Viewing Quadratic Gravity through the Lense of the Event Horizon Telescope

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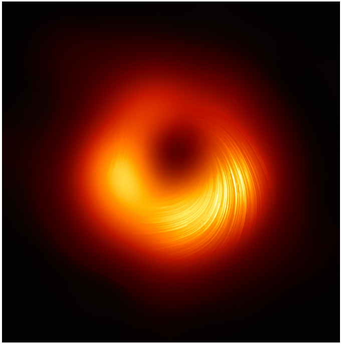
Motivation

K. Akiyama, et. al. [Event Horizon Telescope collaboration], '19
K. Akiyama, et. al. [Event Horizon Telescope collaboration], '21



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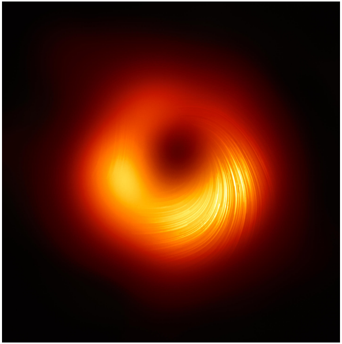

- is this a black hole known from general relativity?
- can we use the EHT to probe quantum gravity?

Outline

1. Quadratic Gravity - a brief introduction
2. Asymptotically flat vacuum solutions
3. Phase space of vacuum solutions
4. Discriminating geometries by shadow imaging
5. Outlook - there is a whole universe to explore

Quadratic Gravity

Einstein-Hilbert action:

$$S = \frac{1}{16\pi} \int d^4x \sqrt{-g} \left[\gamma R \qquad\qquad\qquad\qquad \right]$$

Quadratic Gravity

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$$S = \frac{1}{16\pi} \int d^4x \sqrt{-g} \left[\gamma R - \alpha C_{\mu\nu\rho\sigma} C^{\mu\nu\rho\sigma} + \beta R^2 \right]$$

(Weyl tensor)^2 (Ricci scalar)^2

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(Weyl tensor)^2 (Ricci scalar)^2

- two new coupling constants α, β
- well-motivated extension of general relativity:
  - renormalizable quantum theory for gravity
  - leading corrections in effective field theory

Quadratic Gravity:

$$S = \frac{1}{16\pi} \int d^4x \sqrt{-g} \left[\gamma R - \alpha C_{\mu\nu\rho\sigma} C^{\mu\nu\rho\sigma} + \beta R^2 \right]$$

equations of motion:

$$\gamma \left(R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R \right) - 4\alpha \left(D^\rho D^\sigma + \frac{1}{2} R^{\rho\sigma} \right) C_{\mu\rho\nu\sigma} + 2\beta \left(R_{\mu\nu} - \frac{1}{4} R g_{\mu\nu} - D_\mu D_\nu + g_{\mu\nu} D^2 \right) R = 0$$

- 4th order differential equations
- solutions no longer Ricci-flat
    - Birkhoff's theorem no longer holds

phase space of black hole-type geometries

static, spherically symmetric, asymptotic flat

Static, spherically symmetric solutions

metric ansatz

$$ds^2 = -h(r)dt^2 + \frac{dr^2}{f(r)} + r^2 \left(d\theta^2 + \sin^2\theta d\phi\right) \, .$$

- reduces e.o.m. to two coupled third-order equations
- Schwarzschild solution: $h(r) = f(r) = 1 - \frac{2M}{r}$

Static, spherically symmetric solutions

metric ansatz

$$ds^2 = -h(r)dt^2 + \frac{dr^2}{f(r)} + r^2 \left(d\theta^2 + \sin^2\theta d\phi\right) .$$

- reduces e.o.m. to two coupled third-order equations
- Schwarzschild solution: $h(r) = f(r) = 1 - \frac{2M}{r}$
- weak-field solution:

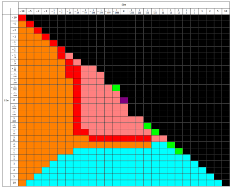
$$h(r) = 1 - \frac{2M}{r} + 2S_2^- \frac{e^{-m_2 r}}{r} + S_0^- \frac{e^{-m_0 r}}{r} ,$$
$$f(r) = 1 - \frac{2M}{r} + S_2^- \frac{e^{-m_2 r}}{r}(1 + m_2 r) - S_0^- \frac{e^{-m_0 r}}{r}(1 + m_0 r)$$

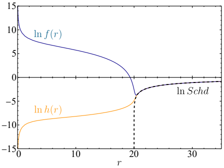
  - five free parameters: $m_2(\alpha), m_0(\beta), M, S_2^-, S_0^-$

Global solutions

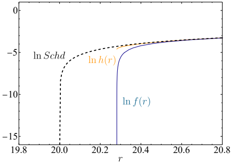
- numerically integrating inward
- matching to analytic scaling behavior

$\beta = 1/6$

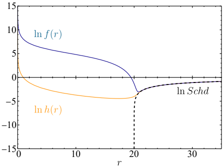




(rose, red, orange)
Type I (naked sing.)
$(2, -2)_0$



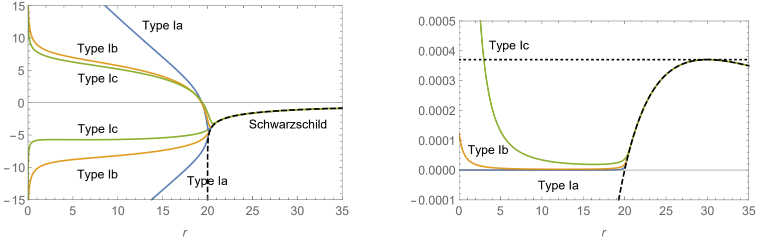
(black)
Type II (wormhole)
$(0, 1)_{r_0}$



(cyan)
Type III (naked sing.)
$(-1, -1)_0$

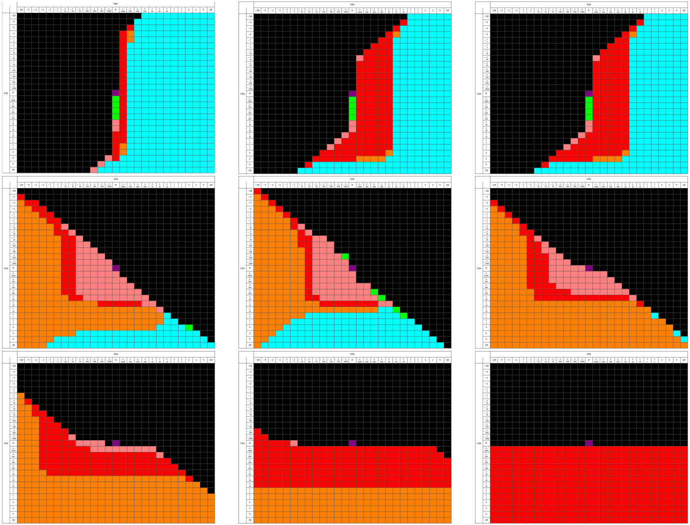
Type I $\mapsto$ Type Ia, Ib, Ic:

effective potential $V_{\text{eff}} = h(r)/r^2$



- Type Ia: V_{eff} decreases monotonically
- Type Ib: V_{eff} stable minimum at $r < 2M$
- Type Ic: $V_{\text{eff}}(0) > V_{\text{eff}}(3M)$

Constructing 10^4 geometries numerically:



shadow imaging

A simple accretion model

radially free-falling gas emitting monochromous radiation

$$j(\nu_e) \propto \frac{\delta(\nu_e - \nu_*)}{r^2}$$

intensity at observers screen

$$I_{\rm obs}(\nu_{\rm obs}, X, Y) = \int_\gamma g^3 \, j(\nu_e) \, dl_{\rm prop}$$

redshift factors

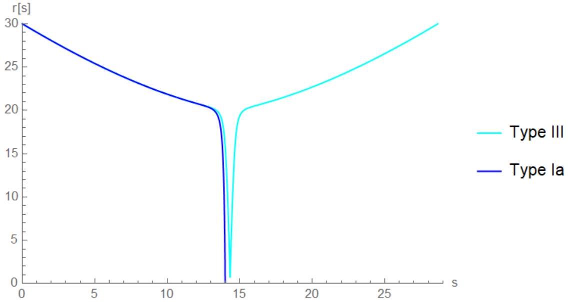
$$g_\pm = \left(\frac{1}{h} \mp \frac{|k_r|}{k_t} \sqrt{(1-h)\frac{f}{h}} \right)^{-1}$$

integrated intensity (impact parameter $b^2 = X^2 + Y^2$)

$$I_{\rm obs}(X, Y) \propto \int_\gamma \frac{g^3 \, k_t \, dr}{r^2 |k^r|}$$

Creating a Shadow

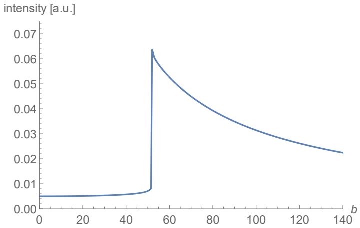
backward ray-tracing through spacetime

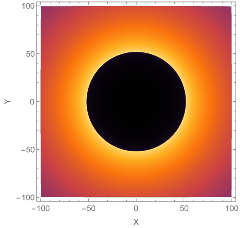


- rays captured by the object (short paths: dark)
- rays deflected by the object (long paths: bright)

Shadows of compact objects

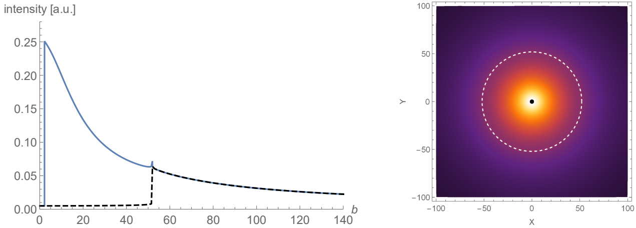
Type Ia, Ib, II:





- indistinguishable from Schwarzschild

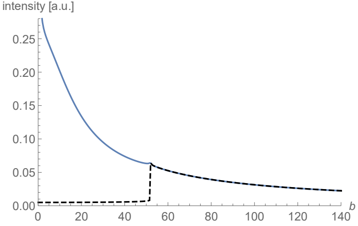
Type Ic:

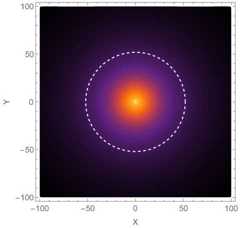


- smaller shadow region
- excess brightness for $b < b_{\text{crit}}$

Shadows of compact objects

Type III:

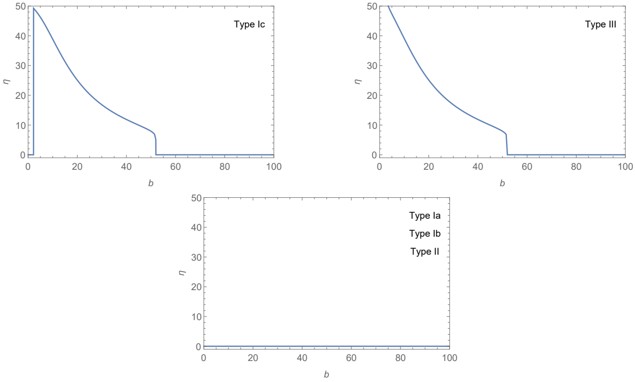




- no shadow region
- substantially increased intensity for $b < b_{\text{crit}}$

Excess intensity

$$\eta(b) = \frac{I_{\text{model}} - I_{\text{Schwarzschild}}}{I_{\text{Schwarzschild}}}$$



effect of order unity!

summary and outlook

summary

quadratic gravity

- rich phase space of black-hole type solutions

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- rich phase space of black-hole type solutions

possibility to discriminate by shadow measurements

Type	distinguishable by EHT
Ia, II	no
Ib	likely: need better accretion model
Ic, III	yes

summary

quadratic gravity

- rich phase space of black-hole type solutions

possibility to discriminate by shadow measurements

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Ia, II	no
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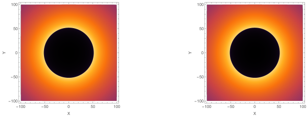
naked singularity/wormhole lookalikes:



- EHT can not say if an object has a horizon

outlook

- construct geometries including angular momentum

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- more realistic intensity profiles
    - use software developed by the EHT collaboration

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  - use software developed by the EHT collaboration
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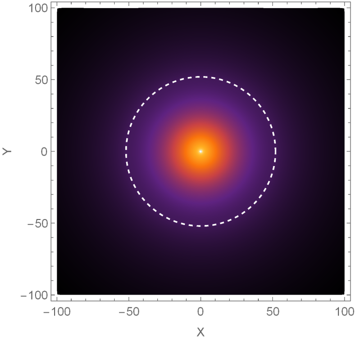
- improve image resolution

outlook

- construct geometries including angular momentum
- more realistic intensity profiles
  - use software developed by the EHT collaboration
- including quantum corrections
- improve image resolution
- additional observables
  - probes associated with gravitational wave signals?

lets play spot the difference:

EHT observation



Type III solution

Thank you!