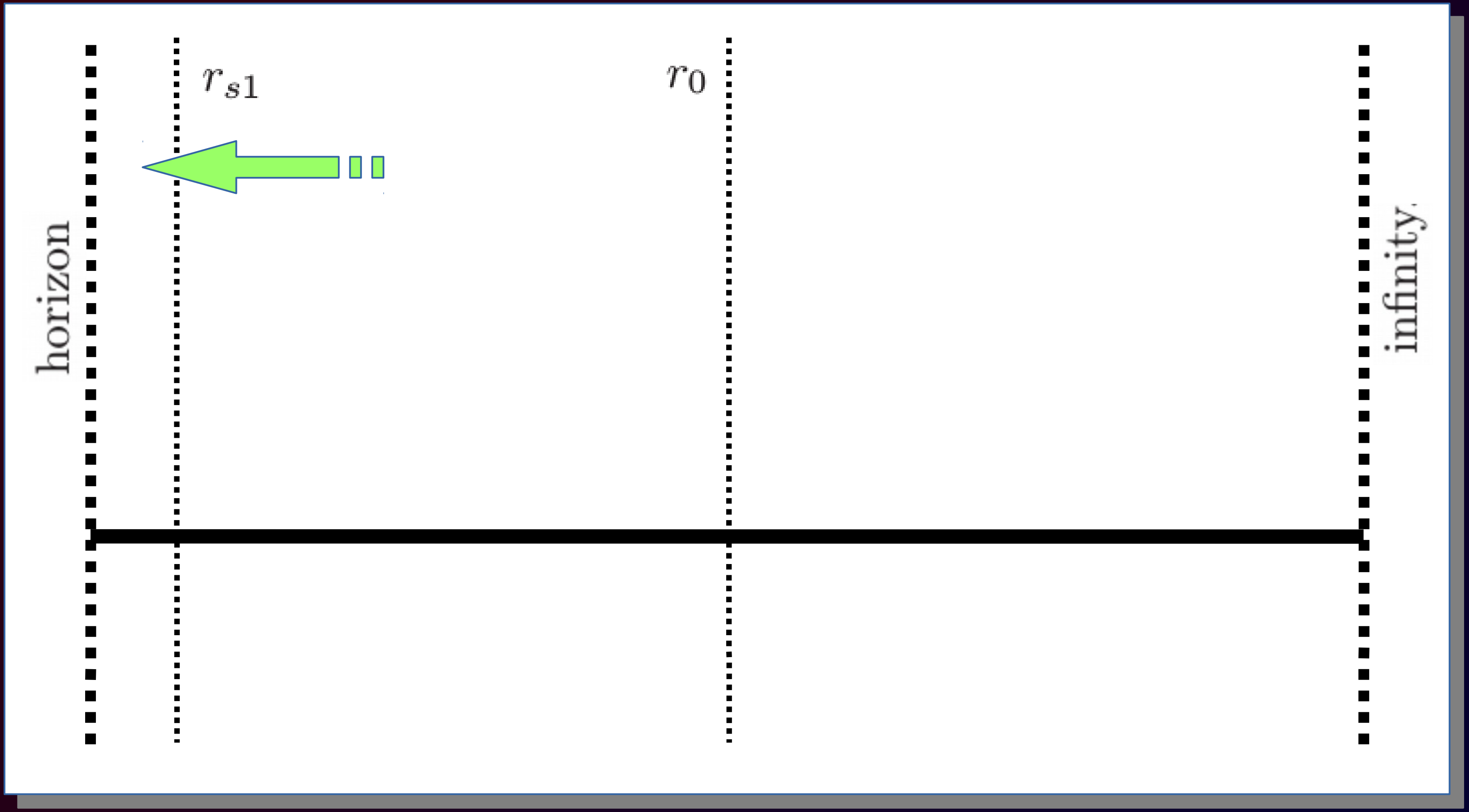

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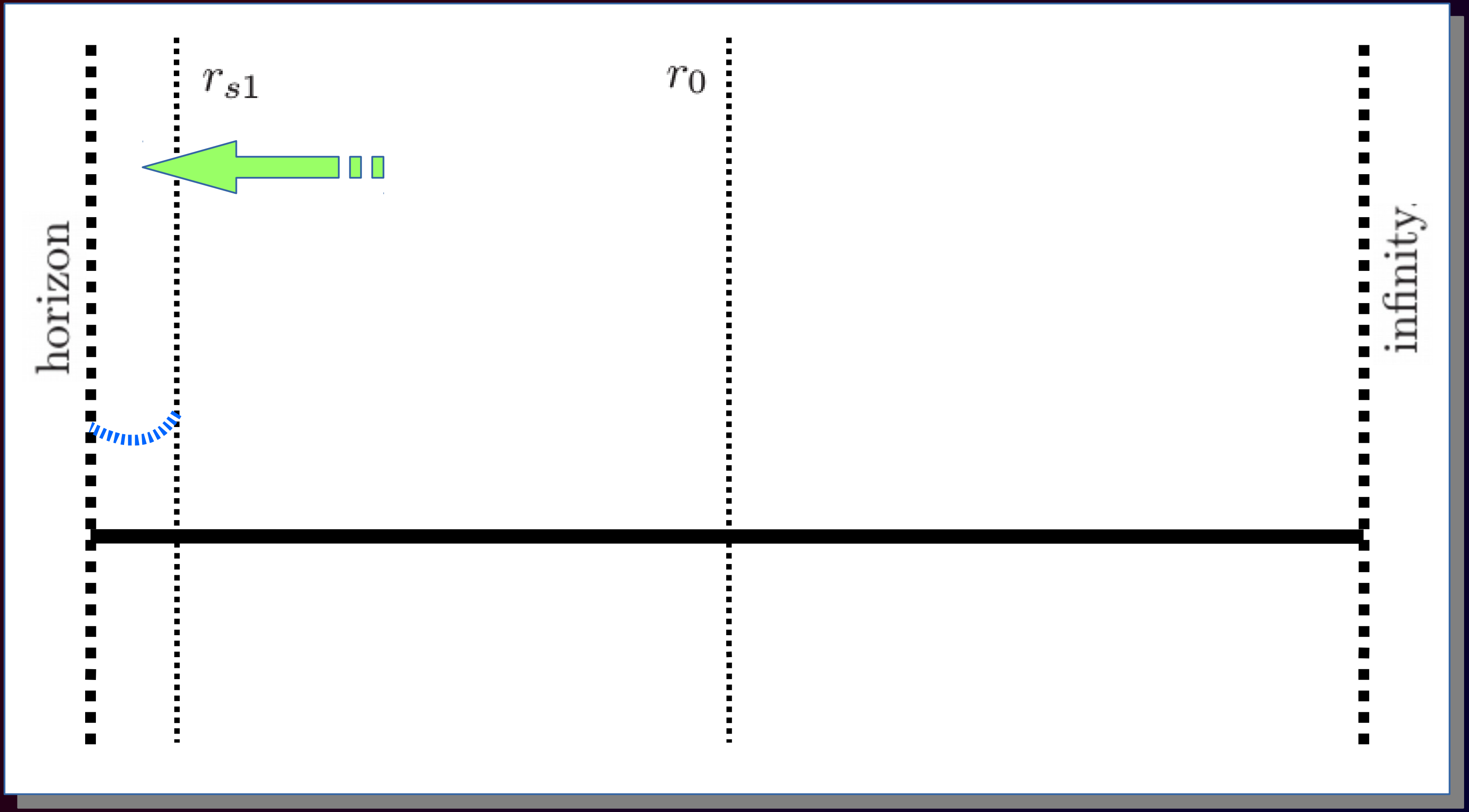

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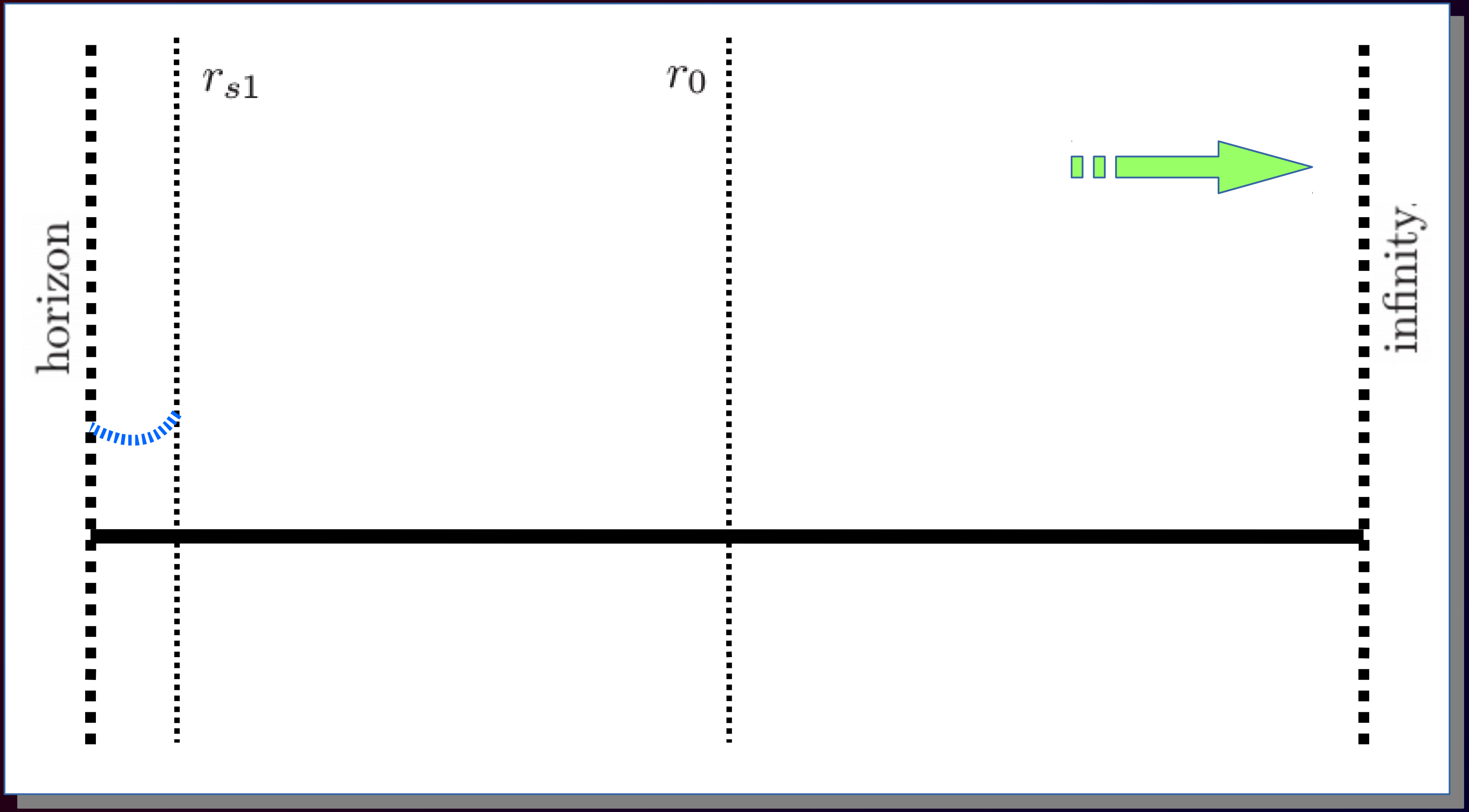

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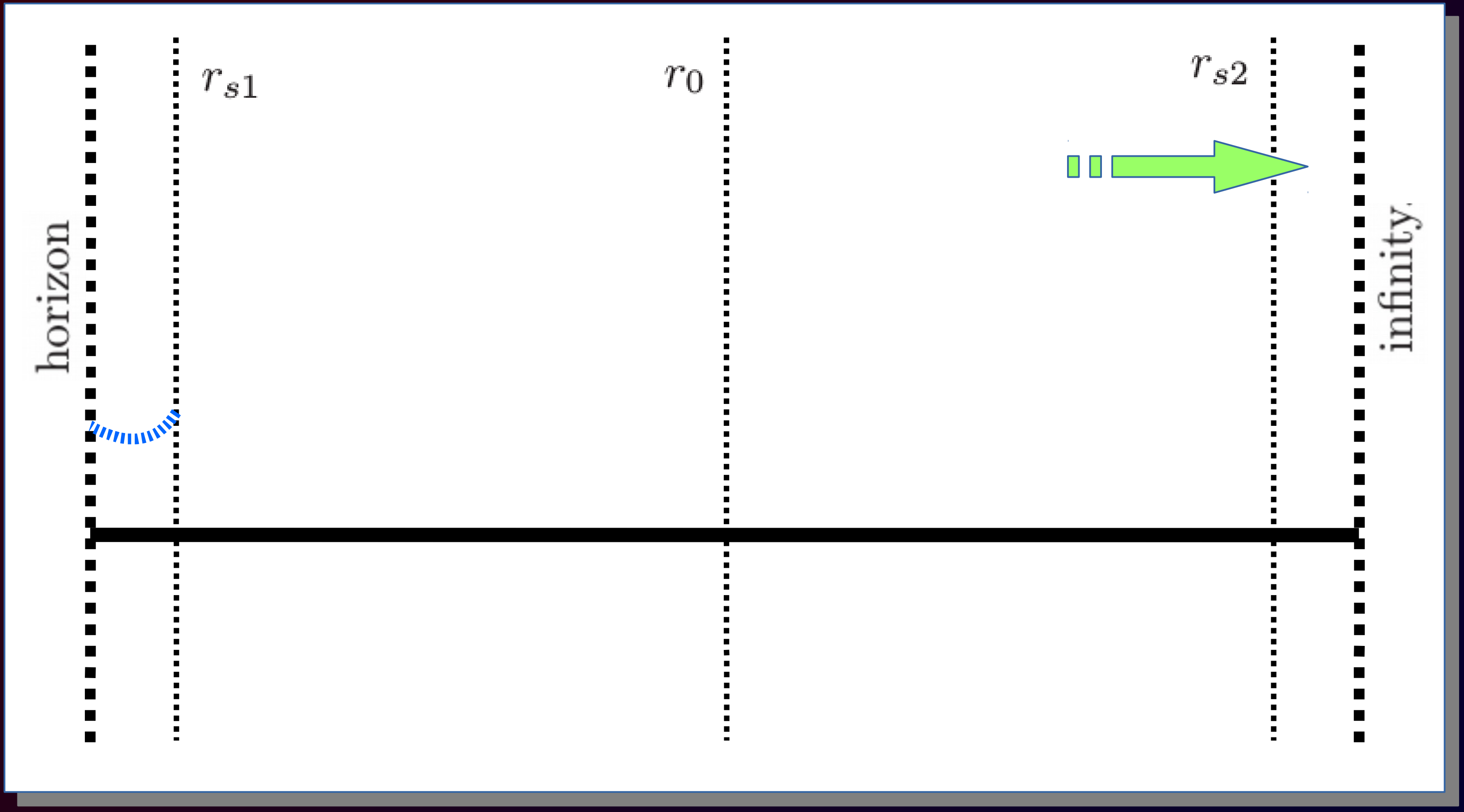

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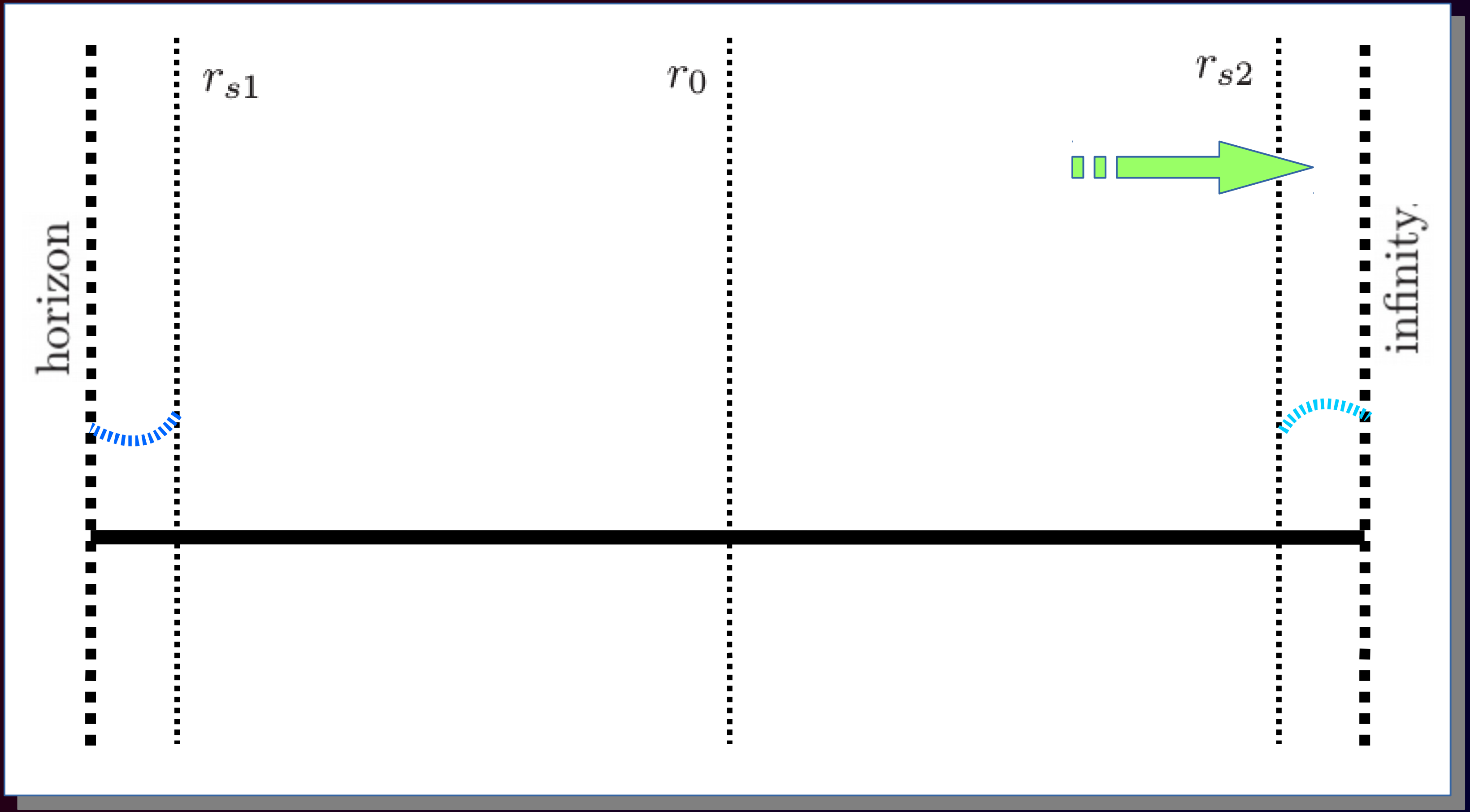
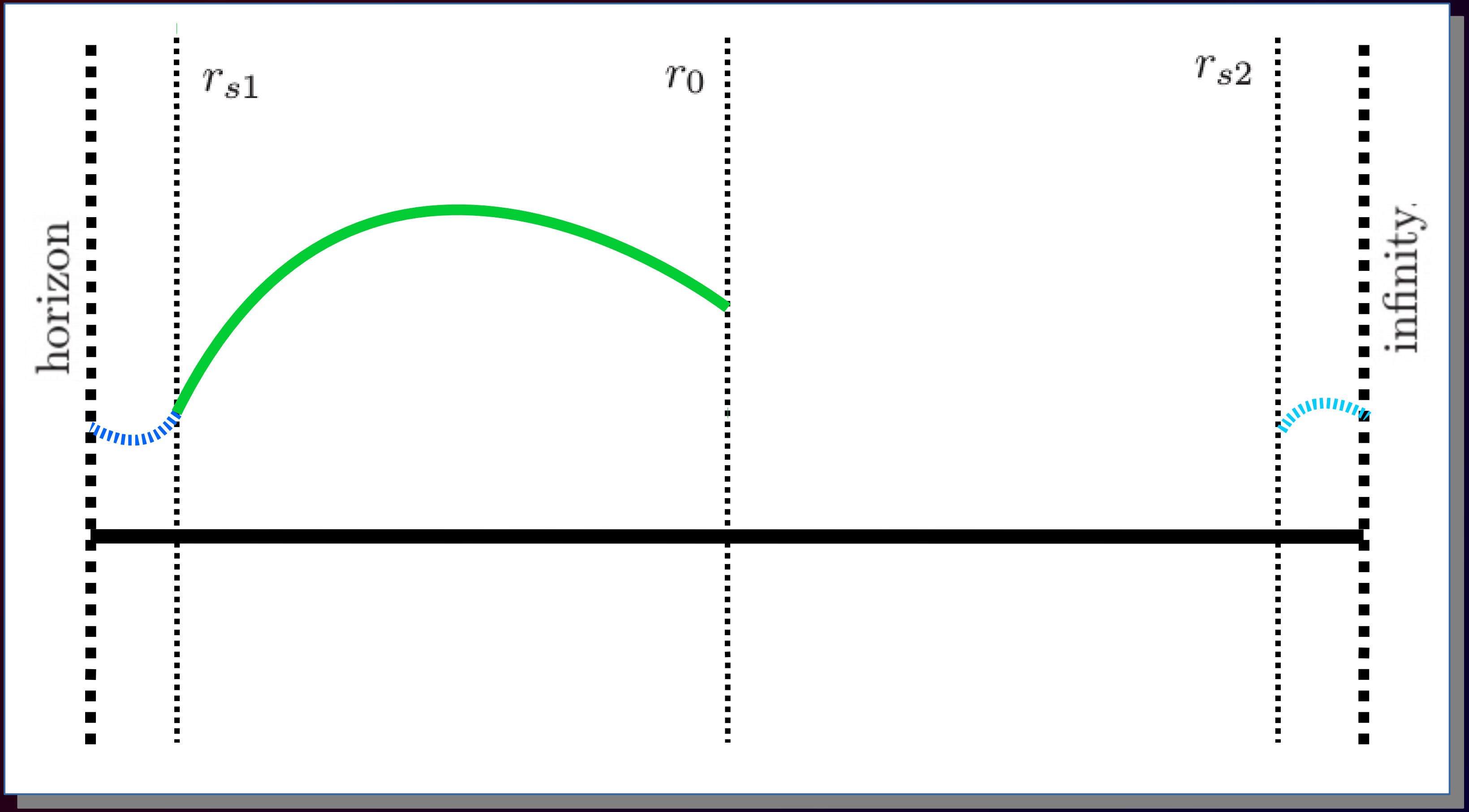


2. a) Perturbation theory and quasinormal modes

Numerical implementation:

Generate perturbations at each piece (numerical)



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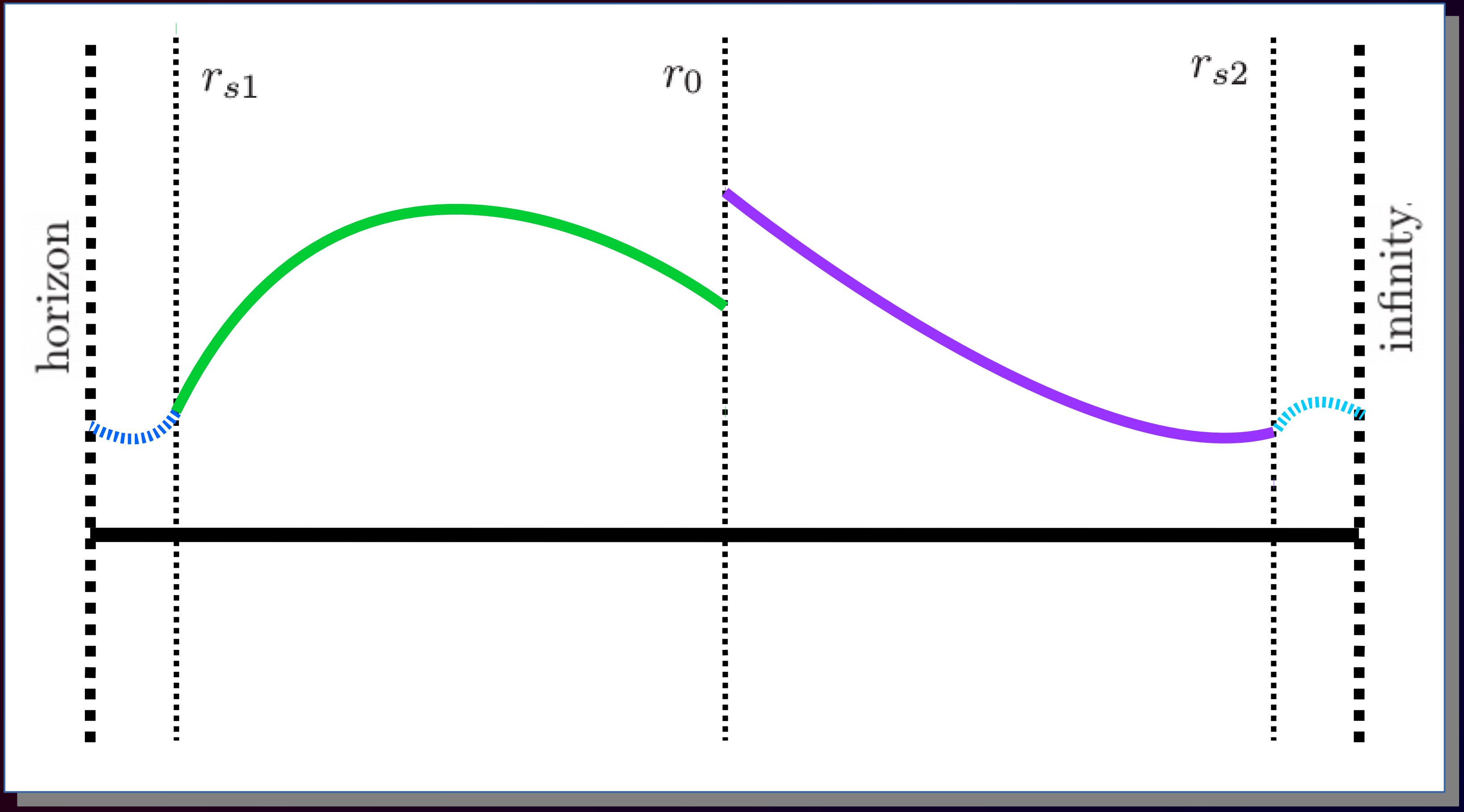
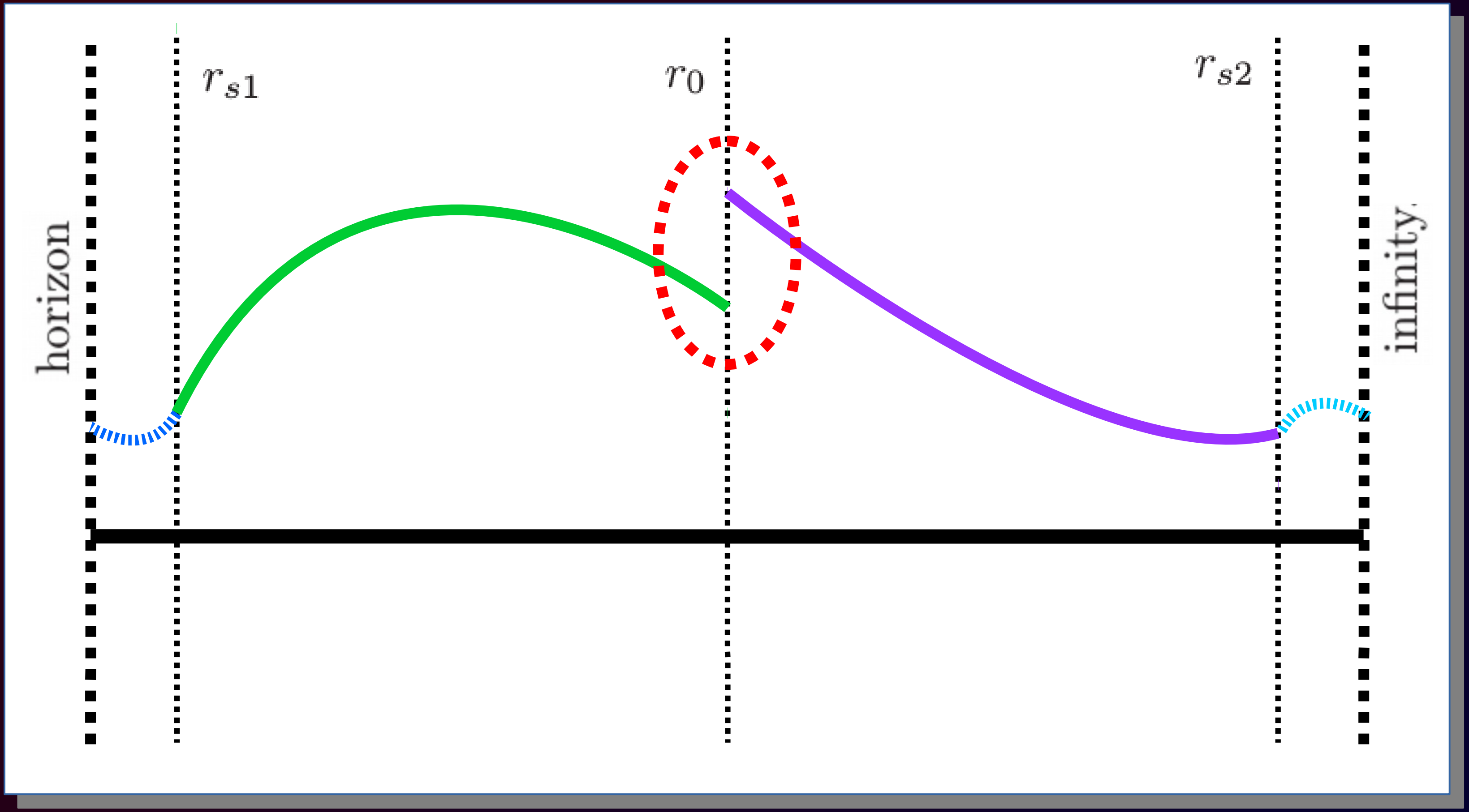


2. a) Perturbation theory and quasinormal modes

Numerical implementation:

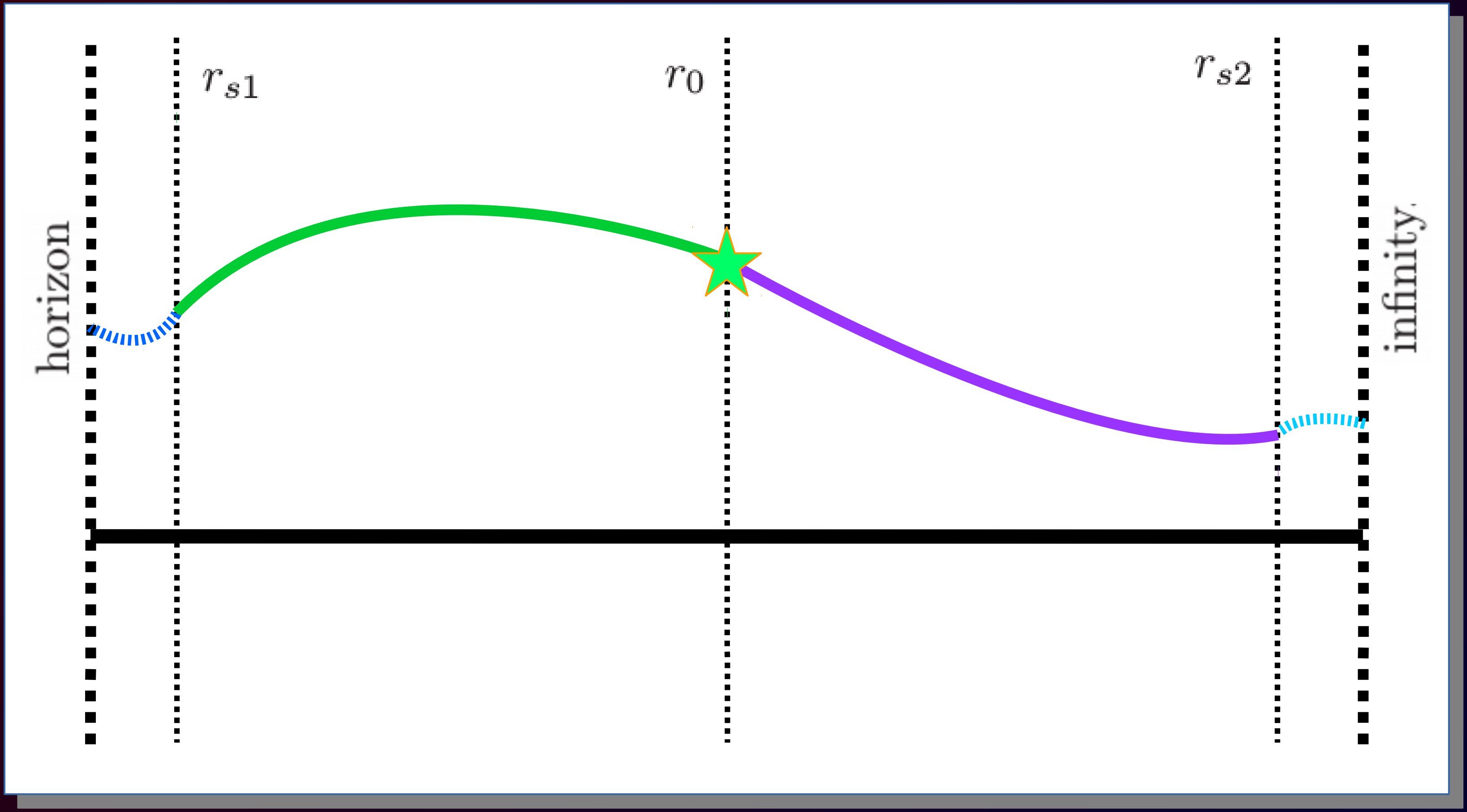
In general the perturbations are not continuous



2. a) Perturbation theory and quasinormal modes

Numerical implementation:

Repeat until the ω that satisfies junction conditions are satisfied



2. Black holes sEGB theory

b) Spectrum of the dilatonic black holes

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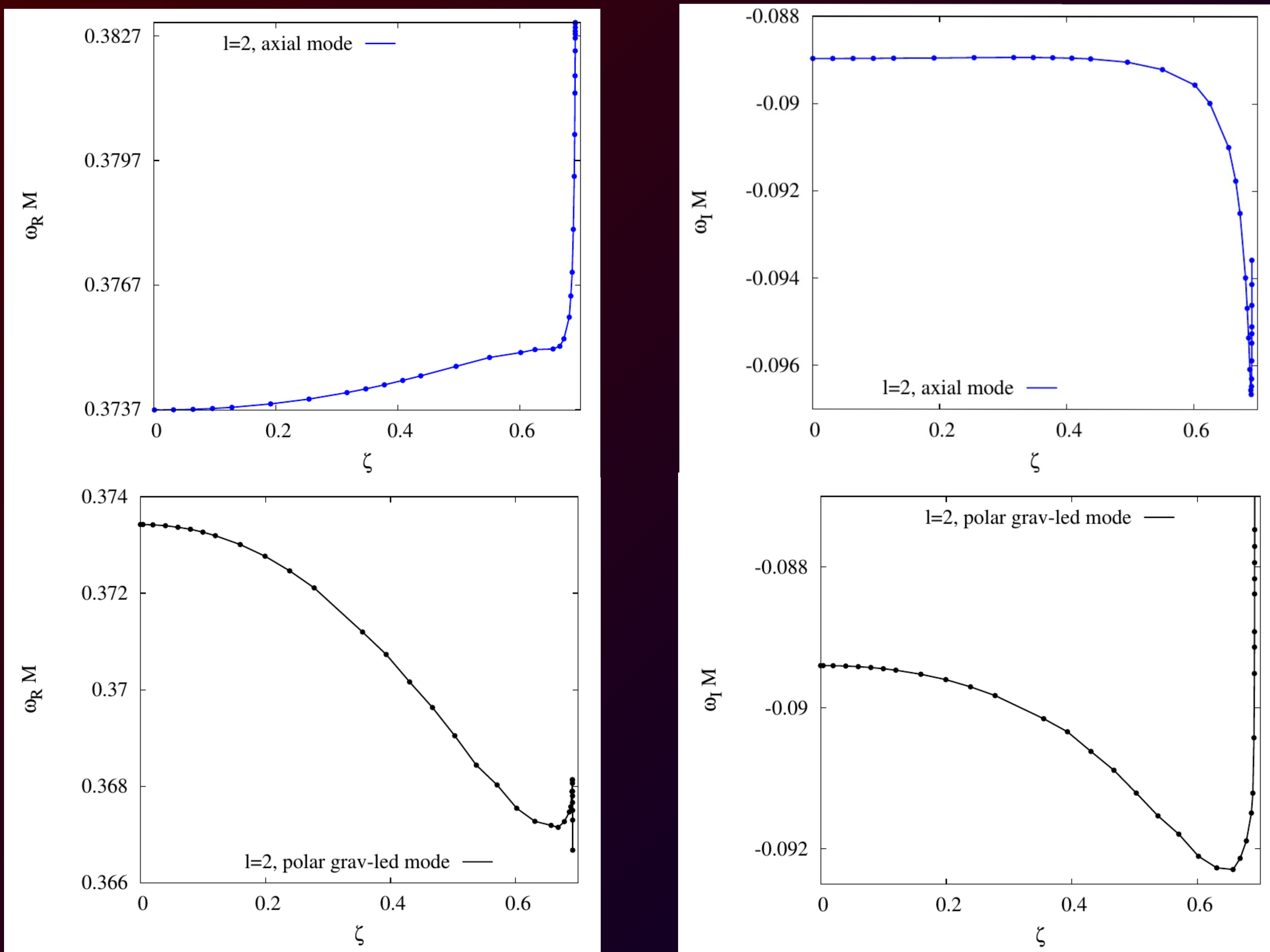
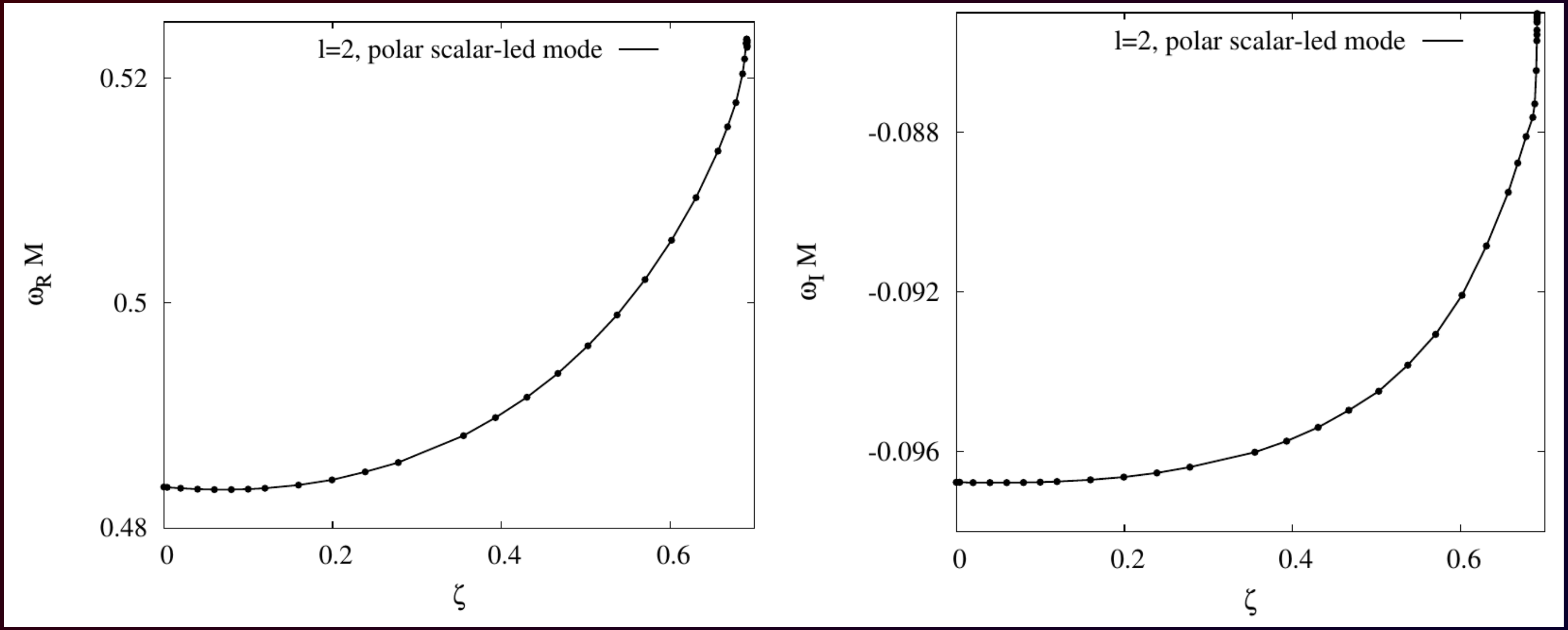
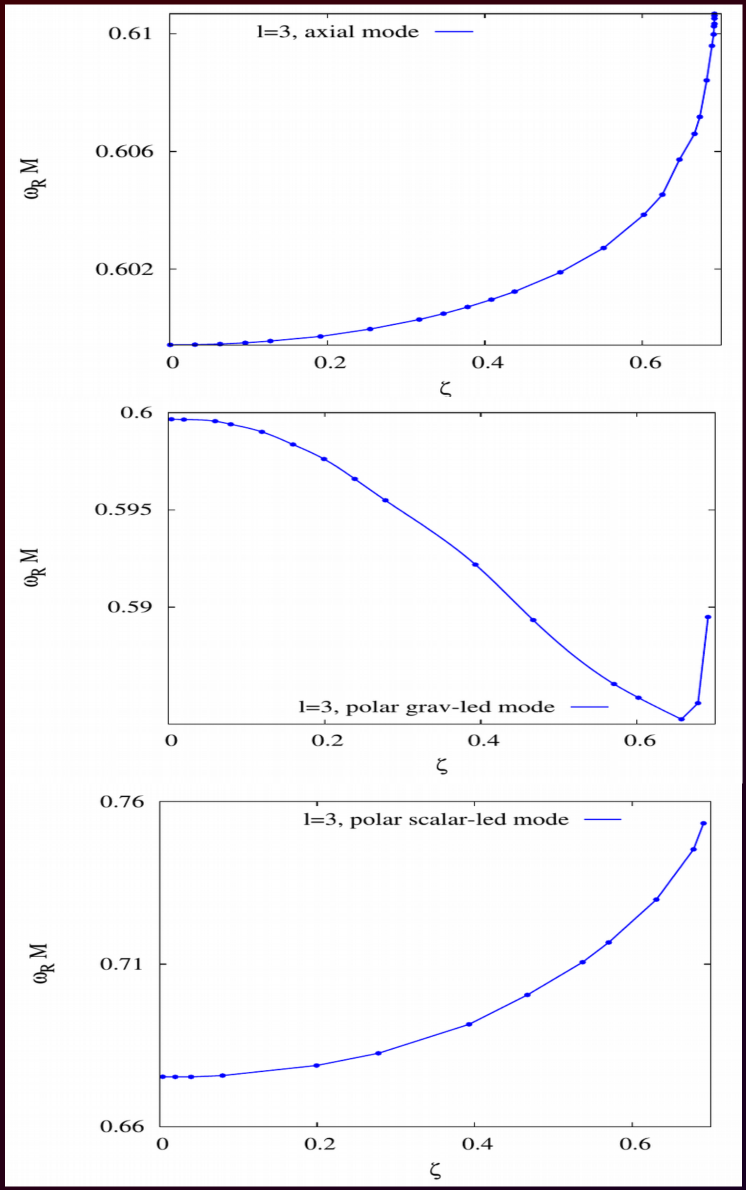
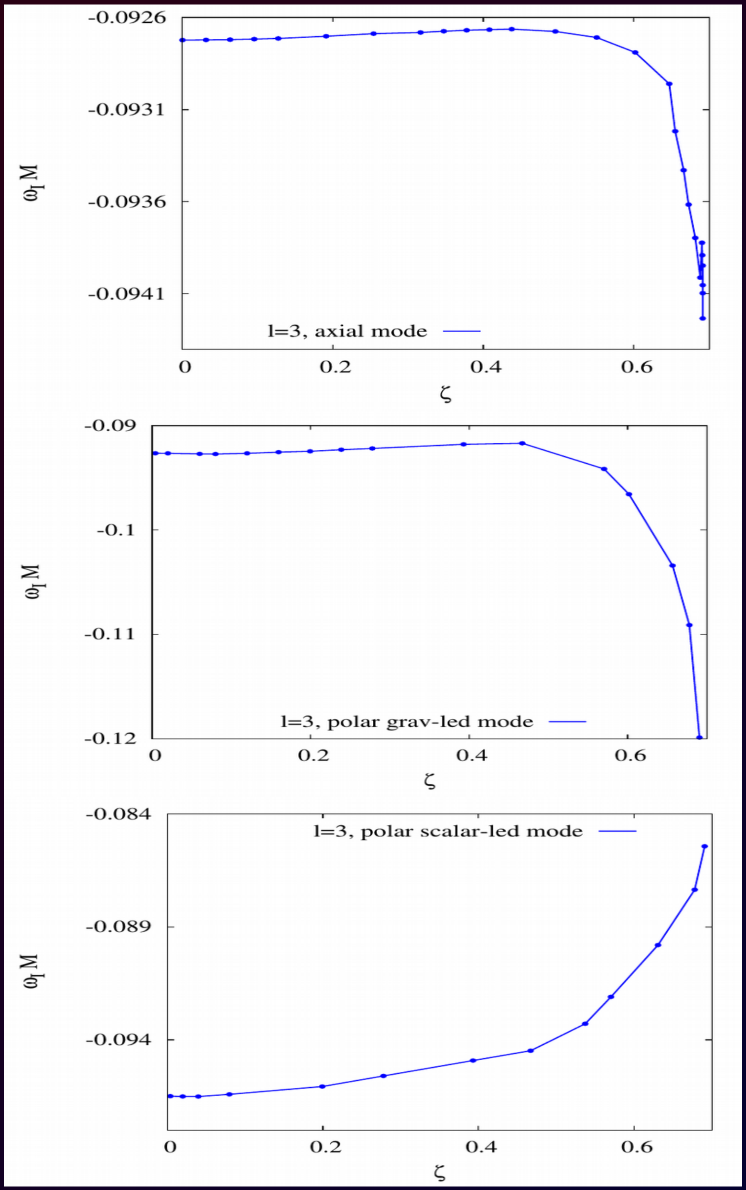


2. b) Spectrum of the dilatonic black holes



2. b) Spectrum of the dilatonic black holes





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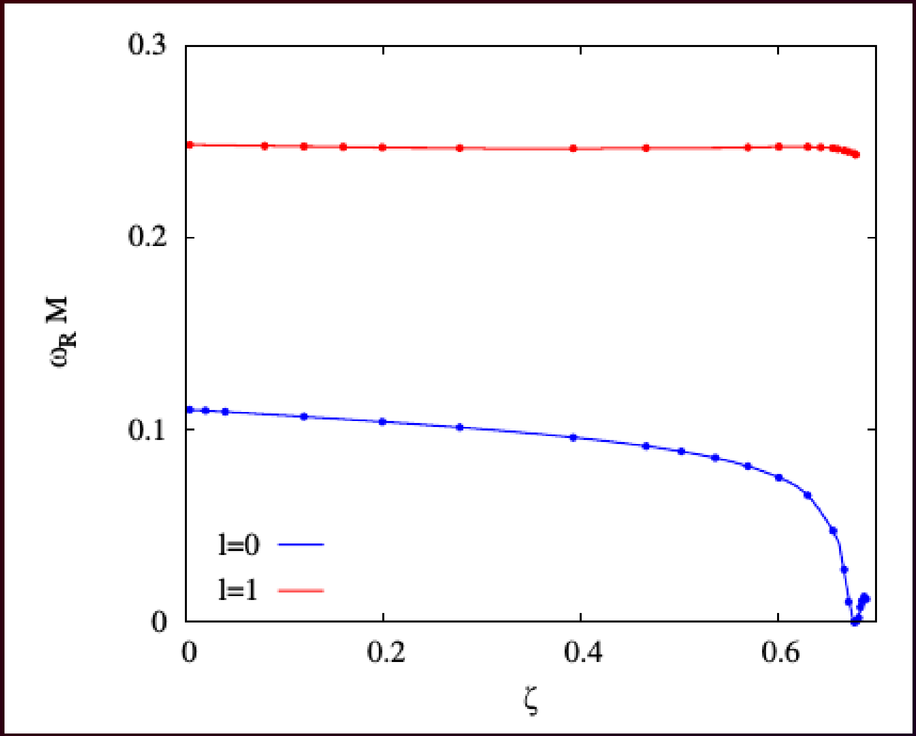
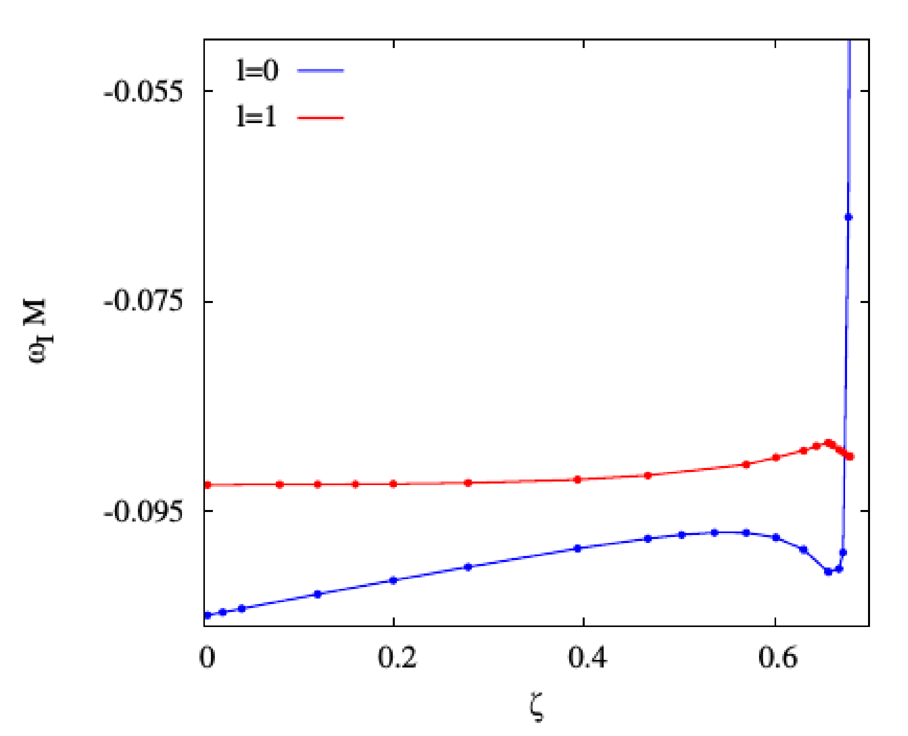
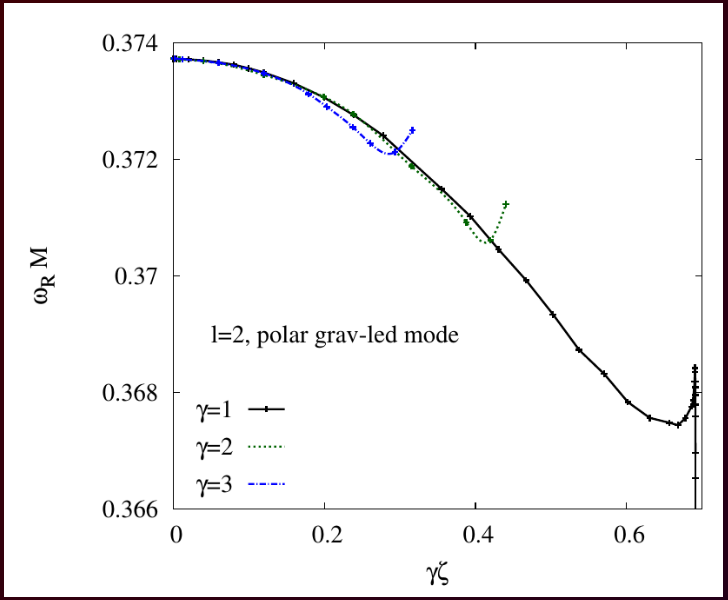
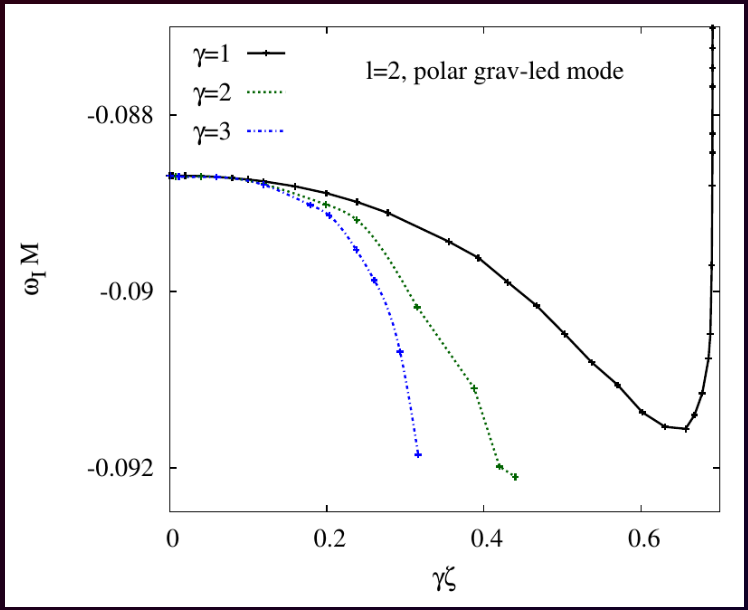
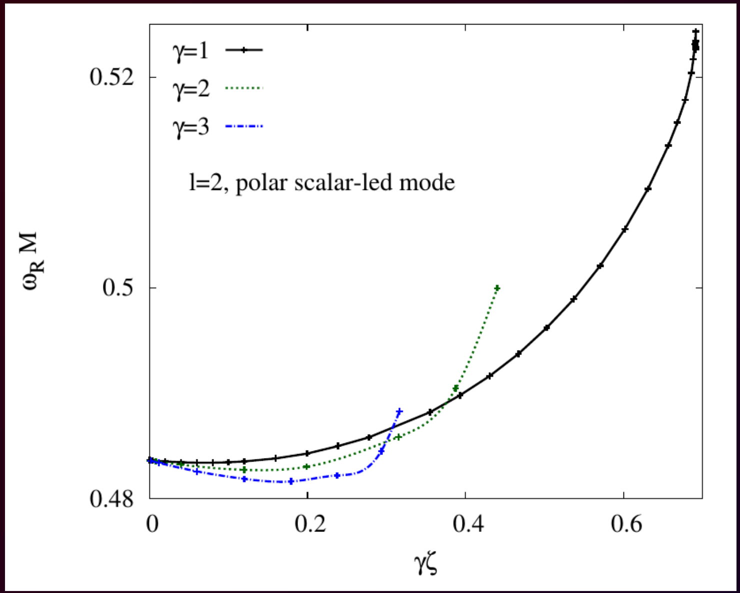


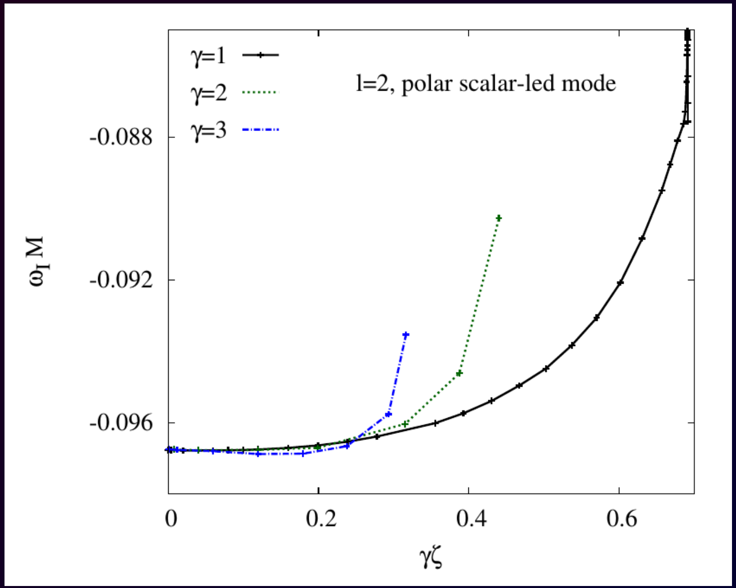


2. b) Spectrum of the dilatonic black holes









2. Black holes in sEGB theory

c) Stability: dilatonic vs scalarized

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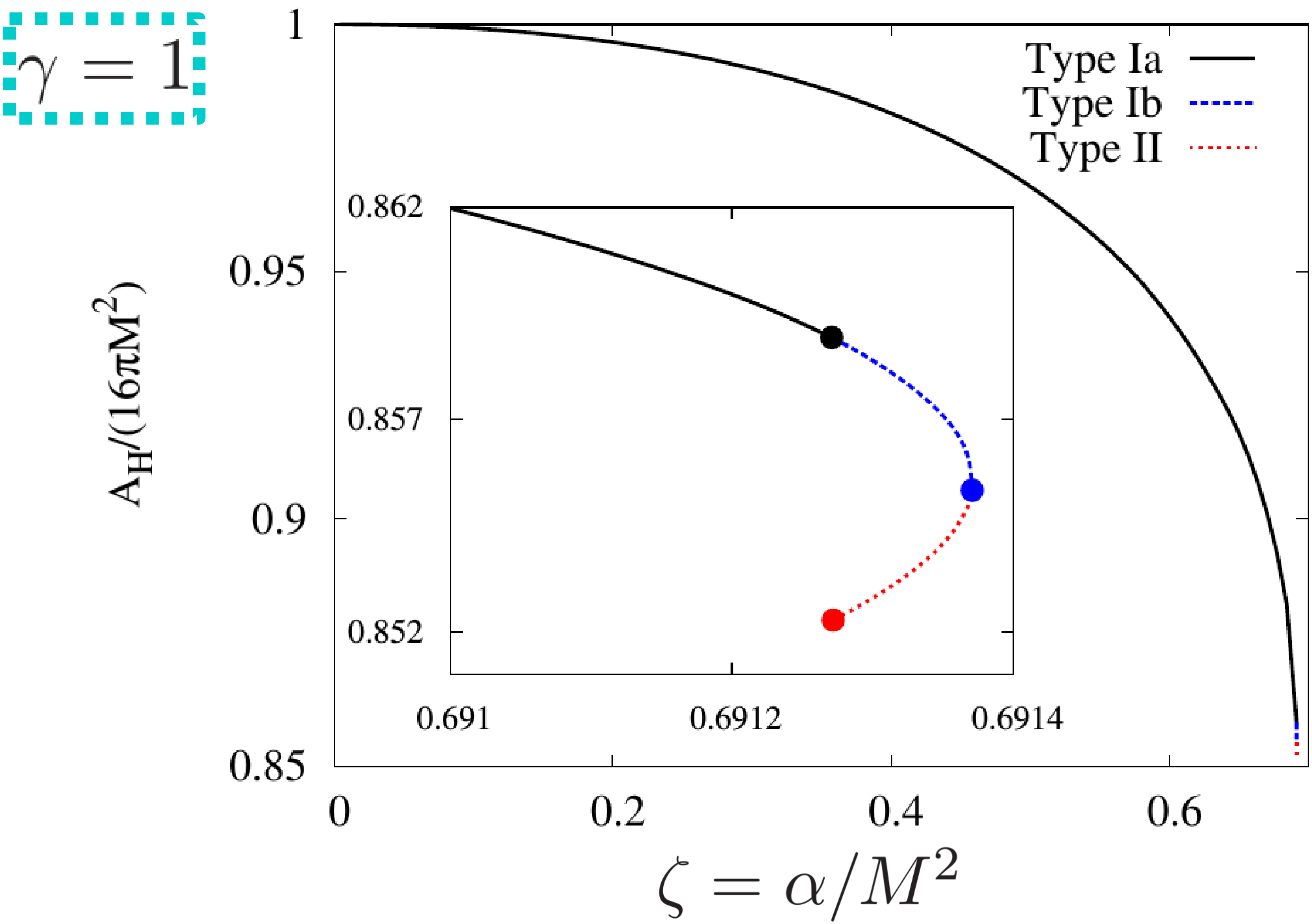

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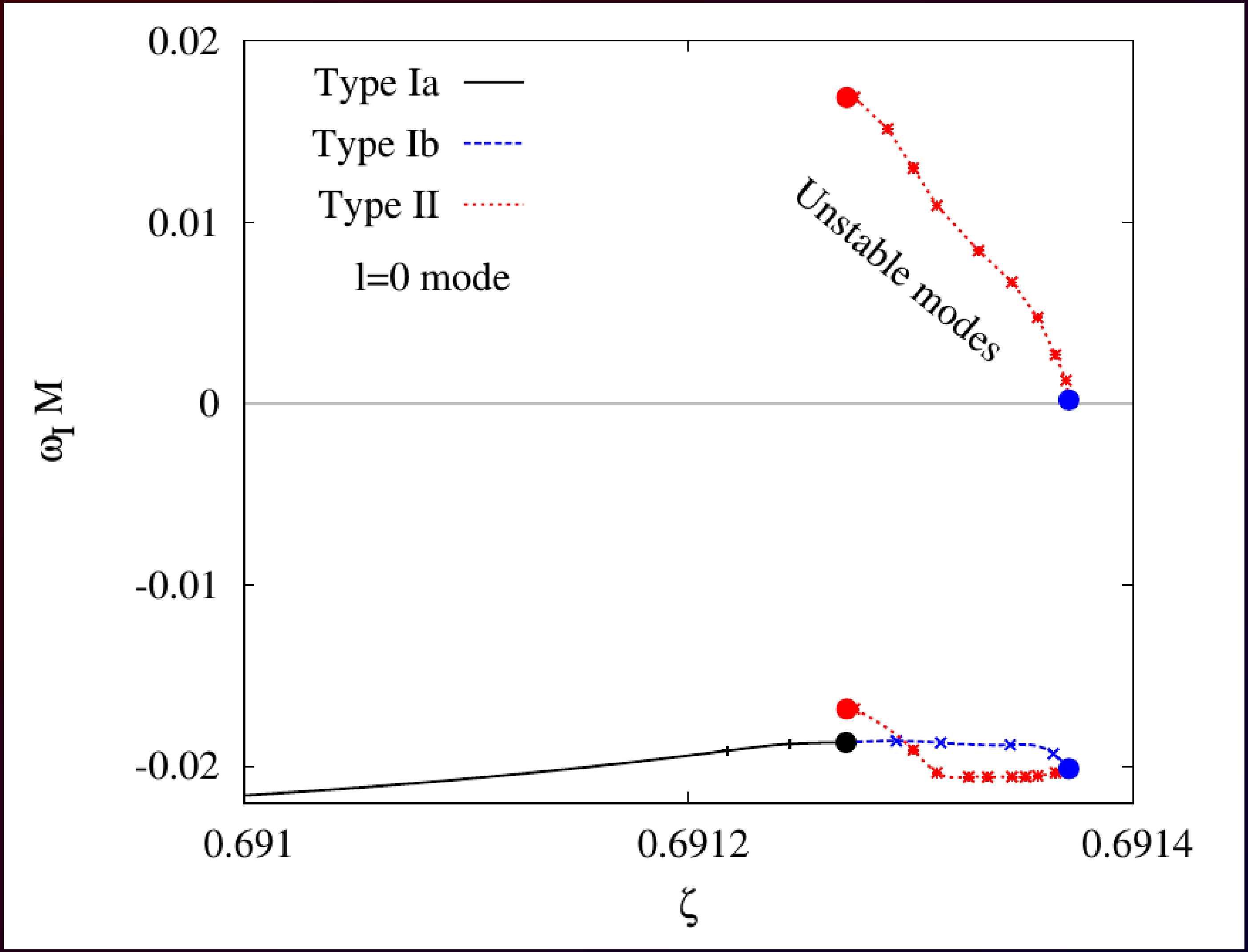

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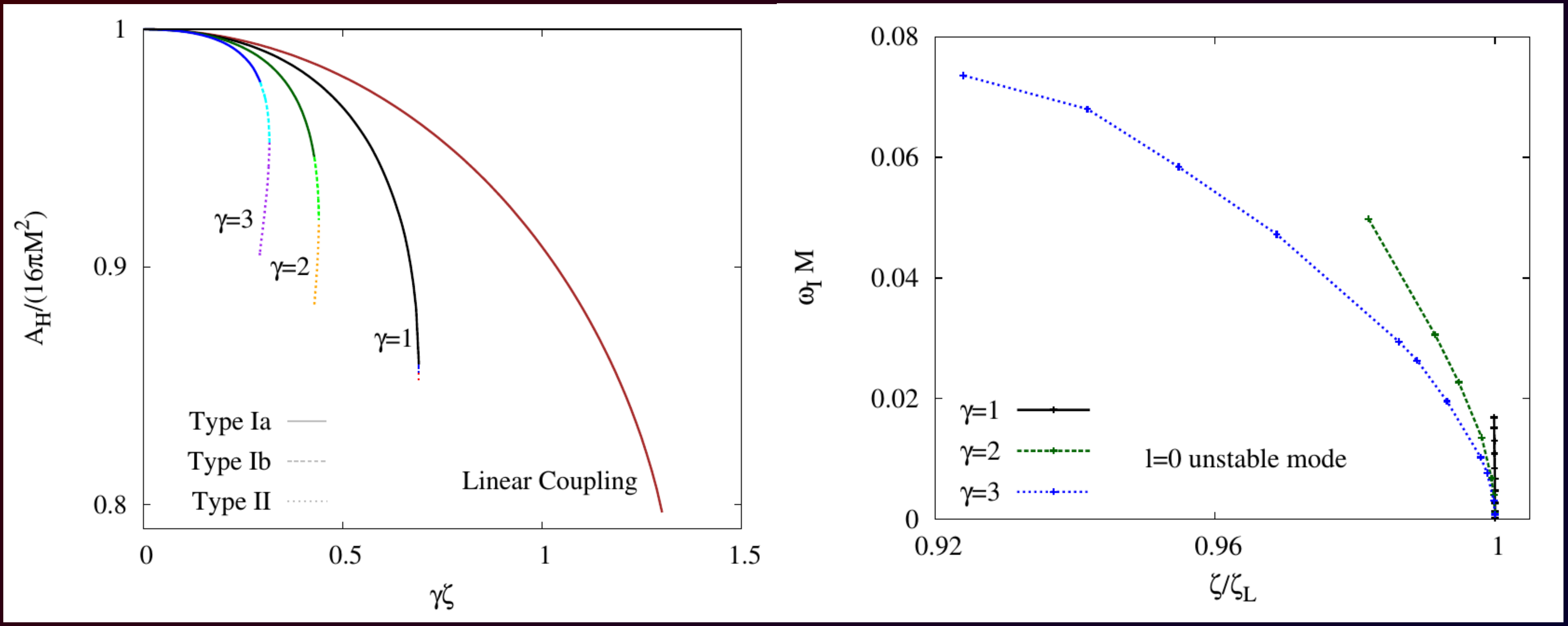

2. c) Stability: dilatonic vs scalarized

$$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}\Big[R - 2\nabla_\mu\varphi\nabla^\mu\varphi - V(\varphi) + \lambda^2 f(\varphi)\mathcal{R}^2_{GB}\Big]$$

Dilatonic: $f(\varphi) = e^{2\gamma\varphi}$ $\lambda^2 = \frac{\alpha}{4}$

New class of scalarized black holes:

Doneva & Yazadjiev, PRL 120 131103 (2018) [arXiv:1711.01187]
Silva, Sakstein, Gualtieri, Sotiriou, Berti, PRL 120 131104 (2018) [arXiv:1711.02080]
Antoniou, Bakopoulos, Kanti, PRL 120, 131102 (2018) [arXiv:1711.03390]
Antoniou, Bakopoulos, Kanti, PRD 97, 084037 (2018) [arXiv:1711.07431]

$$f(\varphi) = \frac{1}{12}\left(1 - e^{-6\varphi^2}\right)$$

$$f(\varphi) = \frac{1}{2}\varphi^2$$

2. c) Stability: dilatonic vs scalarized

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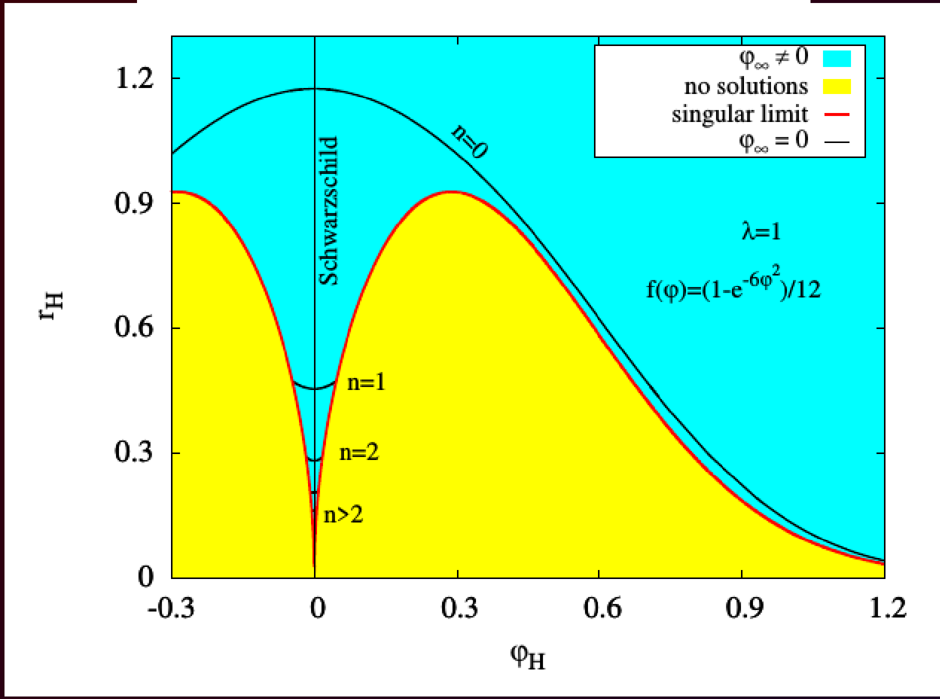

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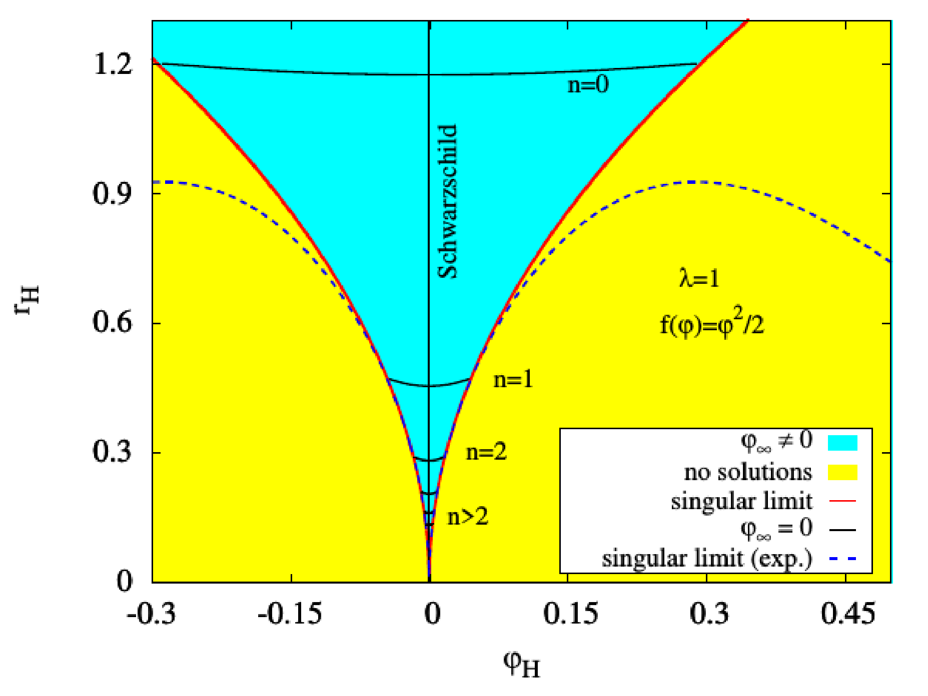

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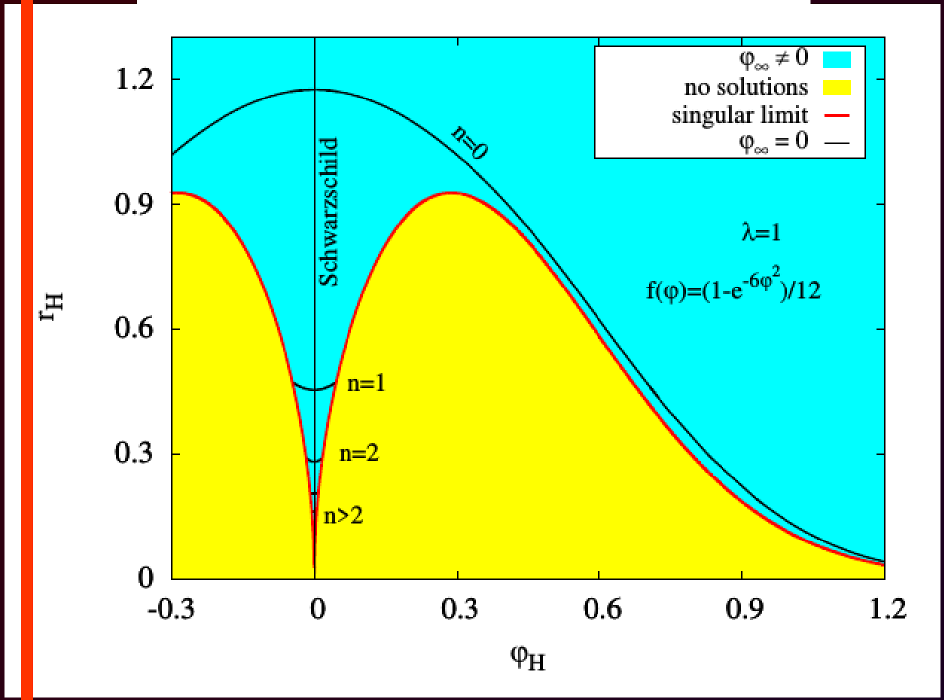

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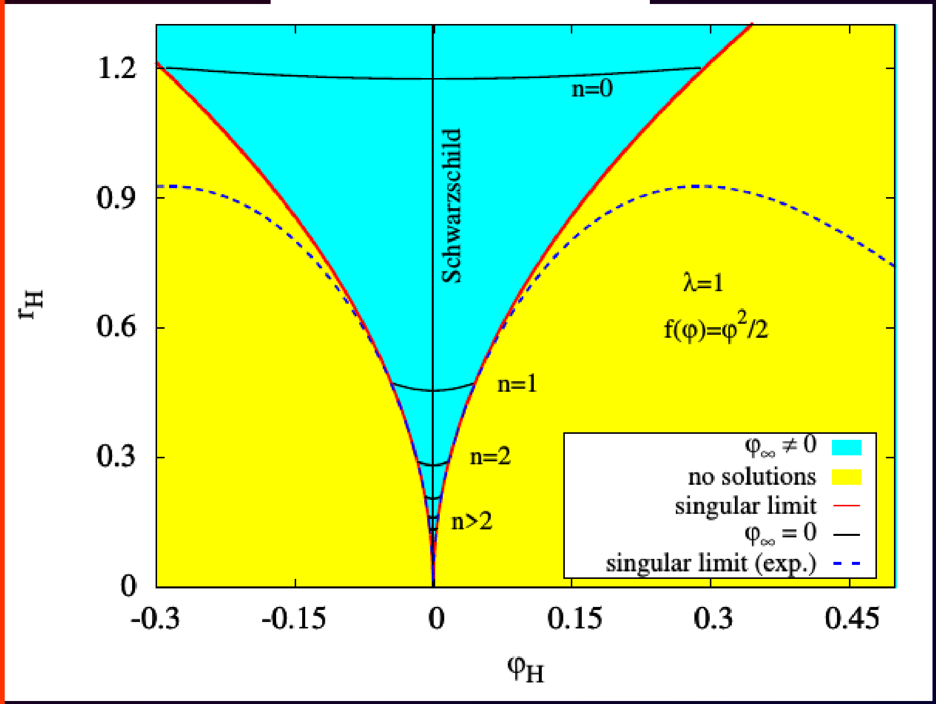

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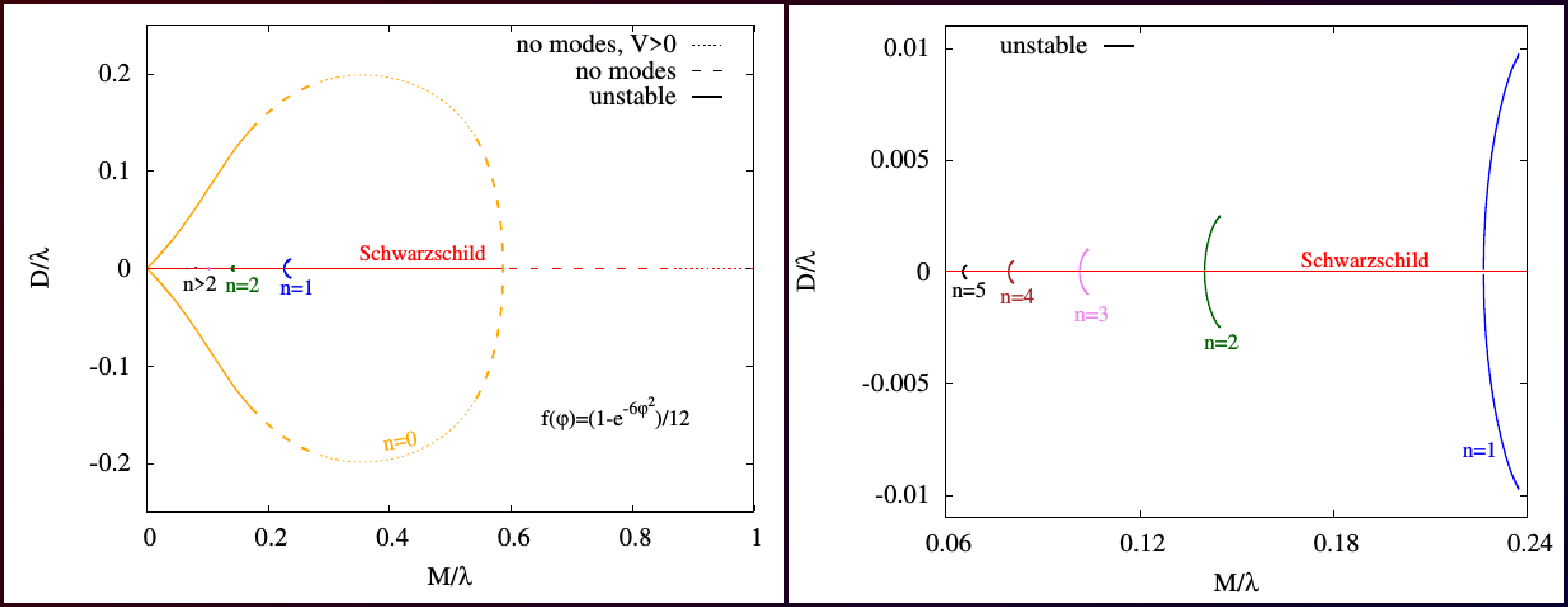

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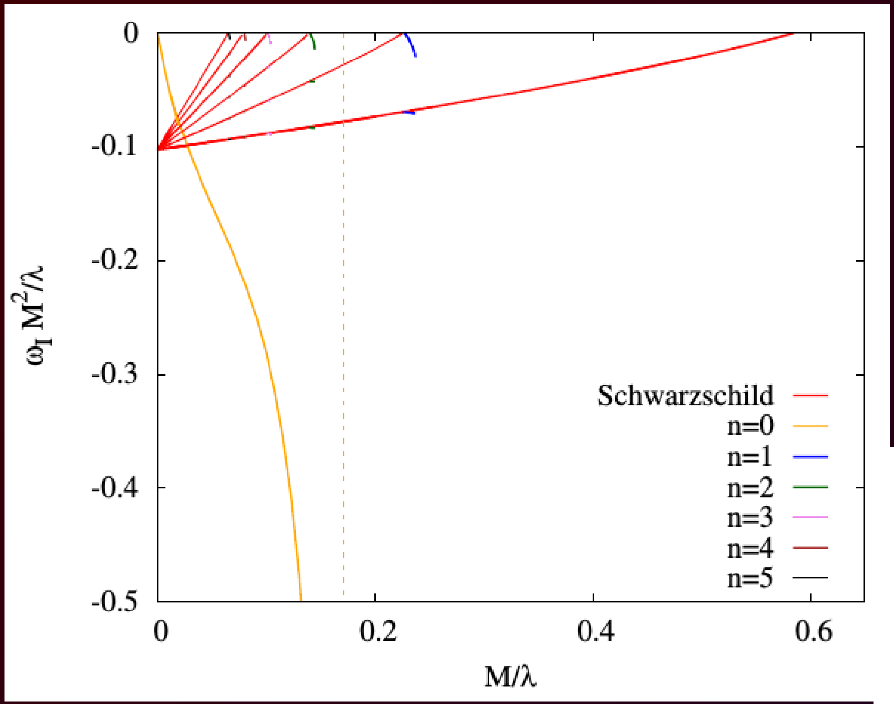
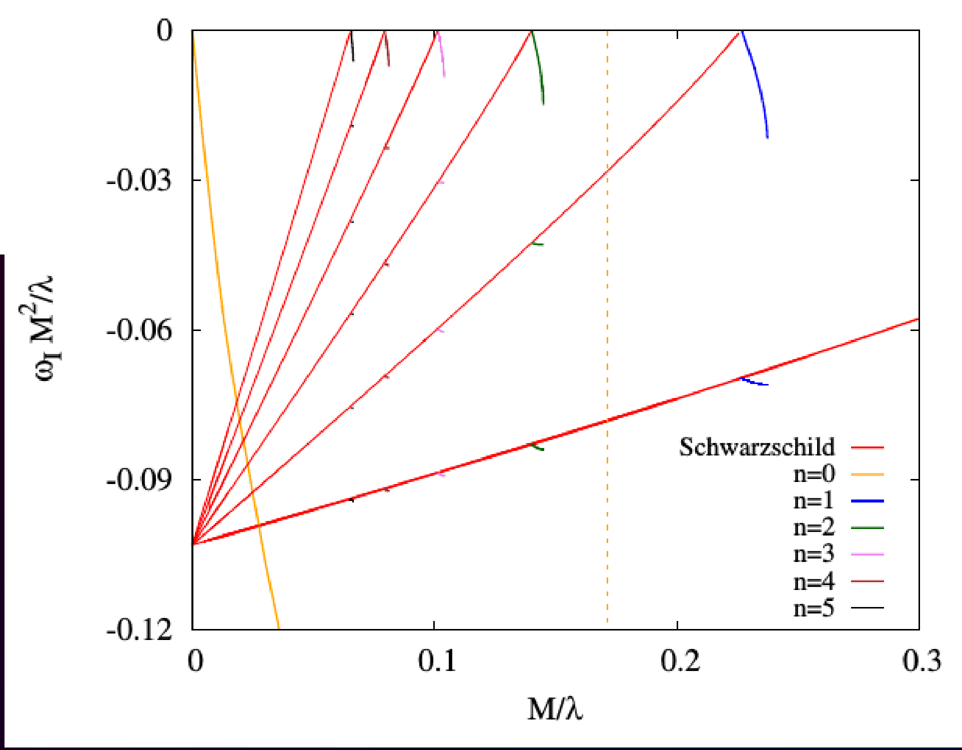


Radial perturbations of the scalarized black holes

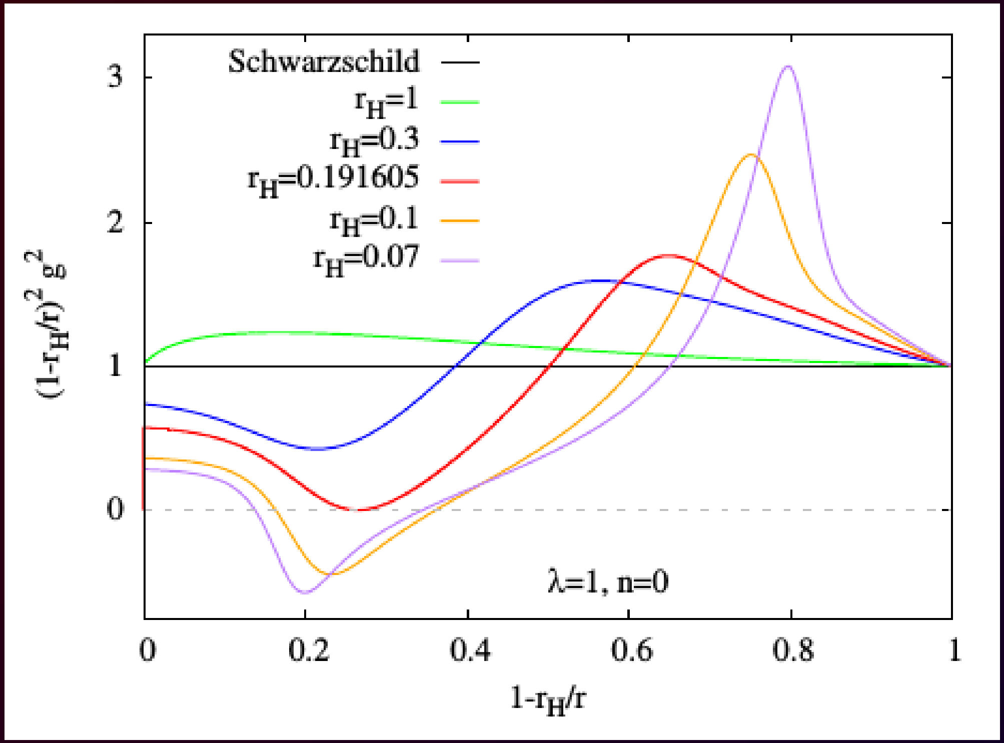
Unstable modes

JLBS, Doneva, Kunz, Yazadjiev [arXiv:1805.05755]



2. c) Stability: dilatonic vs scalarized

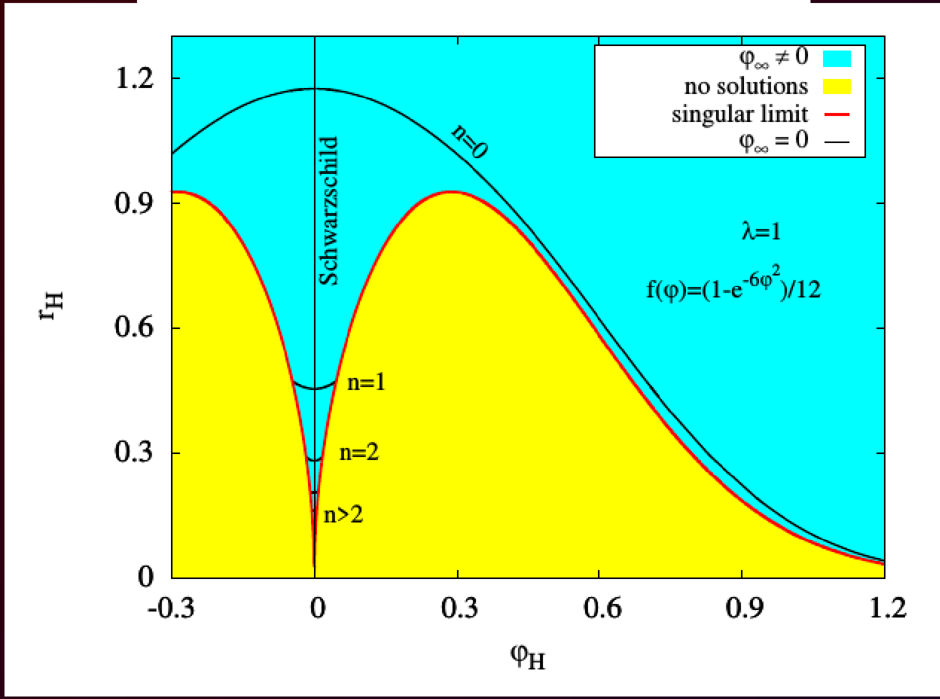
$$\frac{dR}{dr} = g$$



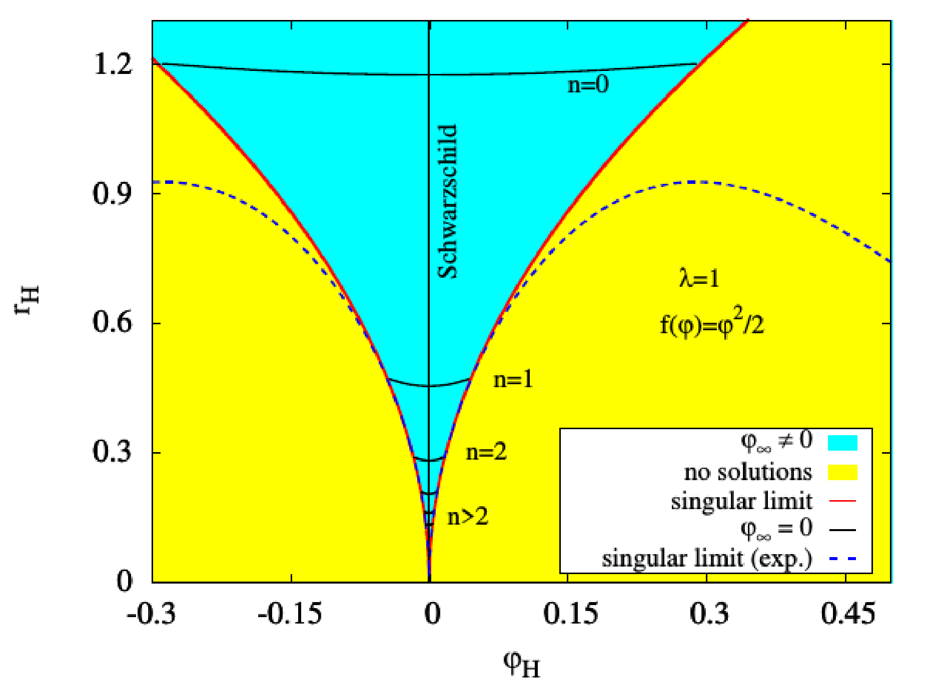
M < 0.171 λ

2. c) Stability: dilatonic vs scalarized

$$f(\varphi) = \frac{1}{12}\left(1 - e^{-6\varphi^2}\right)$$



$$f(\varphi) = \frac{1}{2}\varphi^2$$



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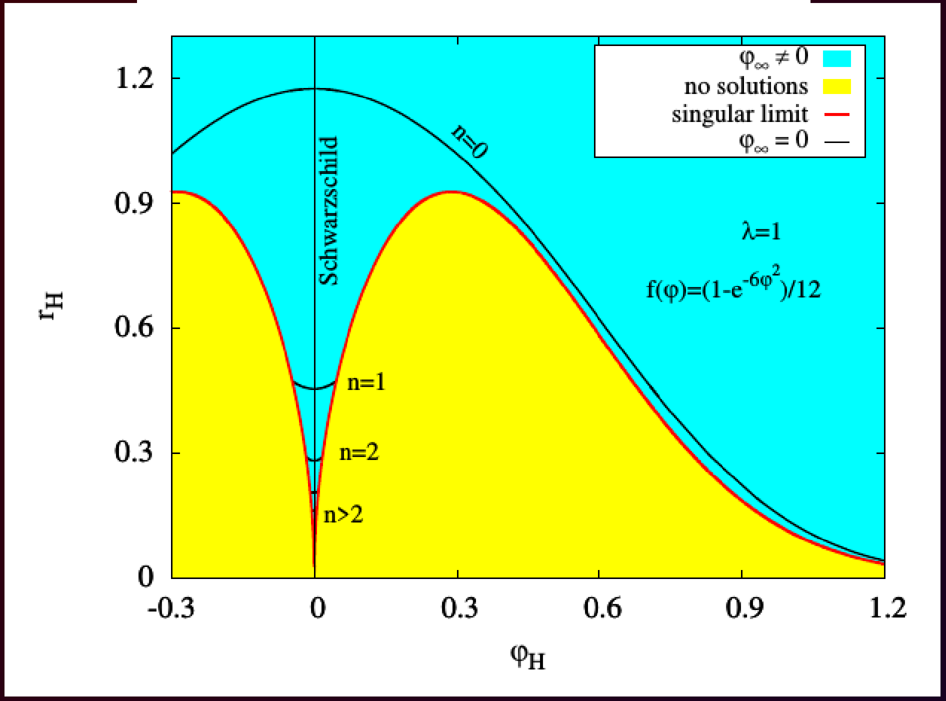

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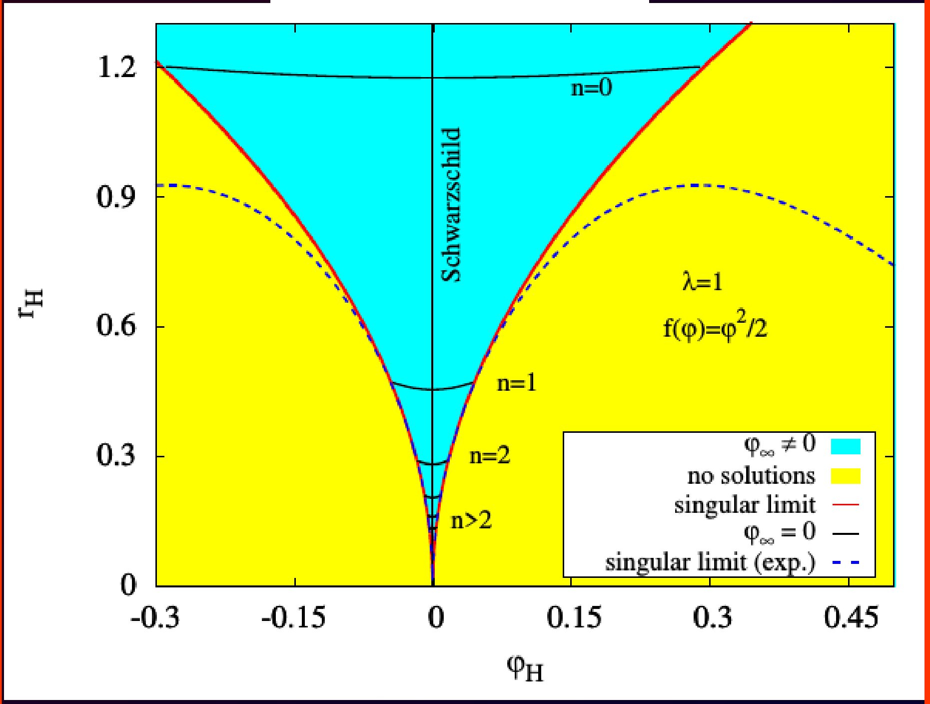

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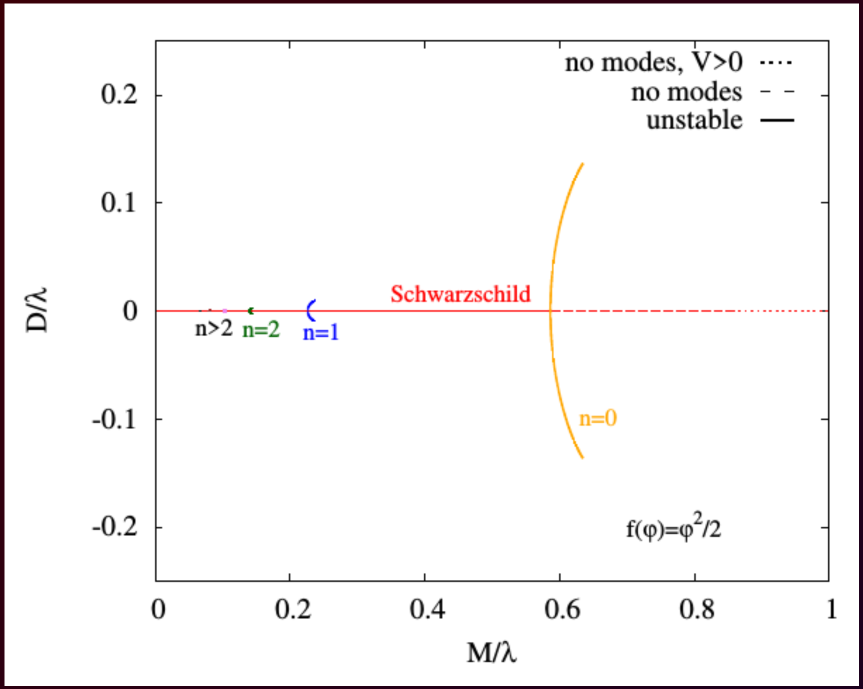

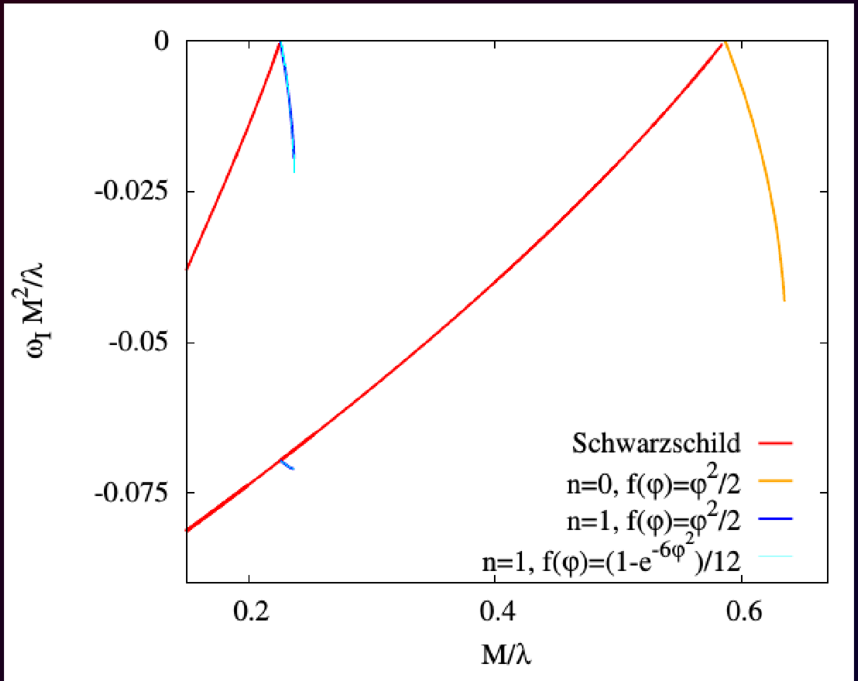

$$f(\varphi) = \frac{1}{2}\varphi^2$$

2. Black holes in sEGB theory

d) Implications for astrophysical black holes

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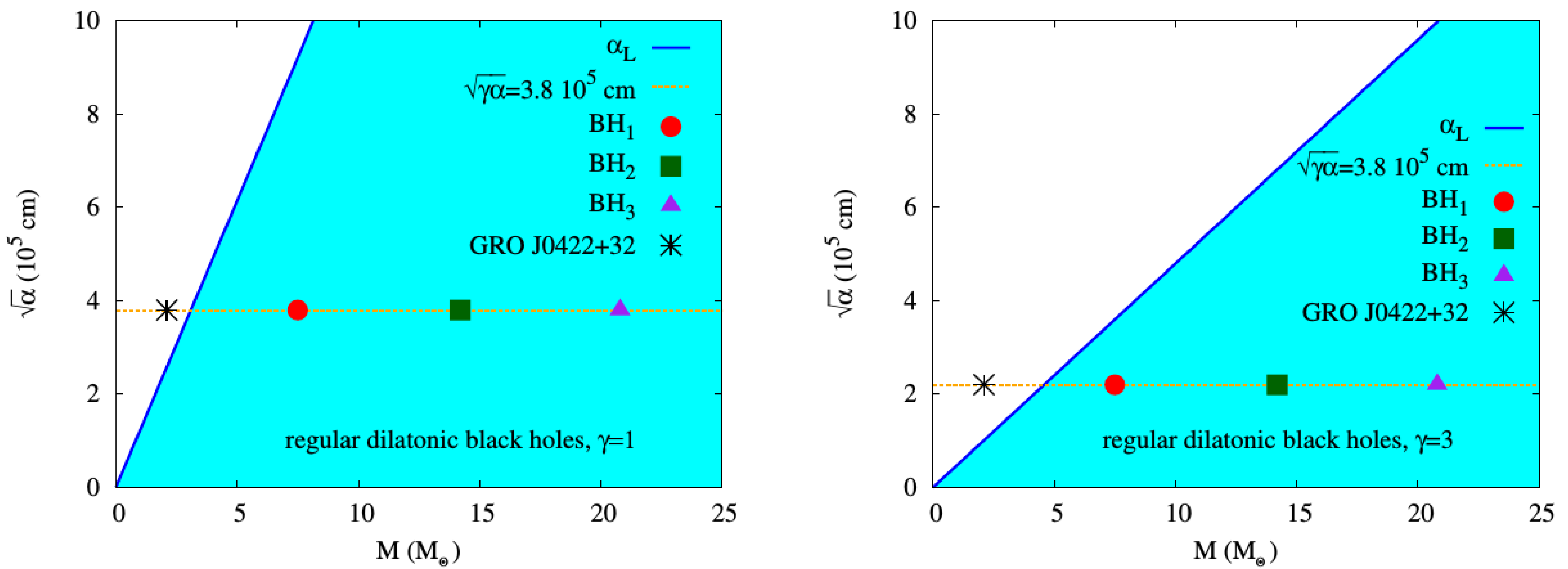
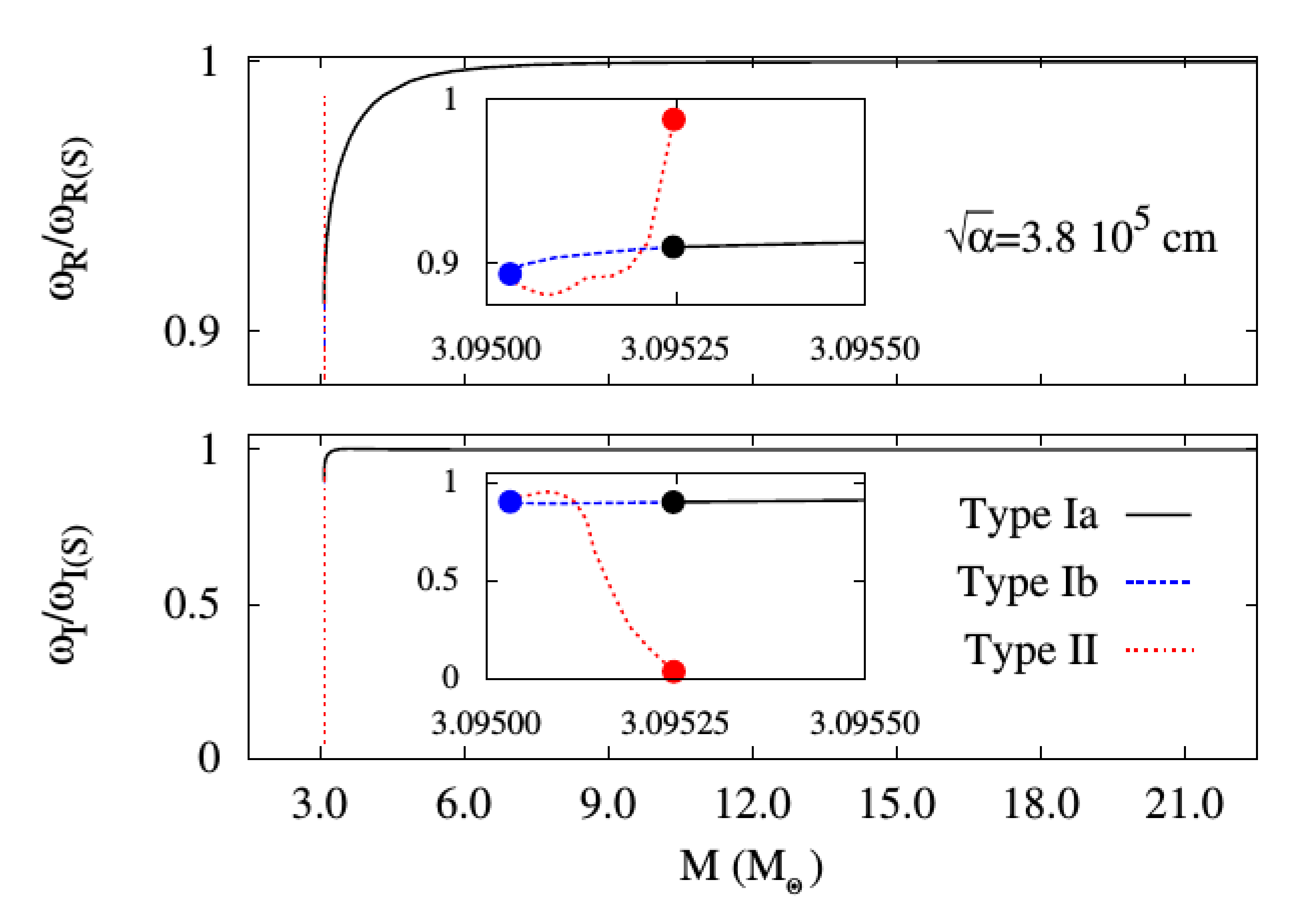
GW151226

BH1: 7.5 M_o BH2: 14.2 M_o BH3: 20.8 M_o

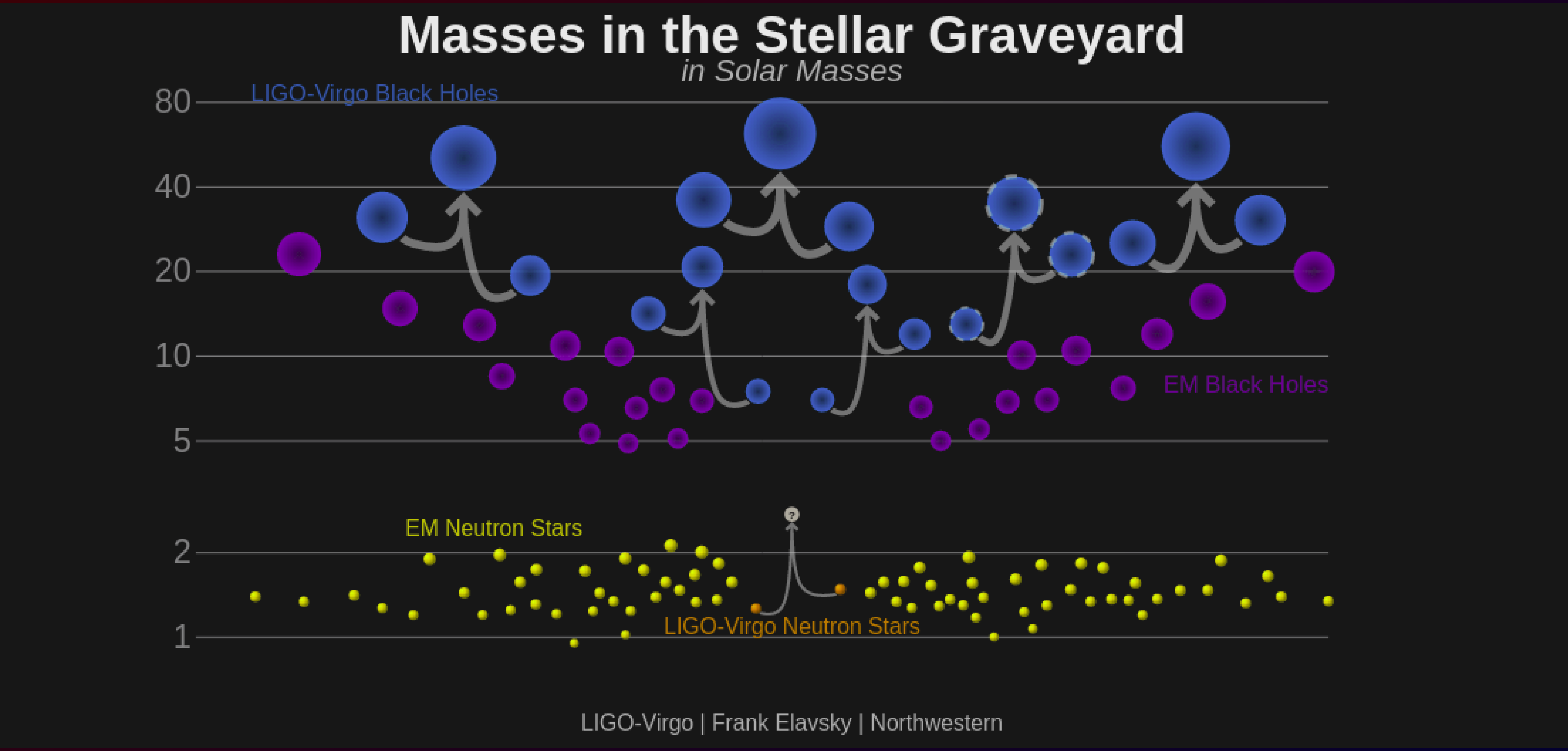


2. d) Implications for astrophysical black holes

Dilatonic EGB black holes
l=2 polar grav-led mode



2. d) Implications for astrophysical black holes



3. Scalarized neutron stars: spectrum and universal relations

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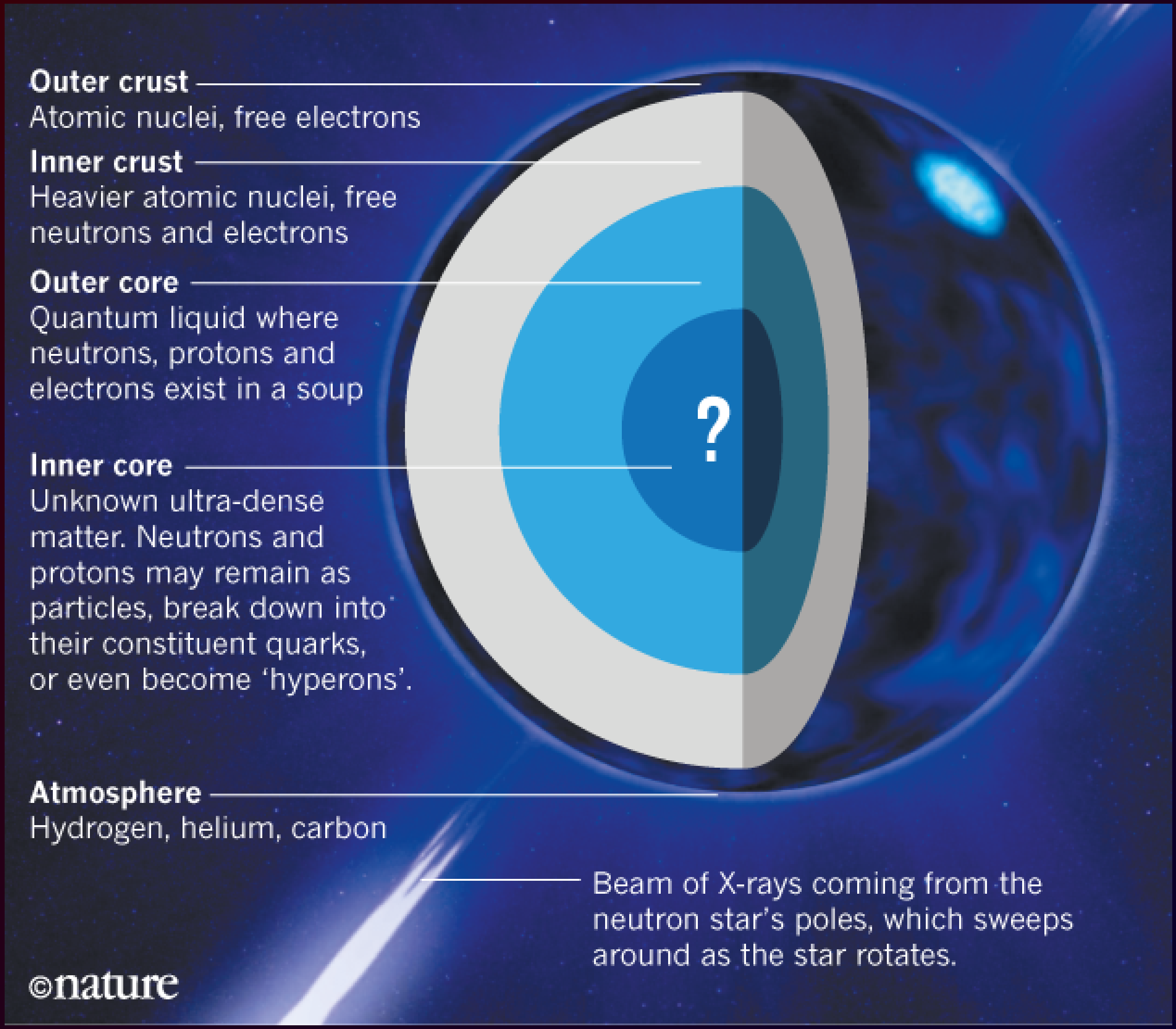
$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\,\left[R - 2g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi - V(\varphi)\right] + S_{\rm matter}$$

$$V(\varphi) = \frac{1}{4a}\left(1 - e^{-\frac{2\varphi}{\sqrt{3}}}\right)^2$$

3. Scalarized neutron stars: spectrum and universal relations

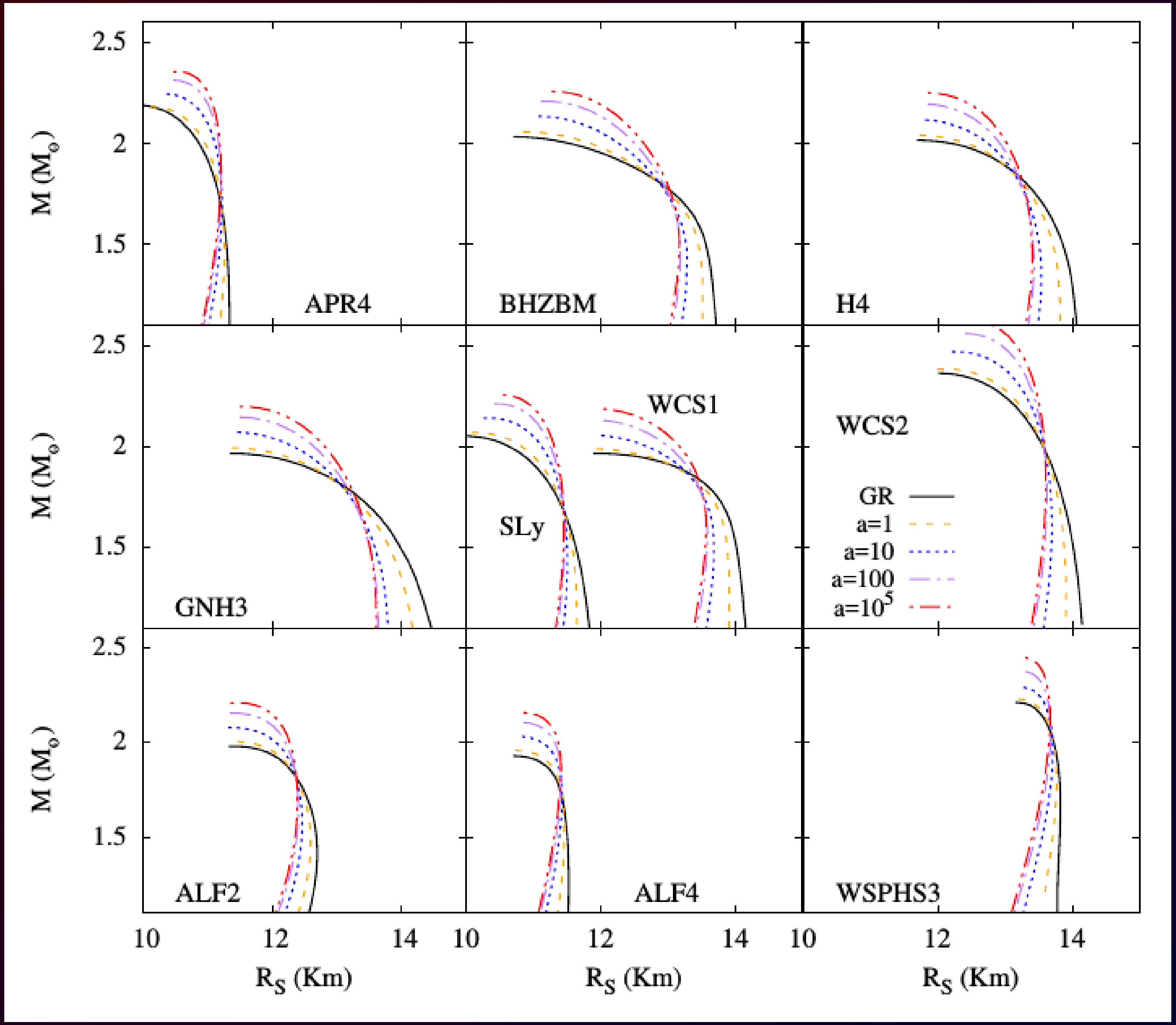
Interior of a neutron star:



3. Scalarized neutron stars: spectrum and universal relations

Scalarized neutron stars with realistic equations of state

Yazadjiev et al.
JCAP 1406 (2014) 003



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Scalarized neutron stars with realistic equations of state

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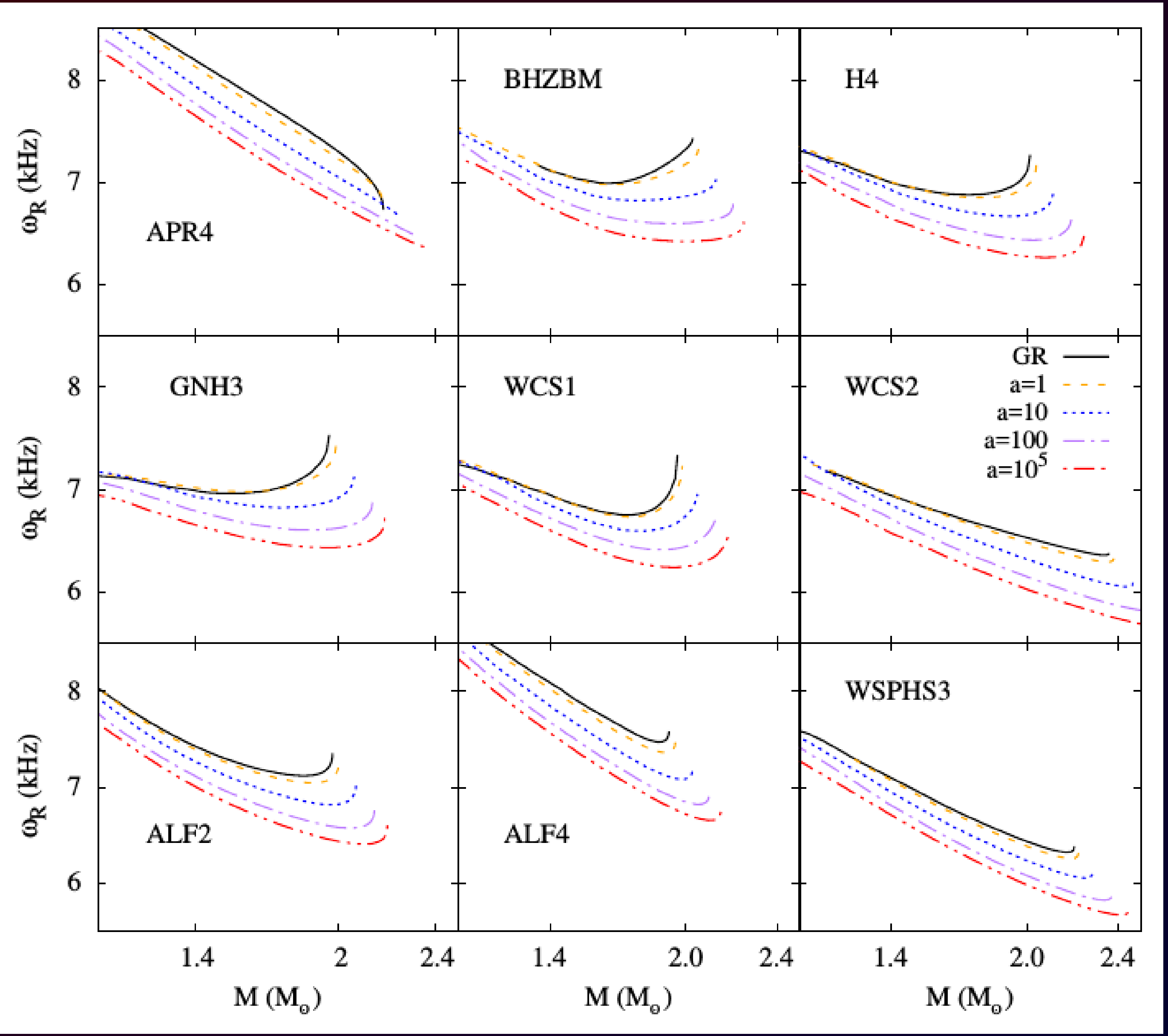

Fundamental l=2 axial mode

3. Scalarized neutron stars: spectrum and universal relations

Scalarized neutron stars with realistic equations of state

Yazadjiev et al.
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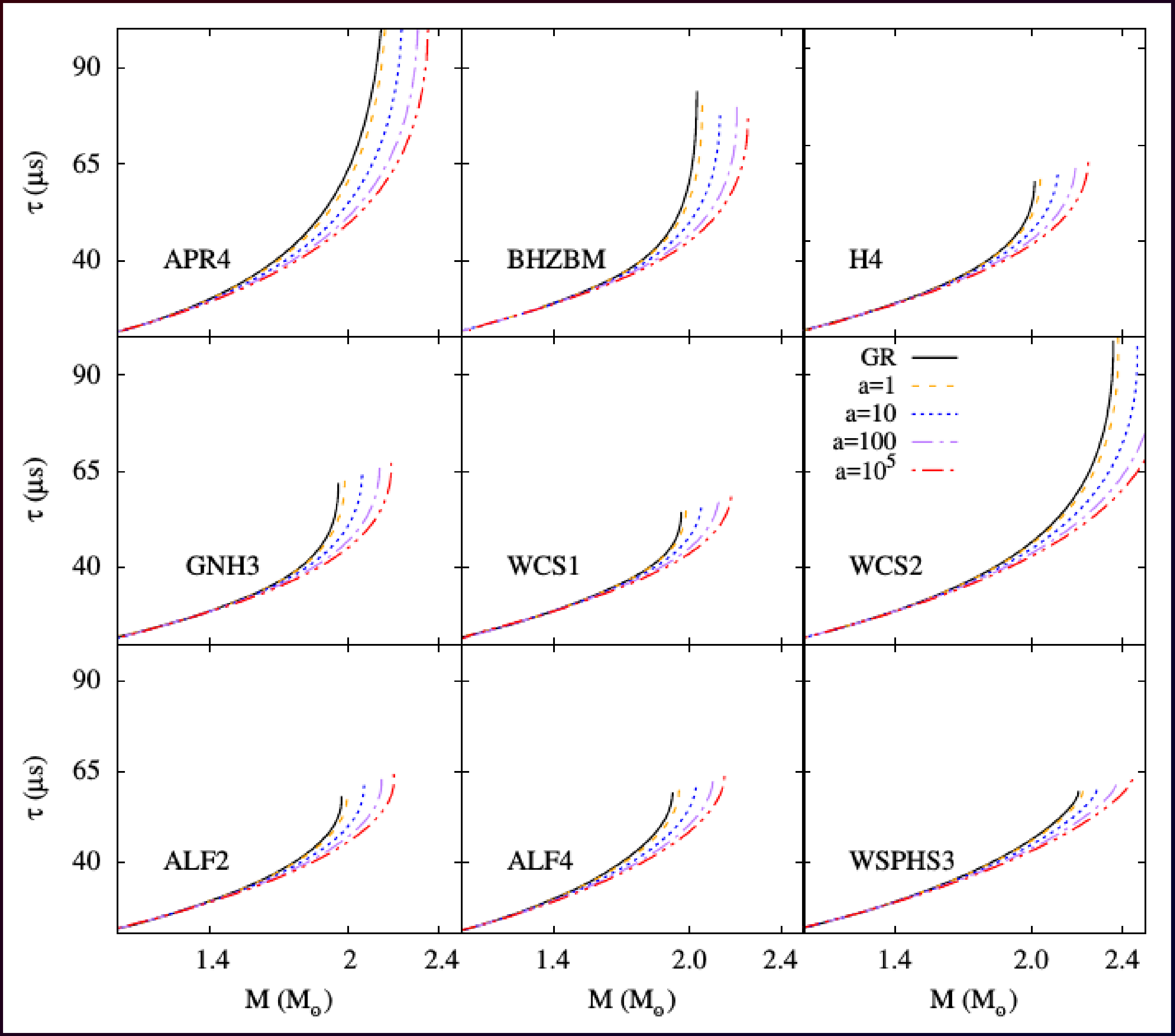

Fundamental l=2 axial mode

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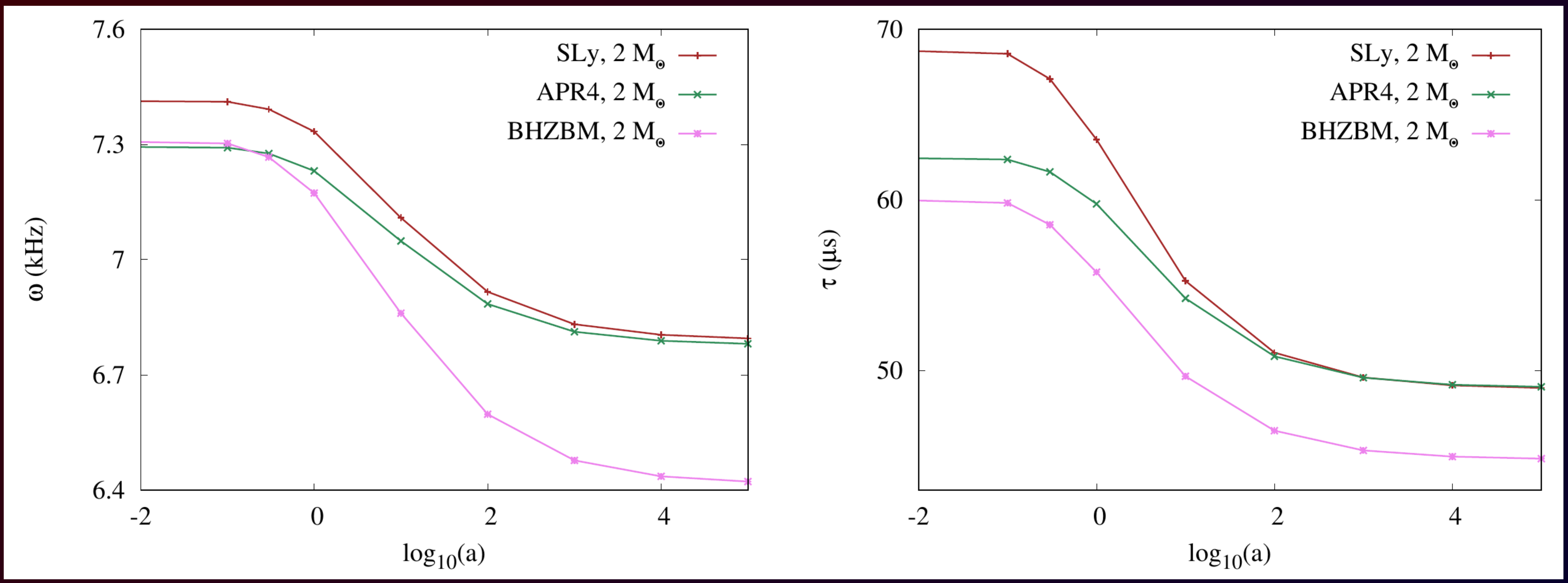

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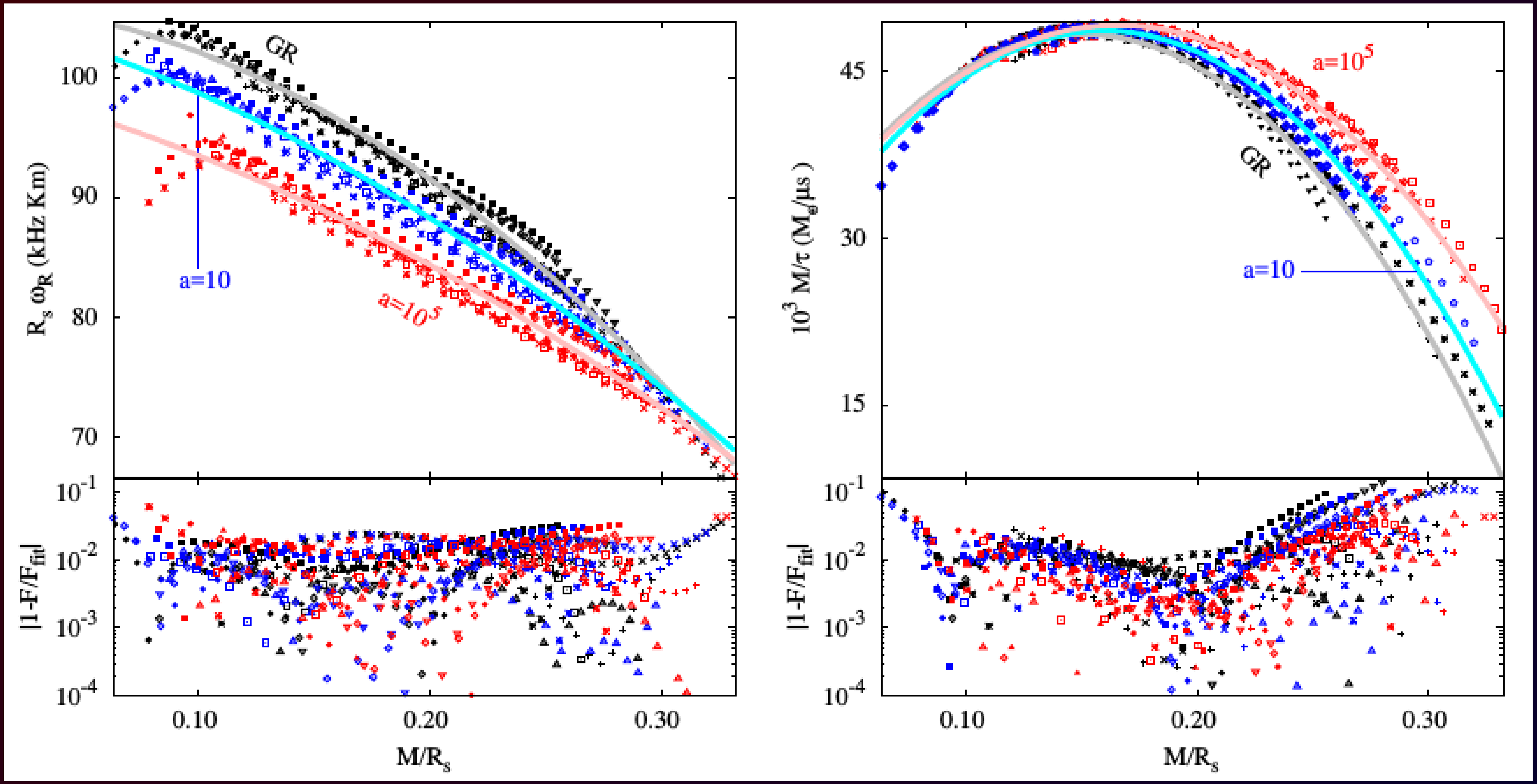
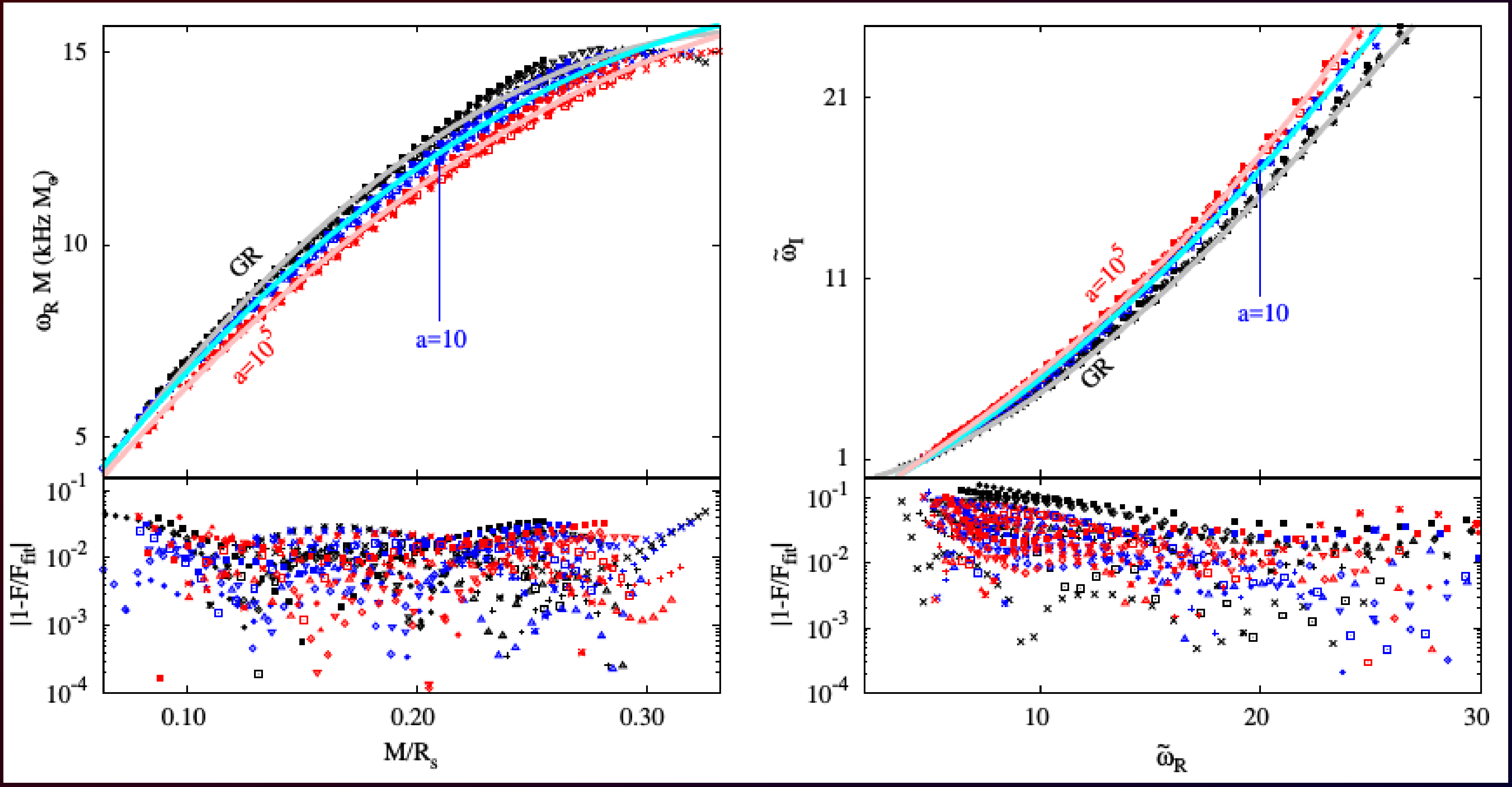


$$\omega[kHz] \cdot R_s[Km]$$

$$\frac{M[M_\odot]}{\tau[\mu s]}$$

3. Scalarized neutron stars: spectrum and universal relations



$$\omega_R[\mathrm{kHz}] \cdot \mathrm{M}[\mathrm{M}_\odot]$$

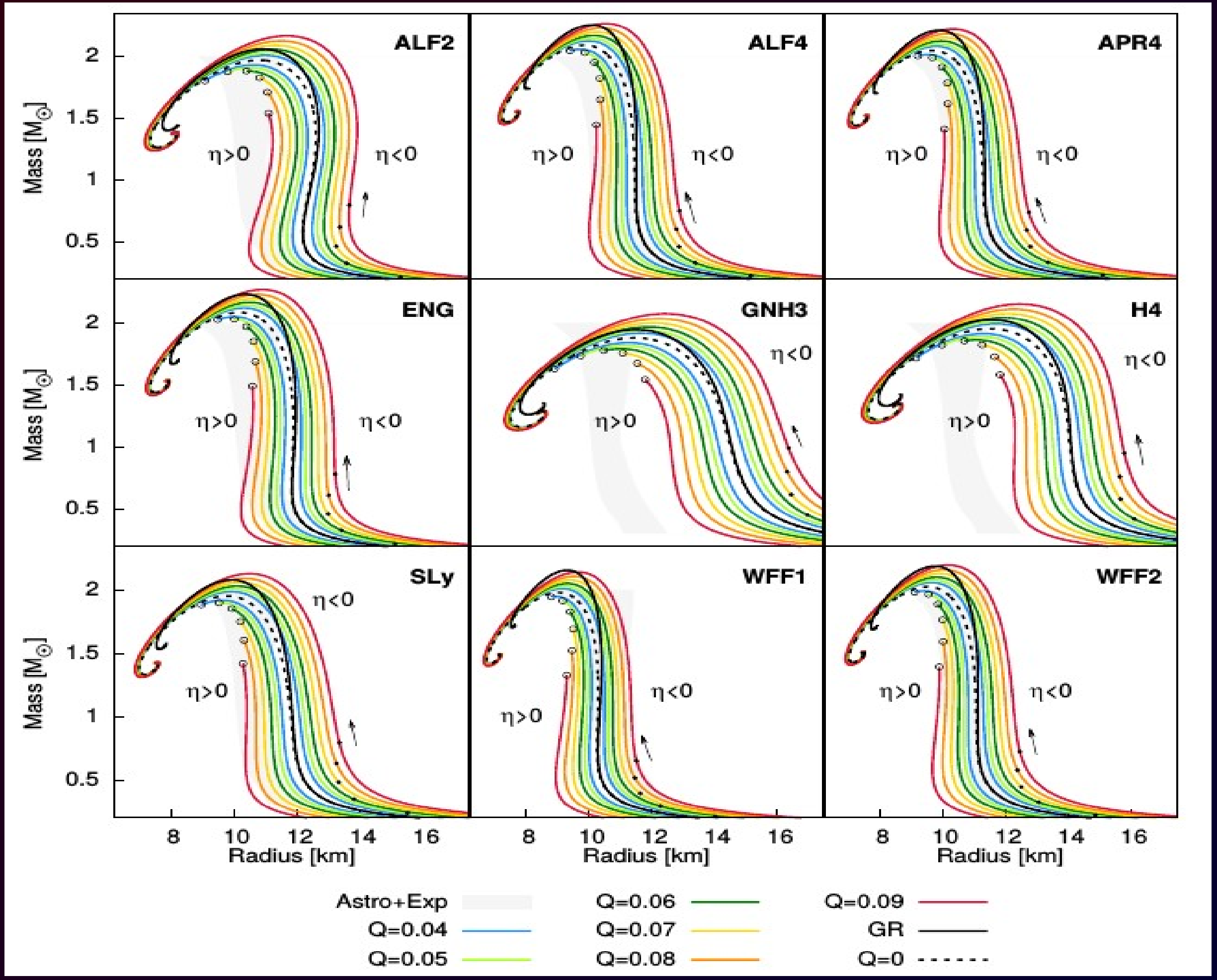
$$\tilde{\omega} = \omega / \sqrt{\hat{p}_0}$$

3. Scalarized neutron stars: spectrum and universal relations

$$S = \int d^4x\sqrt{-g}\left[R + \eta G^{\mu\nu}\ \nabla_\mu\phi\nabla_\nu\phi \right] + \ S_{\rm matter}$$

Scalarized neutron stars with realistic equations of state

Cisterna et al.
PRD92 (2015) 044050



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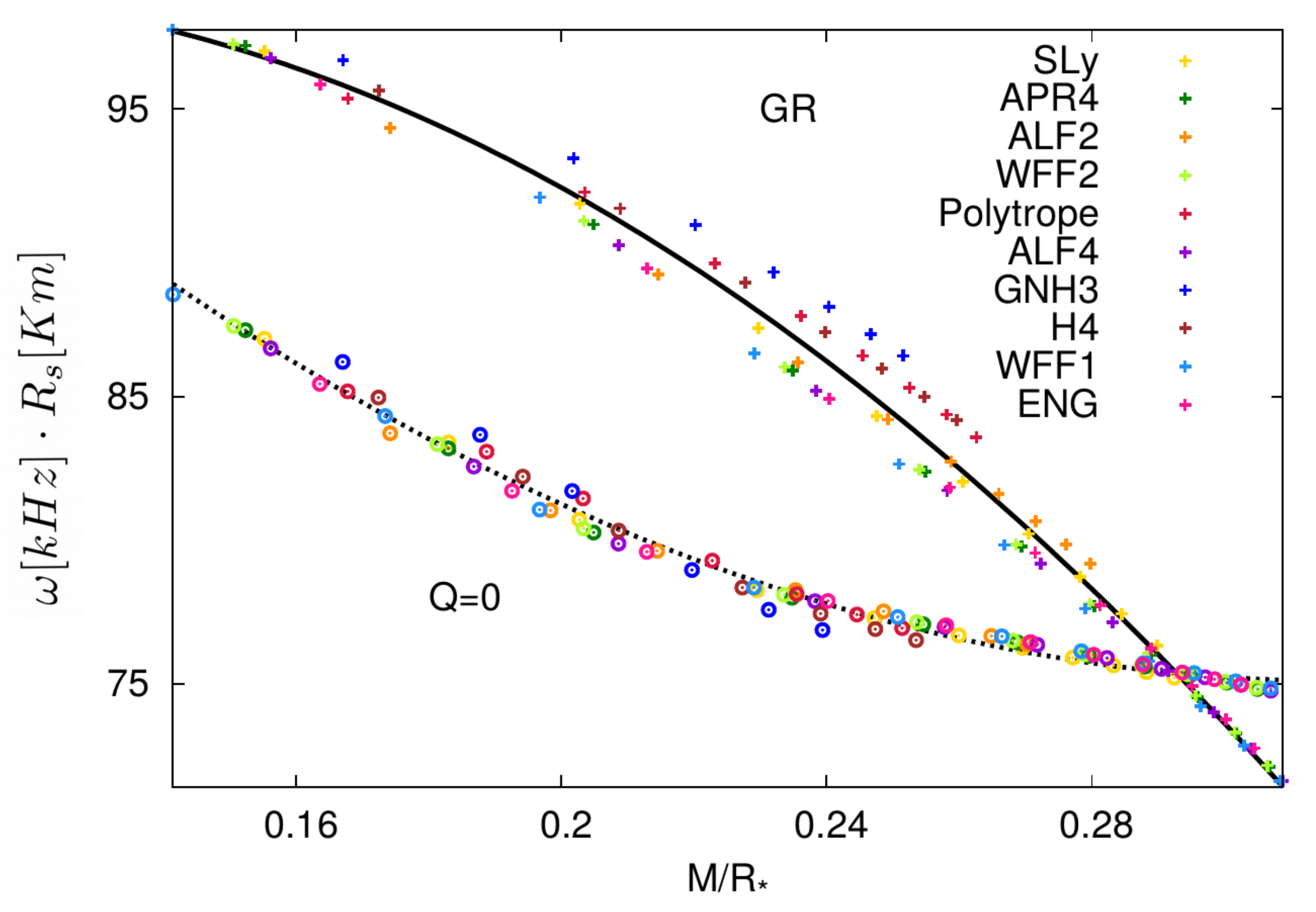
$$S = \int d^4x \sqrt{-g} \left[R + \eta G^{\mu\nu} \nabla_\mu \phi \nabla_\nu \phi \right] + S_{\text{matter}}$$

Scalarized neutron stars with realistic equations of state

JLBS, Kevin Eickhoff
PRD97 (2018) 104002



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Scalarized neutron stars with realistic equations of state

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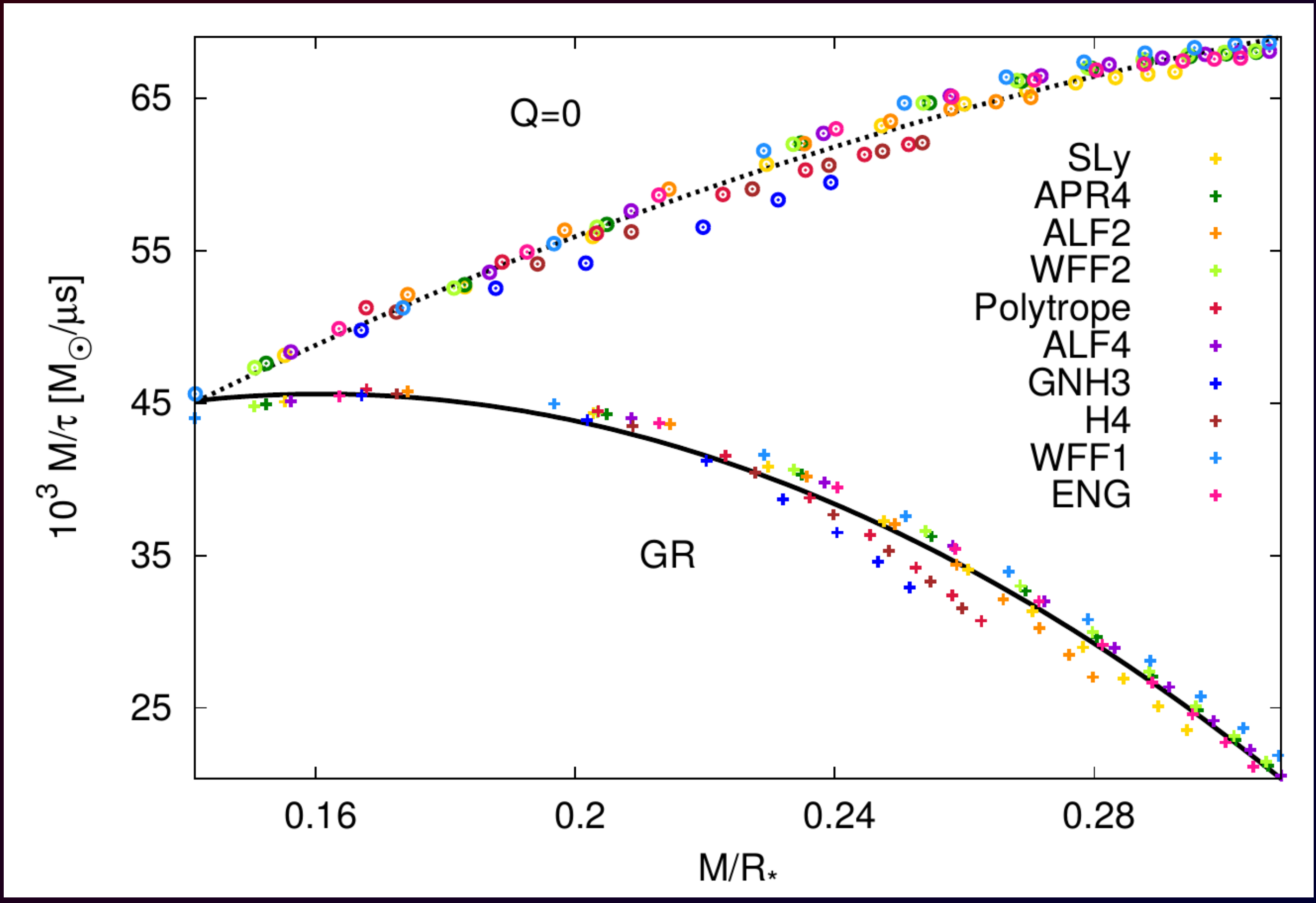
PRD97 (2018) 104002



4. Conclusions and Outlook

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First steps in the calculation of QNM spectrum of compact objects in alternative theories of gravity

New channel of emission (scalar-led modes), resulting in a richer spectrum (breaking of isospectrality)

Instabilities of black holes with scalar hair (radial unstable mode)

Minimum black hole mass in scalar-EGB theory, related with the appearance of the unstable mode in the strong coupling regime

Precise measurement of the ringdown phase could be used to constrain the theory coupling parameters

In the case of neutron stars, deviations in the matter independent universal relations can be used to constrain the scalar charge

4. Conclusions and Outlook

Outlook:

- Polar QNM of neutron stars with scalar hair

- QNM of rotating configurations

Realistic models of the ring-down phase
should include the effect of rotation

- QNM of other compact objects
  Wormholes [arXiv:1806.03282]
  Boson stars...

- Other theories: more general scalar-tensor theories, …

4. Conclusions and Outlook

Thank you very much for your attention!

JLBS, Daniela D. Doneva, Jutta Kunz, Stoytcho S. Yazadjiev [arXiv:1805.05755]

JLBS, Daniela D. Doneva, Jutta Kunz, Kalin V. Staykov, Stoytcho S. Yazadjiev [arXiv:1804.04060]

JLBS, Kevin Eickhoff PRD97 (2018) 104002 [arXiv:1803.01655]

JLBS, Fech Scen Khoo, Jutta Kunz, PRD96 (2017) 064008 [arxiv:1706.03262 gr-qc]

JLBS, Caio Macedo, Vitor Cardoso, Valeria Ferrari, Leonardo Gualtieri, Fech Scen Khoo, Jutta Kunz, Paolo Pani PRD94 (2016) 104024 [arxiv:1609.01286 gr-qc]