Black Holes
in Einstein-Gauss-Bonnet-Dilaton Theory

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RESEARCH TRAINING GROUP
Models of Gravity

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FAKULTÄT V

IAUS 324: New Frontiers in Black Hole Astrophysics

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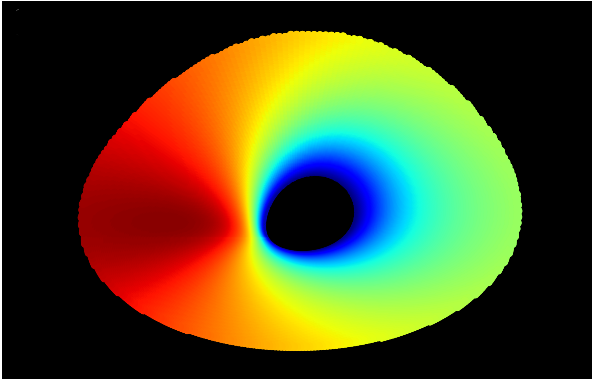
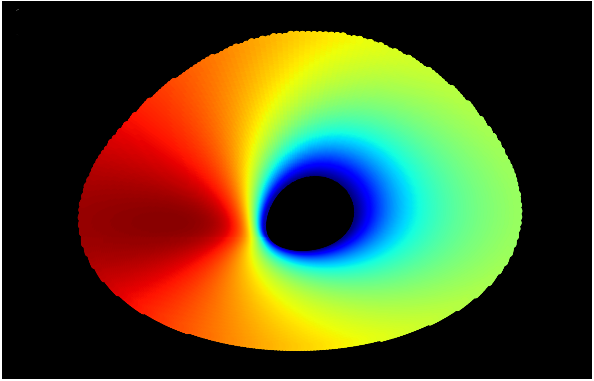
Outline



Outline

1. Introduction
2. Black Holes
   - Static BH
   - Rotating BH
   - Geodesics
   - Shadow
   - QNMs
3. Wormholes
4. Conclusions



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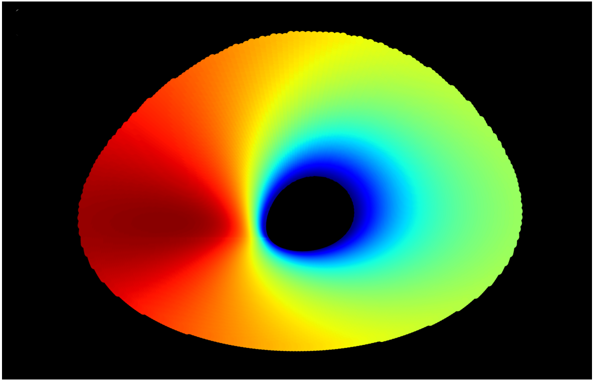

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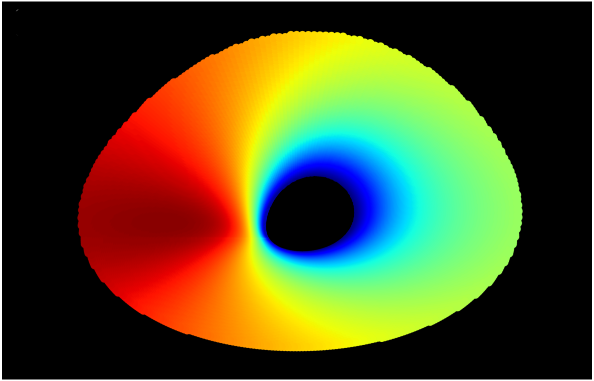

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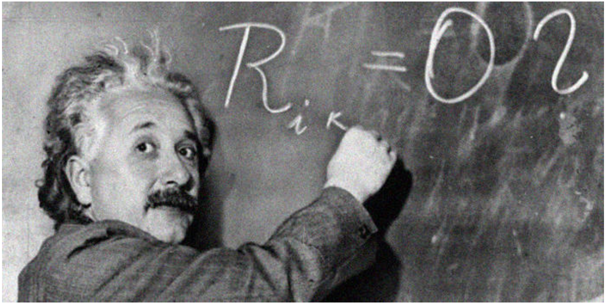
Motivation

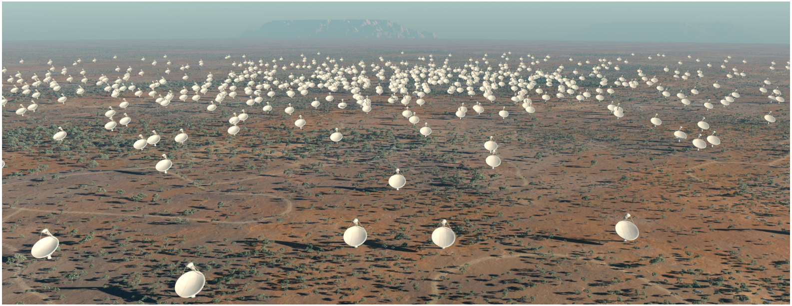
General Relativity



- Incompatibility with Quantum Mechanics
- Singularities
- Dark Matter, Dark Energy
- Tests in Strong Fields
- ...

Motivation

GR or Alternative Theories of Gravity



- Scalar-tensor theories
- $f(R)$ theories
- Higher curvature theories
- ...

Motivation

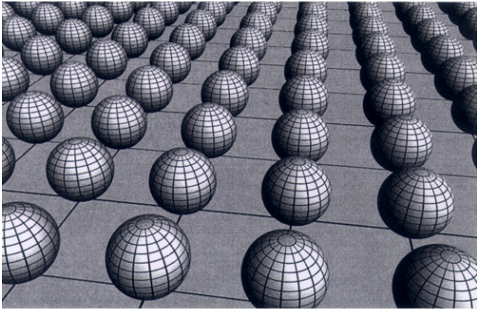
For instance: String Theory

unification of all fundamental interactions

dimensional reduction to 4 spacetime dimensions:

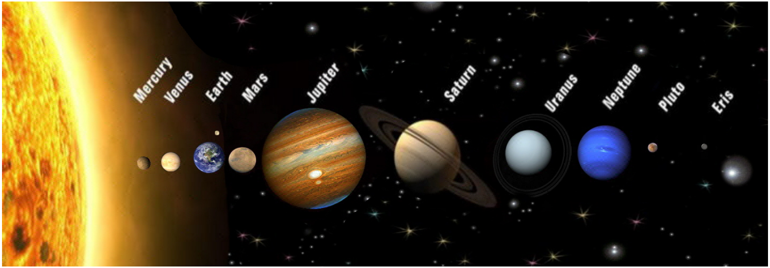
low energy effective theories

- additional fields
  - dilaton
  - axion
  - Maxwell fields
  - Yang-Mills fields
  - ...
- higher order curvature corrections
  - Gauss-Bonnet term
  - ...
- ...



Motivation

For Instance: Einstein-Gauss-Bonnet-Dilaton Theory



- One of the simplest consistent modifications of GR
  - Compatible with all solar system tests
  - Observational consequences in the strong gravity regime
    - Black holes
    - Neutron stars
    - Wormholes

Einstein-Gauss-Bonnet-dilaton gravity

Action

$$S = \frac{1}{16\pi} \int d^4x \sqrt{-g} \left[R - \frac{1}{2} (\partial_\mu \phi)^2 + \alpha' e^{-\gamma\phi} R^2_{\rm GB} \right]$$

Gauss-Bonnet term: quadratic in the curvature

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

- α' Gauss-Bonnet coupling constant
- γ dilaton coupling constant ($\gamma = 1$)

In 4 spacetime dimensions the coupling to the dilaton is needed.
The resulting set of equations of motion are of second order.

Einstein-Gauss-Bonnet-dilaton gravity

‘modified’ Einstein equations

$$\boxed{G_{\mu\nu} = \frac{1}{2}\, T^{\rm eff}_{\mu\nu}}$$

$$T^{\rm eff}_{\mu\nu} \quad = \quad T^{(\phi)}_{\mu\nu} - 2\alpha' e^{-\gamma\phi} T^{\rm (GBd)}_{\mu\nu}$$

where

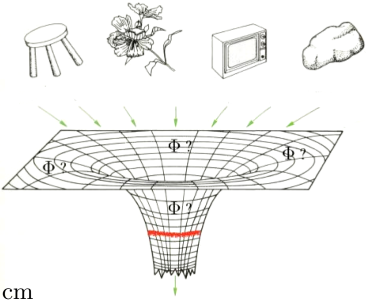
$$T^{(\phi)}_{\mu\nu} \quad = \quad \nabla_\mu\phi\nabla_\nu\phi - \frac{1}{2} g_{\mu\nu}\nabla_\lambda\phi\nabla^\lambda\phi$$

$$T^{\rm (GBd)}_{\mu\nu} \quad = \quad H_{\mu\nu} + 4\left(\gamma^2\nabla^\rho\phi\nabla^\sigma\phi - \gamma\nabla^\rho\nabla^\sigma\phi\right) P_{\mu\rho\nu\sigma}$$

dilaton equation

$$\boxed{\nabla^2\phi = \alpha'\gamma e^{-\gamma\phi} R^2_{\rm GB}}$$

Einstein-Gauss-Bonnet-dilaton gravity



consequences

- scalar "hair": dilaton "hair"
- negative energy density

bounds on α'

- observational
  - Shapiro time delay

$$\sqrt{\alpha'} \lesssim 10^{13}\mathrm{cm}$$

  - BH low-mass X-ray binaries

$$\sqrt{\alpha'} \lesssim 5 \times 10^{6}\mathrm{cm}$$

- theoretical
  - $\sqrt{\alpha'}$ smaller than horizon size

$$\frac{\alpha'}{M^2} \lesssim 0.691$$

Outline

Black Holes in GR

Schwarzschild 1916

- black hole with mass M
  - static spherically symmetric
  - event horizon

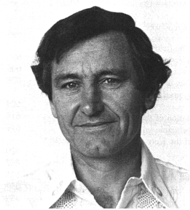
$$r_H = 2M$$

Karl Schwarzschild 1873 — 1916

Kerr 1963

- black hole with mass M
  and angular momentum J
  - stationary rotating
  - event horizon

$$r_H = M + \sqrt{M^2 - a^2}$$



Roy Kerr *1934

Black Holes in GR

Israel, Penrose, Wheeler, ...

No-hair theorem:
A stationary vacuum black hole is uniquely characterized by its mass M and angular momentum J.

Geroch, J. Math. Phys. (1970); Hansen, J. Math. Phys. (1974)

Multipole moments M_l and S_l

All multiple moments can be expressed in terms of only two quantities:

$$M_0 = M \qquad\qquad S_1 = J$$

$$M_l + iS_l = M\left(i\frac{J}{M}\right)^l$$

Quadrupole moment

$$M_2 = Q = -\frac{J^2}{M}$$

Black Holes in GR

Kerr black holes

- astrophysical black holes
- angular momentum bound

$$\frac{J}{M^2} \leq 1$$

- < 1 non-extremal black hole
- $= 1$ extremal black hole
- > 1 naked singularity (cosmic censorship)

Outline

Static EGBD Black Holes

PHYSICAL REVIEW D VOLUME 54, NUMBER 8 15 OCTOBER 1996

Dilatonic black holes in higher curvature string gravity

P. Kanti,[1] N. E. Mavromatos,[2] J. Rizos,[3] K. Tamvakis,[3,*] and E. Winstanley[2]
[1]*Division of Theoretical Physics, Physics Department, University of Ioannina, Ioannina GR-451 10, Greece*
[2]*Department of Physics (Theoretical Physics), University of Oxford, 1 Keble Road, Oxford OX1 3NP, United Kingdom*
[3]*European Organization for Nuclear Research (CERN), Theory Division, 1211 Geneva 23, Switzerland*
(Received 10 November 1995)

We give analytical arguments and demonstrate numerically the existence of black hole solutions of the 4D effective superstring action in the presence of Gauss-Bonnet quadratic curvature terms. The solutions possess nontrivial dilaton hair. The hair, however, is of ''secondary type,'' in the sense that the dilaton charge is expressed in terms of the black hole mass. Our solutions are not covered by the assumptions of existing proofs of the ''no-hair'' theorem. We also find some alternative solutions with singular metric behavior, but finite energy. The absence of naked singularities in this system is pointed out. [S0556-2821(96)01920-0]

Static EGBD Black Holes

P. Kanti et al. PRD54, 5049 (1996).

static spherically symmetric metric

$$ds^2 = A(r)dt^2 + B(r)^{-1}dr^2 + r^2\left(d\theta^2 + \sin^2\theta d\varphi^2\right)$$

expansion at the event horizon r_h

$$\begin{aligned}\phi(r) &= \phi_h + \phi'_h(r - r_h) + \phi''_h(r - r_h)^2 + \ldots \\ A(r) &= \ldots \qquad\qquad B(r) = \ldots\end{aligned}$$

insertion into the eoms: relevant relation

$$\phi'_h = \frac{r_h}{\alpha'}e^{-\phi_h}\left(-1 \pm \sqrt{1 - 6\frac{\alpha'^2}{r_h^4}e^{2\phi_h}}\right)$$

square root: ϕ'_h real

Static EGBD Black Holes

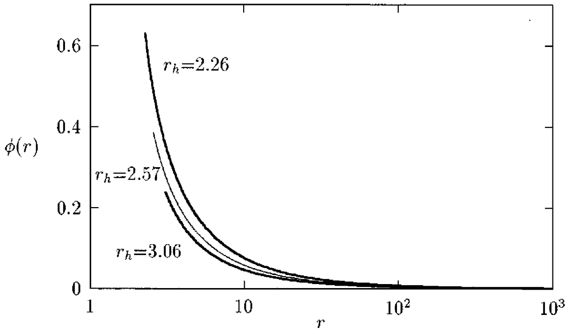
P. Kanti et al. PRD54, 5049 (1996).

critical black holes:

horizon expansion

$$\sqrt{1 - 6\frac{\alpha'^2}{r_h^4}e^{2\phi_h}}$$

lower bound
on the horizon size
for fixed α'



lower bound on the horizon size

Static EGBD Black Holes

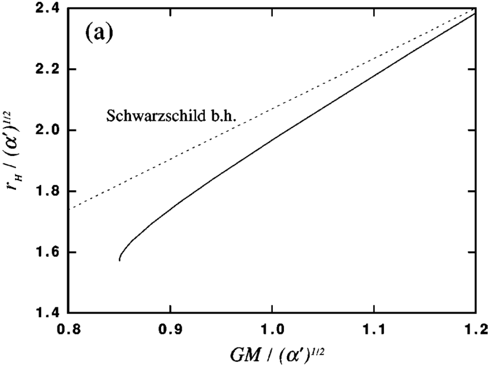
T. Torii et al. PRD58, 084004 (1998).

critical black holes:

horizon expansion

$$\sqrt{1 - 6\frac{\alpha'^2}{r_h^4}e^{2\phi_h}}$$

lower bound
on the horizon size
for fixed α'



lower bound on the mass

Static EGBD Black Holes

P. Kanti et al. PRD54, 5049 (1996), P. Kanti et al. PRD57, 6255 (1998)

asymptotically flat solutions

asymptotic expansion

$$\begin{aligned} A(r) &= 1 - \frac{2M}{r} + \ldots \\ \phi(r) &= -\frac{D}{r} + \ldots \end{aligned}$$

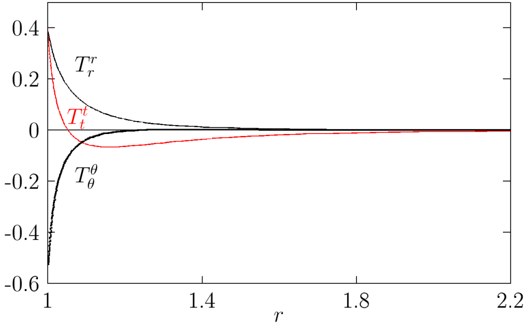
global charges: mass M, dilaton charge D

linear mode stability radial perturbations ...

Static EGBD Black Holes

P. Kanti et al. PRD54, 5049 (1996).

components of the energy momentum tensor



- region with negative energy density
- strange further solutions

Outline

Slowly Rotating EGBD Black Holes

PHYSICAL REVIEW D **79,** 084031 (2009)

Are black holes in alternative theories serious astrophysical candidates? The case for Einstein-dilaton-Gauss-Bonnet black holes

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Vitor Cardoso†
Centro Multidisciplinar de Astrofísica-CENTRA, Departamento de Física, Instituto Superior Técnico, Avenida Rovisco Pais 1, 1049-001 Lisboa, Portugal, and Department of Physics and Astronomy, The University of Mississippi, University, Mississippi 38677-1848, USA
(Received 12 February 2009; published 21 April 2009)

Slowly Rotating EGBD Black Holes

P. Pani et al. PRD79, 084031 (2009).

lowest order perturbation theory

- solutions
  - angular velocity: larger
  - ergoregion: larger
- orbits

$$\mathcal{L} = \frac{1}{2} e^{-2\beta\phi} g_{\mu\nu} \dot{x}^\mu \dot{x}^\nu$$

$\beta = \text{const.}$ ($= 1/2$ for heterotic string theory)

  - orbital frequency: smaller
  - ISCO: larger

higher order perturbation theory

Rapidly Rotating EGBD Black Holes

B. Kleihaus et al. PRL **106**, 151104 (2011), PRD **93**, 044047 (2016)

metric (Lewis-Papapetrou Ansatz in isotropic coordinates)

$$ds^2 = -f_0 dt^2 + f_1 \left(dr^2 + r^2 d\theta^2\right) + f_2 r^2 \sin^2\theta \left(d\varphi - \omega dt\right)^2$$

global charges

mass M, angular momentum J, dilaton charge D

$$f_0 \to 1 - \frac{2M}{r}, \quad \omega \to \frac{2J}{r^3}, \quad \phi \to -\frac{D}{r}.$$

Rapidly Rotating EGBD Black Holes

horizon properties

horizon $r_{\rm H}$:	$f_0(r_{\rm H})$	$= 0$
horizon angular velocity:	Ω	$= \omega(r_{\rm H})$
surface gravity $\kappa_{\rm sg}$:	$\kappa_{\rm sg}^2$	$= -1/4(\nabla_\mu \chi_\nu)(\nabla^\mu \chi^\nu)$
Hawking temperature:	$T_{\rm H}$	$= \kappa_{\rm sg}/2\pi$
horizon area:	$A_{\rm H}$	$= \int_{\Sigma_h} d^2x\sqrt{h}$
entropy:	S	$= \frac{1}{4}\int_{\Sigma_h} d^2x\sqrt{h}(1 + 2\alpha' e^{-\gamma\phi}\tilde{R})$

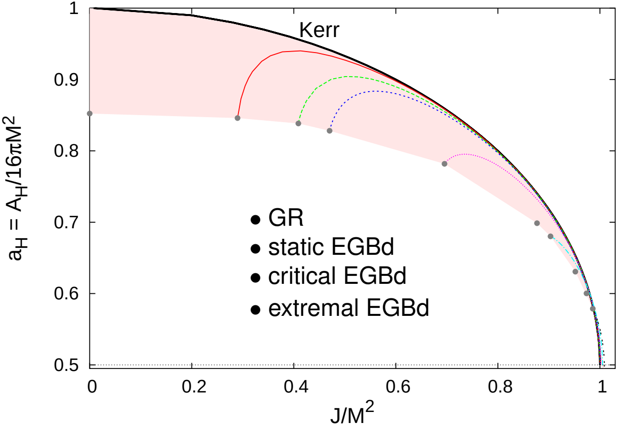
Smarr formula

$$M = 2T_{\rm H}S + 2\Omega J - \frac{D}{2\gamma}$$

relative error of Smarr formula in the calculations $< 10^{-5}$

Results: Global and Horizon Properties

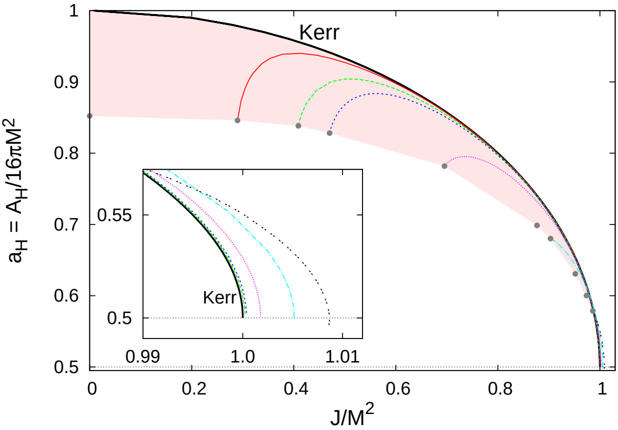
horizon area versus angular momentum



smaller area

Results: Global and Horizon Properties

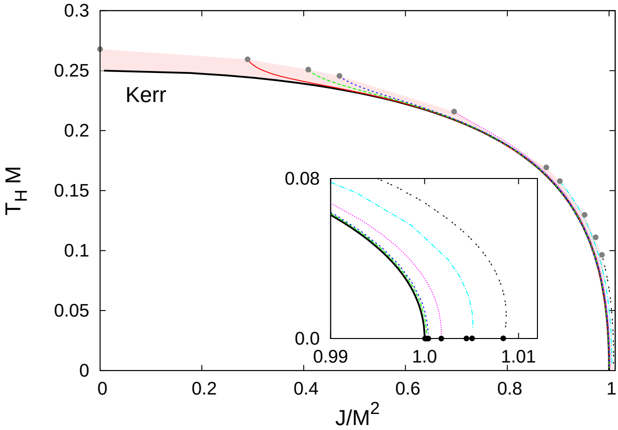
horizon area versus angular momentum



angular momenta beyond the Kerr limit

Results: Global and Horizon Properties

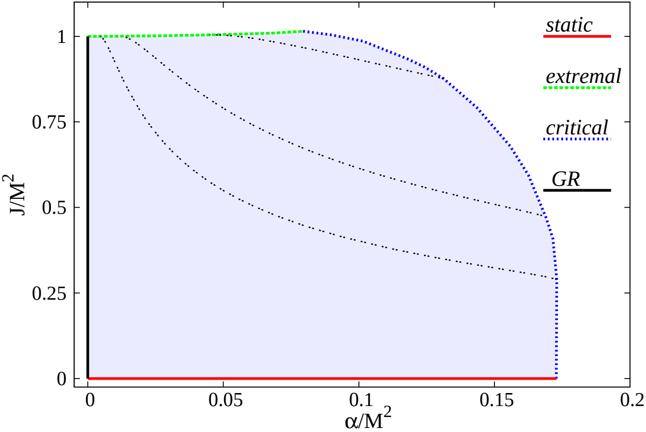
Hawking temperature versus angular momentum



$T_H \to 0$ extremal limit: regular spacetime, dilaton diverges

Results: Global and Horizon Properties

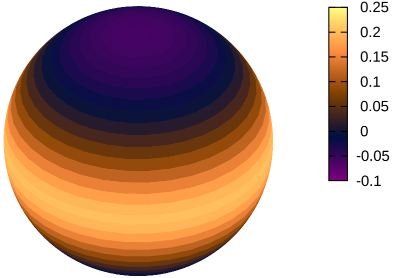
angular momentum versus GB coupling constant



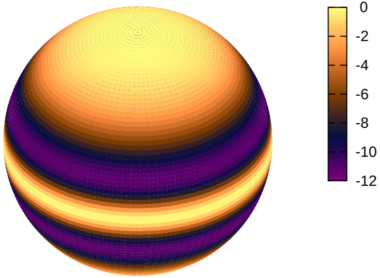
domain of existence

Results: Global and Horizon Properties

scalar field at the black hole horizon



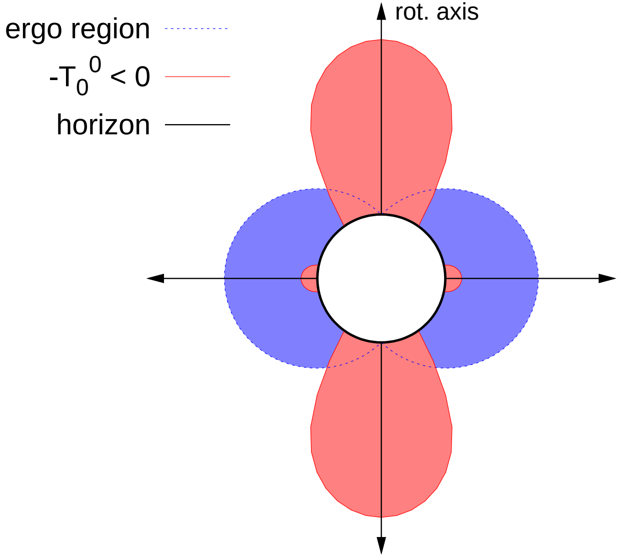
$\phi(r_{\rm H})$



$T_t^{t(\phi)}$

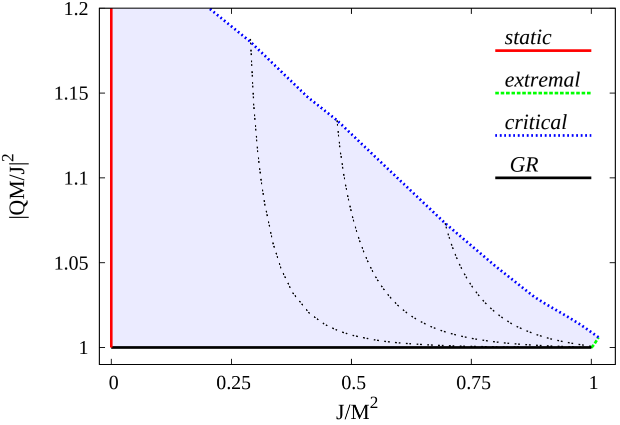
scalar hair

Results: Global and Horizon Properties



Results: Global and Horizon Properties

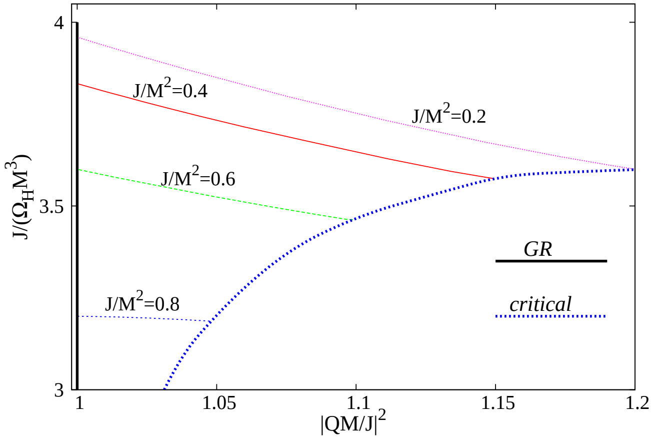
quadrupole moment versus angular momentum



quadrupole moment is larger

Results: Global and Horizon Properties

moment of inertia versus quadrupole moment



Kerr moment of inertia: $J/(\Omega_{\rm H} M^3) = 2\left(1+\sqrt{1-j^2}\right)$, $j = J/M^2$

static: 4 – extremal: 2

Outline

Motion of Testparticles

- Lagrangian

$$\mathcal{L} = \frac{1}{2} e^{-2\beta\phi} g_{\mu\nu} \dot{x}^\mu \dot{x}^\nu$$

$\beta = \mathrm{const.}$ $(= 1/2$ for heterotic string theory)

- Petrov type I

no separability expected

- ISCOs

$$\dot{r}^2 \equiv V(r)$$

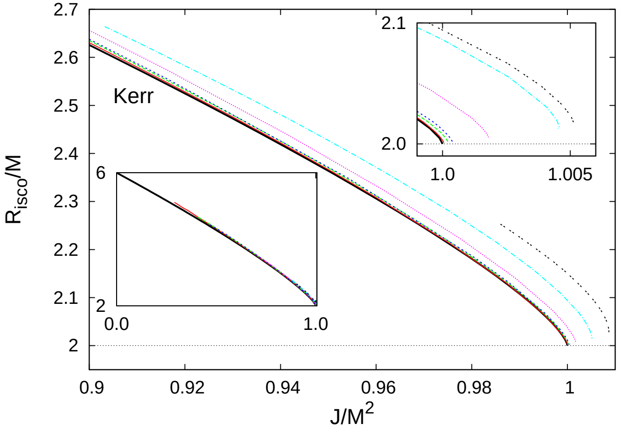
$V(r) = V'(r) = 0$

- orbital angular velocity

$$\Omega_c = \frac{\dot{\varphi}}{\dot{t}}$$

Motion of Testparticles

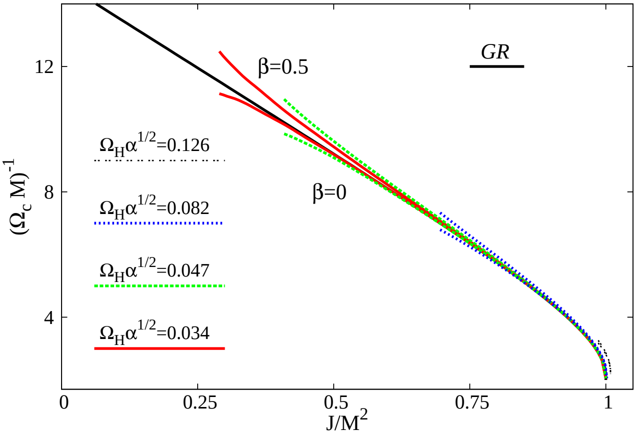
$R_{\rm isco}$: circumferential radius innermost stable circular orbit in the equatorial plane



Testparticles have larger ISCO radius

Motion of Testparticles

inverse orbital frequency versus angular momentum



large percentage deviations close to $J/M^2 = 1$

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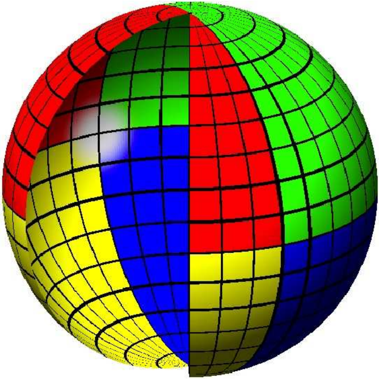
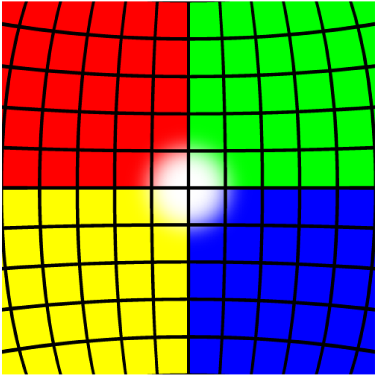
Black Hole Shadow

Black Hole Shadow

P. Cunha et al. PRL 115, 211102 (2015)



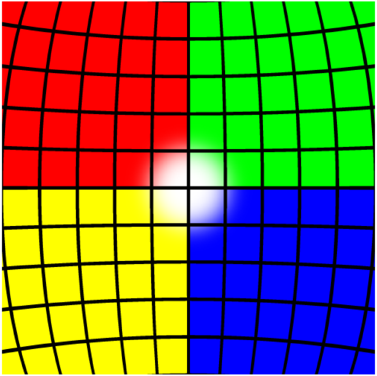
celestial sphere



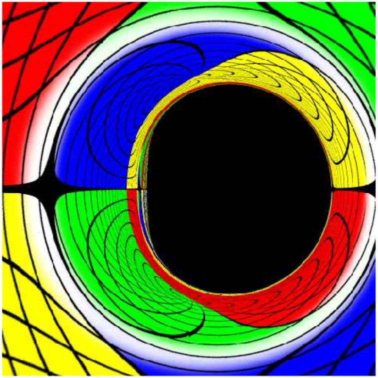
viewing angle

Black Hole Shadow

P. Cunha et al. PRL 115, 211102 (2015)



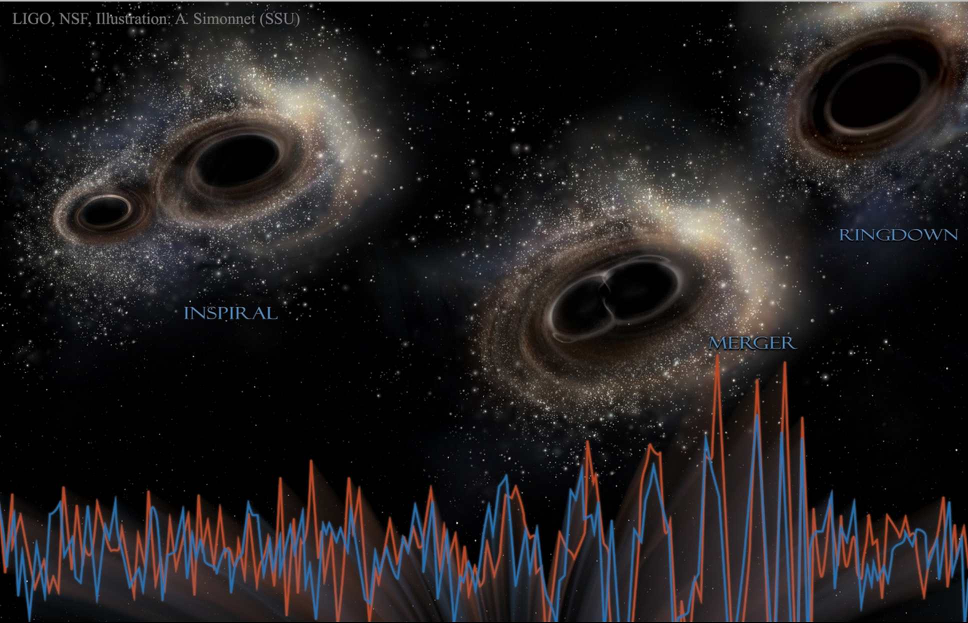
viewing angle



Kerr black hole

Outline

Gravitational Waves



Quasinormal Modes

P. Pani et al. PRD 79, 084031 (2009), J. Blázquez-Salcedo et al. 1609.01286

response of black holes to small perturbations

- fluctuations of the metric of dilaton
  ringdown signal from distorted black hole in coalescence
- small external perturbing object
  small black holes etc falling into massive black holes

simplest case: static spherically symmetic black hole

perturbations of the metric and the scalar field

$$g_{ab} = g_{ab}^{(0)} + \varepsilon \, h_{ab}$$
$$\phi = \phi_0(r) + \varepsilon \, \delta\phi$$

expansion of the perturbations, energy momentum tensor

Quasinormal Modes

scalar

$$\delta\phi = \sum_{l,m} \int d\omega \phi_1 \, Y^{lm} e^{-i\omega t}$$

polar (even parity): $(-1)^l$

$$h_{ab} = \sum_{l,m} \int d\omega \begin{bmatrix} AH_0 & H_1 & 0 & 0 \\ H_1 & H_2/B & 0 & 0 \\ 0 & 0 & r^2 K & 0 \\ 0 & 0 & 0 & r^2 \sin^2\theta K \end{bmatrix} Y^{lm} e^{-i\omega t}$$

axial (odd parity): $(-1)^{l+1}$

$$h_{ab} = \sum_{l,m} \int d\omega \begin{bmatrix} 0 & 0 & 0 & \sin\theta \, h_0 \partial_\theta \\ 0 & 0 & 0 & \sin\theta \, h_1 \partial_\theta \\ 0 & 0 & 0 & 0 \\ \sin\theta \, h_0 \partial_\theta & \sin\theta \, h_1 \partial_\theta & 0 & 0 \end{bmatrix} Y^{lm} e^{-i\omega t}$$

Quasinormal Modes

QNMs:

- sourceless wave equation

$$\frac{d}{dr}\Psi_{\mathrm{p,a}} + V_{\mathrm{p,a}}\Psi_{\mathrm{p,a}} = 0$$

- boundary conditions

$$\begin{aligned} r \sim r_h &: \quad e^{-i\omega r_*} \\ r \to \infty &: \quad e^{i\omega r_*} \end{aligned}$$

- linear mode stability: all ω possess negative imaginary part

$$e^{-i\omega t}$$

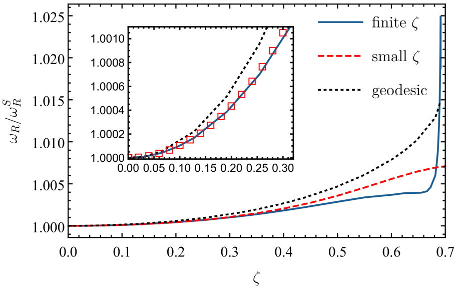
- comparison with Schwarzschild: fundamental $l = 2$ mode

$$\begin{aligned} M\omega^S &\approx 0.3737 - i\,0.08896 \quad \text{gravitational} \\ M\omega^S &\approx 0.4836 - i\,0.09676 \quad \text{scalar} \end{aligned}$$

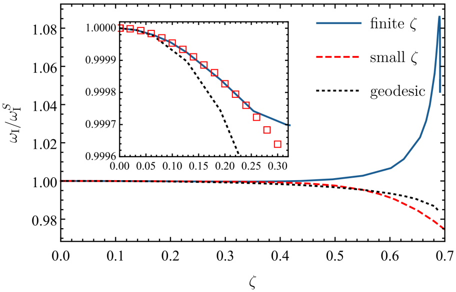
Quasinormal Modes

frequency of fundamental axial $l = 2$ mode versus coupling constant

normalized to the Schwarzschild values



real part



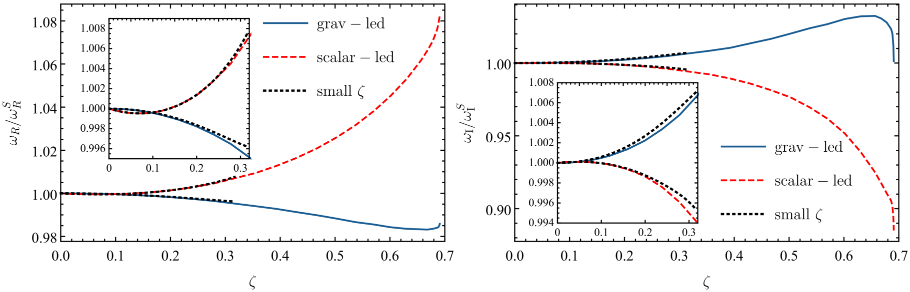
imaginary part

$$\zeta = \frac{\alpha'}{M^2}$$

Quasinormal Modes

frequency of polar $l = 2$ modes versus coupling constant

normalized to the Schwarzschild values

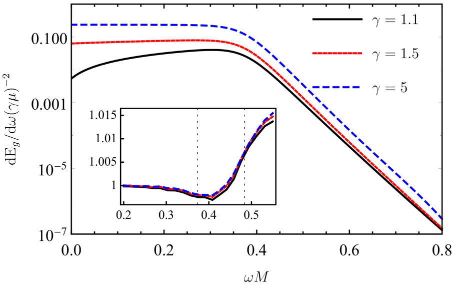


real part imaginary part

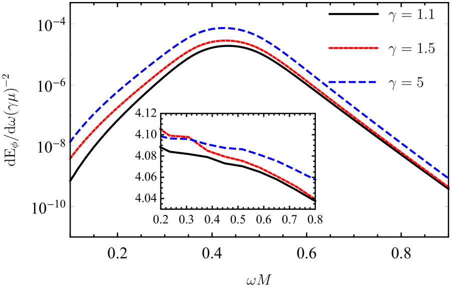
$$\zeta = \frac{\alpha'}{M^2}$$

Quasinormal Modes

quadrupolar flux for radial plunges into black hole versus frequency



gravitational



dilaton

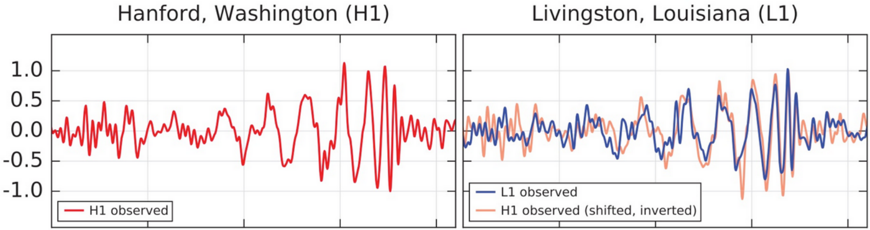
$$\zeta = \frac{\alpha'}{M^2} = 0.1$$

Quasinormal Modes

third generation detectors: Voyager and Einstein telescope

estimate:

$$\sqrt{\alpha'} \lesssim 11 \left(\frac{50}{\rho}\right)^{1/4} \left(\frac{M}{10M_\odot}\right) \text{km}$$



improved signal-to-noise ratio $\rho \approx 100$ for an event like GW150914

$$\sqrt{\alpha'} \lesssim 8 \left(\frac{M}{10M_\odot}\right) \text{km} \qquad \zeta \lesssim 0.4$$

Outline

GR Wormholes

PHYSICAL REVIEW D **76,** 024016 (2007)

Wormholes as black hole foils

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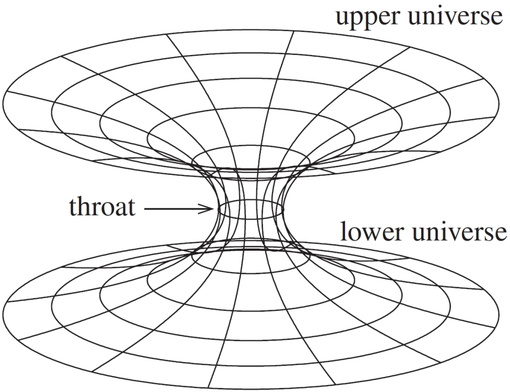
(Received 20 April 2007; published 27 July 2007)

We study to what extent wormholes can mimic the observational features of black holes. It is surprisingly found that many features that could be thought of as "characteristic" of a black hole (endowed with an event horizon) can be closely mimicked by a globally static wormhole, having no event horizon. This is the case for the apparently irreversible accretion of matter down a hole, no-hair properties, quasi-normal-mode ringing, and even the dissipative properties of black hole horizons, such as a finite surface resistivity equal to 377 Ohms. The only way to distinguish the two geometries on an observationally reasonable time scale would be through the detection of Hawking's radiation, which is, however, too weak to be of practical relevance for astrophysical black holes. We point out the existence of an interesting spectrum of quantum microstates trapped in the throat of a wormhole which could be relevant for storing the information lost during a gravitational collapse.

DOI: 10.1103/PhysRevD.76.024016 PACS numbers: 04.70.Dy

GR Wormholes

H. G. Ellis, J. Math. Phys. **14**, 104-118 (1973)



embedding diagram

H. G. Ellis

- 2 asymptotically flat regions
- sphere of minimal surface/radius
- no horizon
- no singularity

GR Wormholes

Wormholes in spacetime and their use for interstellar travel: A tool for teaching general relativity

Wormholes in spacetime and their use for interstellar travel: A tool for teaching general relativity

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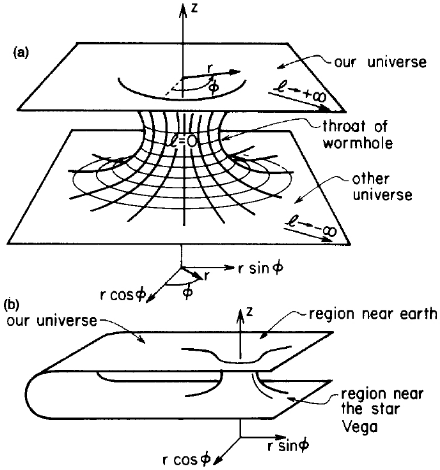
(Received 16 March 1987; accepted for publication 17 July 1987)

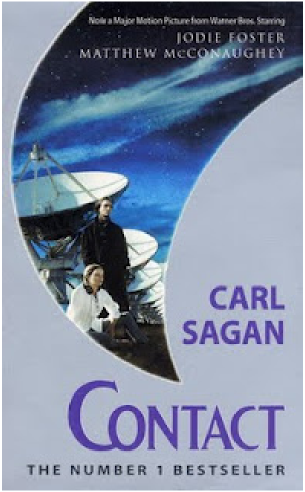
Rapid interstellar travel by means of spacetime wormholes is described in a way that is useful for teaching elementary general relativity. The description touches base with Carl Sagan's novel *Contact*, which, unlike most science fiction novels, treats such travel in a manner that accords with the best 1986 knowledge of the laws of physics. Many objections are given against the use of black holes or Schwarzschild wormholes for rapid interstellar travel. A new class of solutions of the Einstein field equations is presented, which describe wormholes that, in principle, could be traversed by human beings. It is essential in these solutions that the wormhole possess a throat at which there is no horizon; and this property, together with the Einstein field equations, places an extreme constraint on the material that generates the wormhole's spacetime curvature: In the wormhole's throat that material must possess a radial tension τ_0 with the enormous magnitude $\tau_0 \sim$ (pressure at the center of the most massive of neutron stars) $\times$ (20 km)^2/(circumference of throat)^2. Moreover, this tension must exceed the material's density of mass-energy, $\rho_0 c^2$. No known material has this $\tau_0 > \rho_0 c^2$ property, and such material would violate all the "energy conditions" that underlie some deeply cherished theorems in general relativity. However, it is not possible today to rule out firmly the existence of such material; and quantum field theory gives tantalizing hints that such material might, in fact, be possible.



GR Wormholes

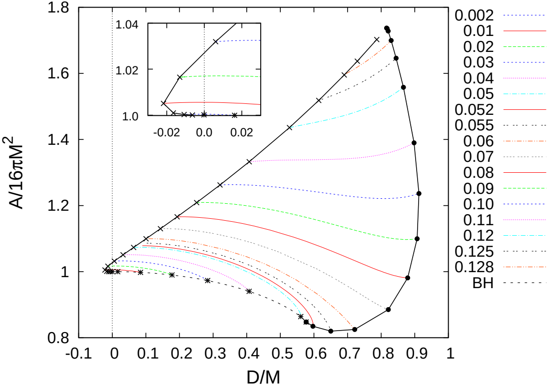
Desired properties of traversible wormholes

- stability
  - non-linear stability analysis
    Shinkai, Hayward, PRD 2002
    - additional negative energy causes expansion
    - reduced negative energy causes collapse
  - linear stability analysis
    Gonzales et al., CQG (2009)
    - unstable radial mode
    - instability seems generic
- reasonable stress-energy tensor
- small tidal forces
  (allowing human beings to travel)
- short travel time
  (allowing human beings to travel)



EGBD Wormholes

P. Kanti et al. PRL107 (2011), PRD85 (2012)



throat area

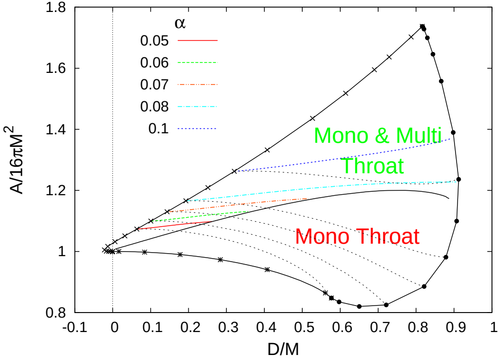
no exotic matter

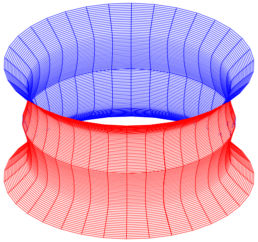
domain of existence

- lower boundary: black hole
- left boundary: $f_0 \to \infty$
- right boundary: singularity

EGBD Wormholes

Multi-throat EGBd wormholes





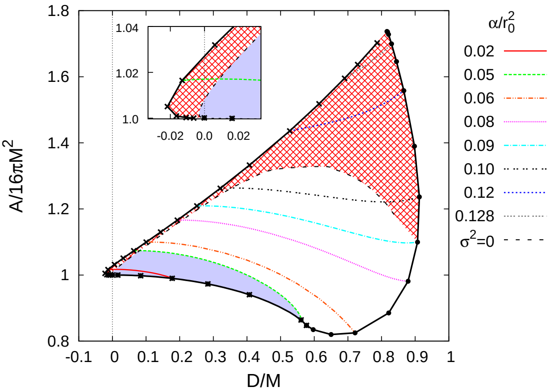
throat area, belly area

embedding

at the right boundary a singularity is encountered

EGBD Wormholes

stability



lilac: stable red: unstable white: undecided

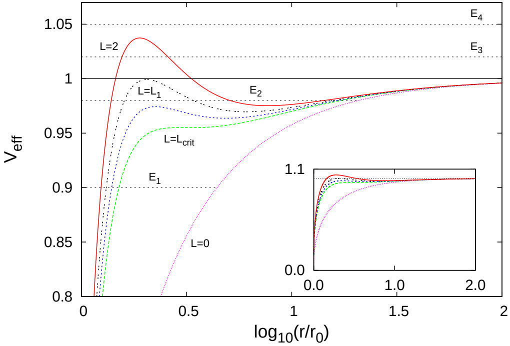
EGBD Wormholes

- geodesics from Lagrangian

$$\mathcal{L} = \frac{1}{2} e^{-2\beta\phi} g_{\mu\nu} \dot{x}^\mu \dot{x}^\nu$$

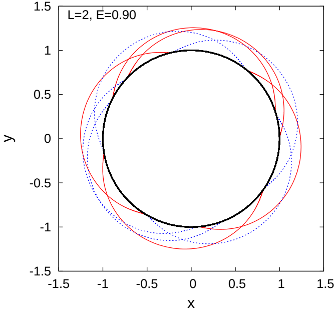
$\beta = \text{const.}$ ($= 1/2$ for heterotic string theory)

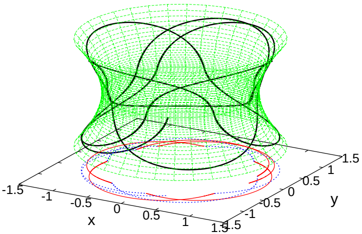
- effective potential: $V_{\text{eff}}^2(l, L) = e^{2\nu} \left(e^{-2\beta\phi} + \dfrac{L^2}{r_0^2 + l^2} \right)$

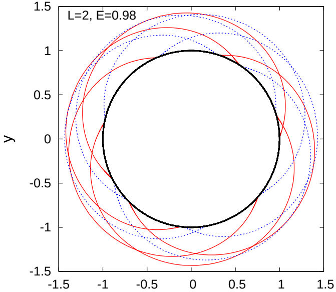


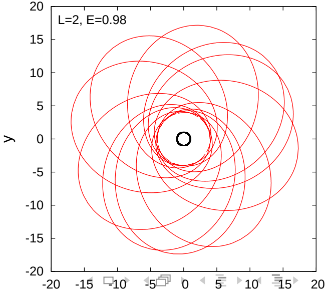
- $E^2 \geq V_{\text{eff}}^2(l, L)$
- turning points l_i:
  $E^2 - V_{\text{eff}}^2(l_i, L) = 0$
- no horizon
- bound orbits:
  motion around the throat
  motion across the throat

EGBD Wormholes









EGBD Wormholes

acceleration of a traveler at the throat?

- $g_\oplus$: acceleration of gravity at the surface of the earth
- acceleration on the order of $g_\oplus$:
  throat radius on the order of
  $(10 - 100)$ light-years

Outline

Conclusions

Gravity with String Theory corrections

- dilaton field
- Gauss-Bonnet term

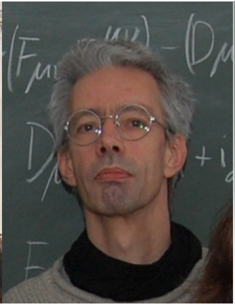
Comparison with Kerr black holes

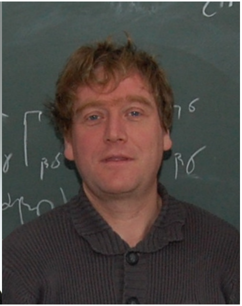
- EGBd black holes with $J/M^2 > 1$ exceed the Kerr bound
- EGBd black holes have smaller horizon area than Kerr black holes (except for large J/M^2)
- EGBd black holes have larger quadrupole moment, larger ISCO radius and smaller/larger orbital frequency

Conclusions

- EGBd black holes
  - shadow
  - shadow with accretion disk?
  - QNMs for rotating black holes?
  - GW templates?
  - ...
- EGBd wormholes
  - no exotic matter
  - static: stable wormholes
  - rotating wormholes?
  - ...

THANKS



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