Cosmic Censorship

- a talk on [redacted]

Stach Kuijpers

05/23/2018

Student seminar

A more general Black Hole

$G = c = 1$

Schwarzschild metric	Kerr-Newman metric
$d\tau^2 = \left(1-\frac{r_s}{r}\right)dt^2 - \left(1-\frac{r_s}{r}\right)^{-1}dr^2 - r^2(d\theta^2 + \sin^2\theta\, d\phi^2)$ $r_s = 2M$	$d\tau^2 = -\left(\frac{dr^2}{\Delta} + d\theta^2\right)\rho^2 + (-a\sin^2\theta\, d\phi + dt)^2\frac{\Delta}{\rho^2} - \left((r^2+a^2)d\phi - a\, dt\right)^2\frac{\sin^2\theta}{\rho^2}$ $r_s = 2M$ $r_Q^2 = \frac{Q^2}{4\pi\epsilon_0}$ $a = \frac{J}{M}$ $\rho^2 = r^2 + a^2\cos^2\theta$ $\Delta = r^2 - r_s r + a^2 + r_Q^2$

A more general Black Hole

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$r_s = 2M$	$r_s = 2M$ $r_Q^2 = \frac{Q^2}{4\pi\epsilon_0}$ $a = \frac{J}{M}$ $\rho^2 = r^2 + a^2\cos^2\theta$ $\Delta = r^2 - r_s r + a^2 + r_Q^2$
Singular when $g_{tt} = 0$ or $g_{rr} \to \infty$	
1 horizon at $r = 2M$	

A more general Black Hole

$G = c = 1$

Schwarzschild metric

$$d\tau^2 = \left(1-\frac{r_s}{r}\right)dt^2 - \left(1-\frac{r_s}{r}\right)^{-1} dr^2 - r^2(d\theta^2 + \sin^2\theta\, d\phi^2)$$

$r_s = 2M$

Singular when $g_{tt} = 0$ or $g_{rr} \to \infty$

1 event horizon at $r = 2M$

Kerr-Newman metric

$$d\tau^2 = -\left(\frac{dr^2}{\Delta} + d\theta^2\right)\rho^2 + (-a\sin^2\theta\, d\phi + dt)^2\frac{\Delta}{\rho^2} - \left((r^2+a^2)d\phi - a\,dt\right)^2\frac{\sin^2\theta}{\rho^2}$$

$r_s = 2M$

$r_Q^2 = \frac{Q^2}{4\pi\epsilon_0}$

$a = \frac{J}{M}$

$\rho^2 = r^2 + a^2\cos^2\theta$

$\Delta = r^2 - r_s r + a^2 + r_Q^2$

$g_{rr} \to \infty$ for $\Delta = 0$

2 event horizons

A more general Black Hole

$G = c = 1$

Schwarzschild metric

$$d\tau^2 =$$
$$\left(1 - \frac{r_s}{r}\right) dt^2 - \left(1 - \frac{r_s}{r}\right)^{-1} dr^2$$
$$-r^2\left(d\theta^2 + \sin^2\theta \, d\phi^2\right)$$

$r_s = 2M$

Singular when $g_{tt} = 0$ or $g_{rr} \to \infty$

1 horizon at $r = 2M$

Kerr-Newman metric

$$d\tau^2 =$$
$$-\left(\frac{dr^2}{\Delta} + d\theta^2\right)\rho^2 + (-a\sin^2\theta \, d\phi + dt)^2 \frac{\Delta}{\rho^2}$$
$$-\left((r^2 + a^2)d\phi - a\,dt\right)^2 \frac{\sin^2\theta}{\rho^2}$$

$r_s = 2M$

$r_Q^2 = \frac{Q^2}{4\pi\epsilon_0}$

$a = \frac{J}{M}$

$\rho^2 = r^2 + a^2\cos^2\theta$

$\Delta = r^2 - r_s r + a^2 + r_Q^2$

$g_{tt} = 0$ for $\Delta - a^2\sin^2\theta = 0$

2 “ergospheres”

A more general Black Hole

$G = c = 1$

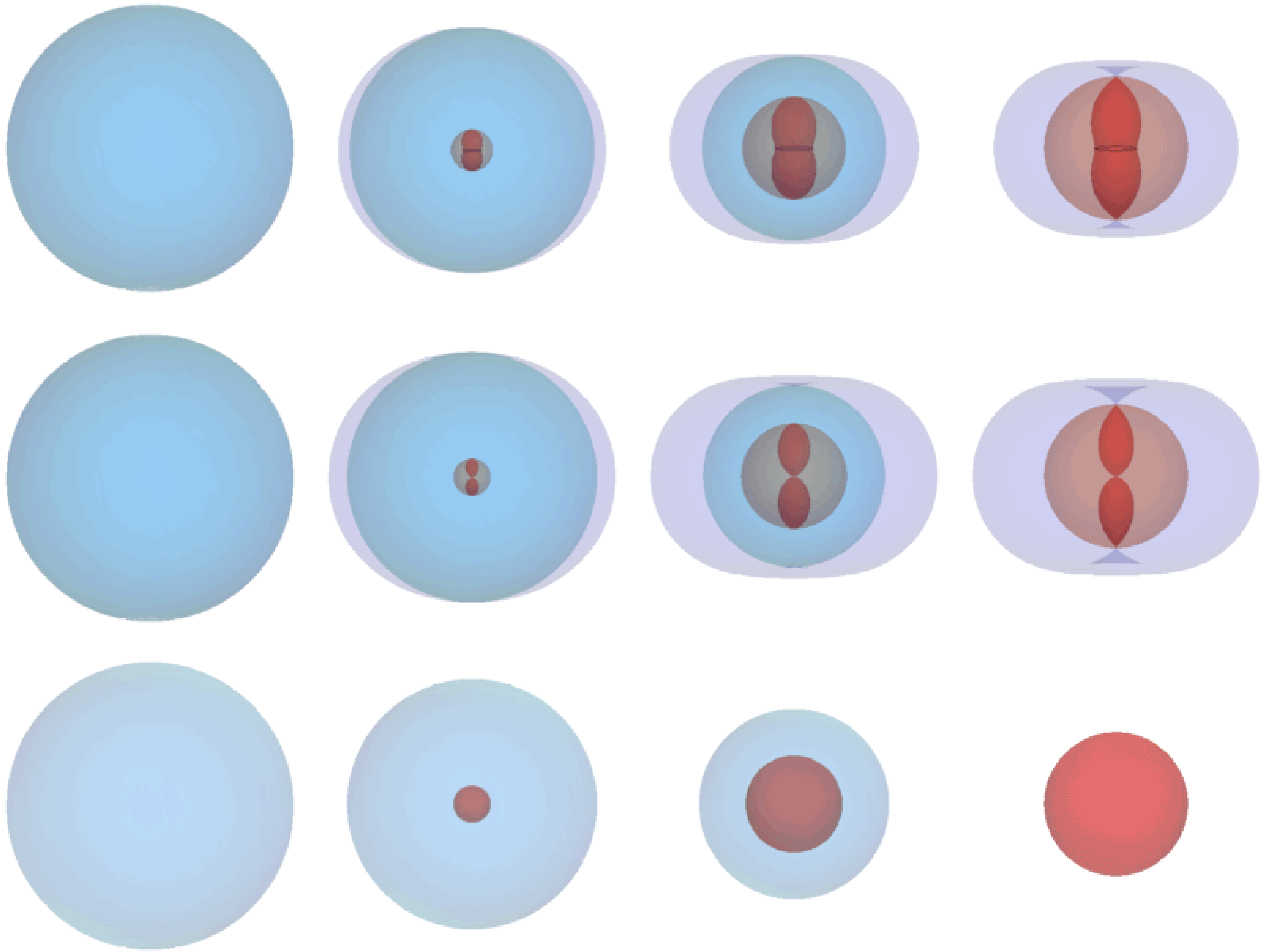
Schwarzschild metric	Kerr-Newman metric
$d\tau^2 = \left(1 - \frac{r_s}{r}\right) dt^2 - \left(1 - \frac{r_s}{r}\right)^{-1} dr^2 - r^2(d\theta^2 + \sin^2\theta\, d\phi^2)$	$d\tau^2 = -\left(\frac{dr^2}{\Delta} + d\theta^2\right)\rho^2 + (-a\sin^2\theta\, d\phi + dt)^2 \frac{\Delta}{\rho^2} - ((r^2 + a^2)d\phi - a\, dt)^2 \frac{\sin^2\theta}{\rho^2}$
$r_s = 2M$	$r_s = 2M$ $r_Q^2 = \frac{Q^2}{4\pi\epsilon_0}$ $a = \frac{J}{M}$ $\rho^2 = r^2 + a^2\cos^2\theta$ $\Delta = r^2 - r_s r + a^2 + r_Q^2$
Singular when $g_{tt} = 0$ or $g_{rr} \to \infty$ → 1 event horizon at $r = 2M$	Up to 4 singular surfaces

Surfaces of a Kerr-Newman Black hole

Rotating and charged
(Kerr-Newman)

Rotating, uncharged
(Kerr)

Non-rotating, charged
(Reissner-Nordström)

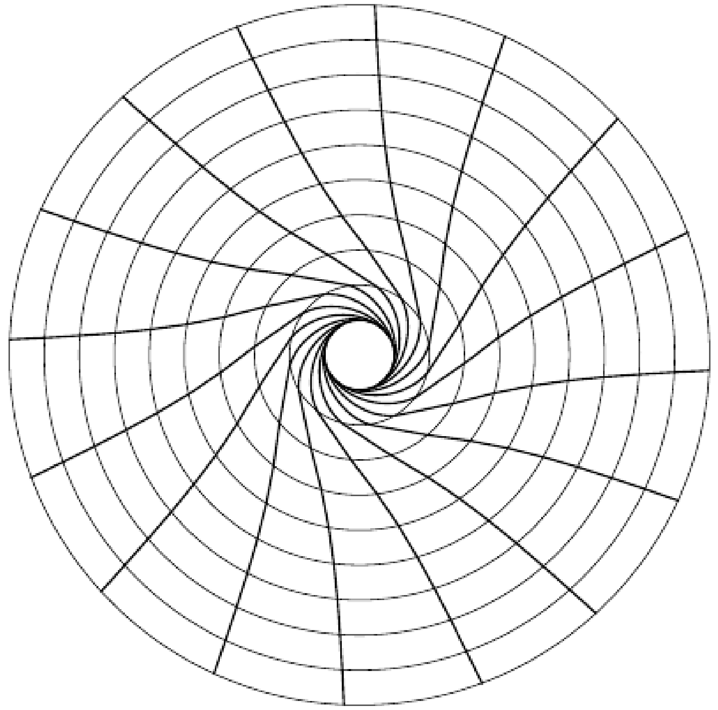


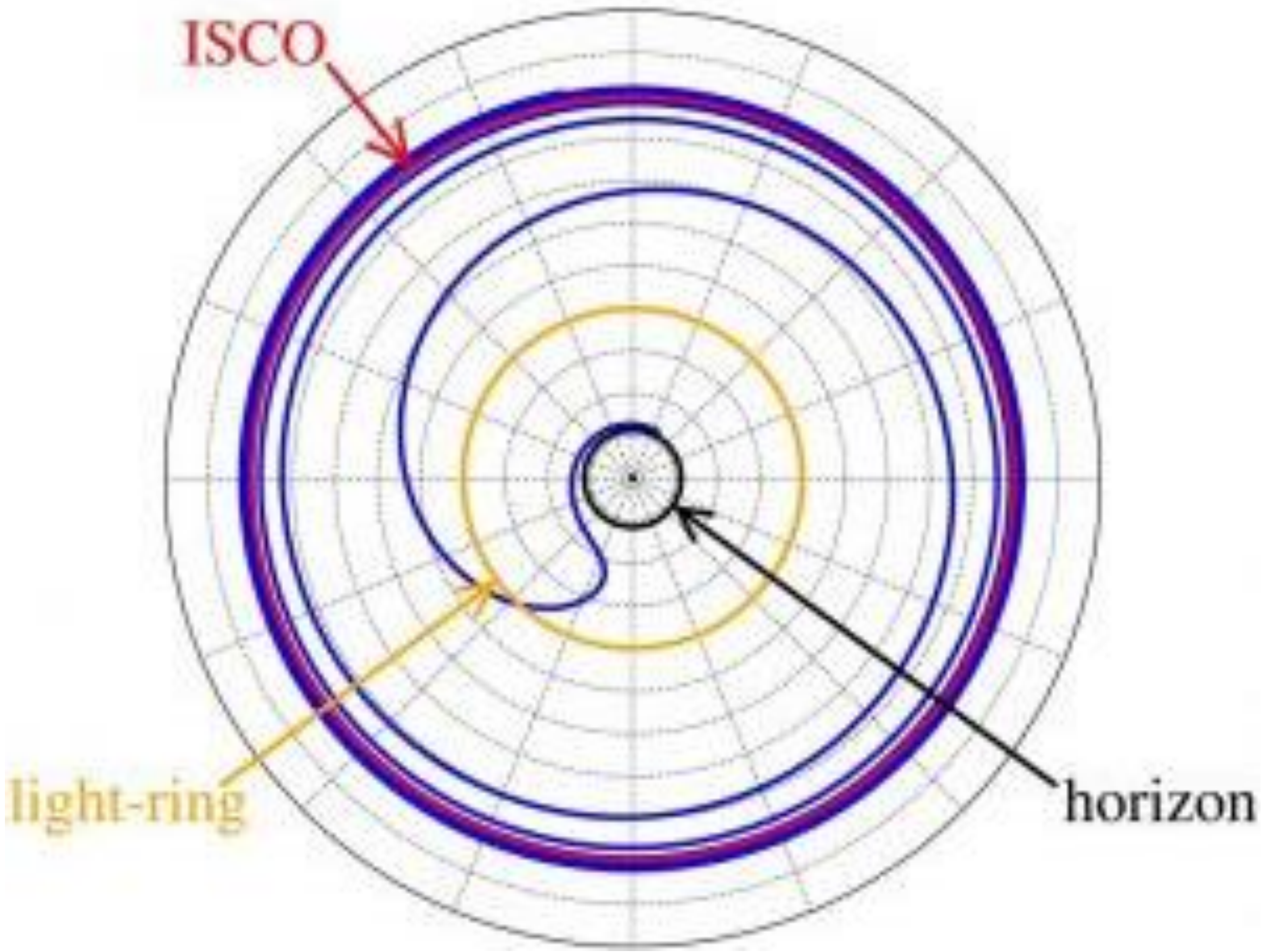
More critical →

http://notizblock.yukterez.net/viewtopic.php?p=426

What is this ergosphere?

- GR breaks down past inner event horizon
  → Inner ergosphere non-physical
- Outer ergosphere
  → surface where local frame velocity equals c
- From greek *ergon* for “work”
  → energy can be extracted from ergosphere
  → more on that later!



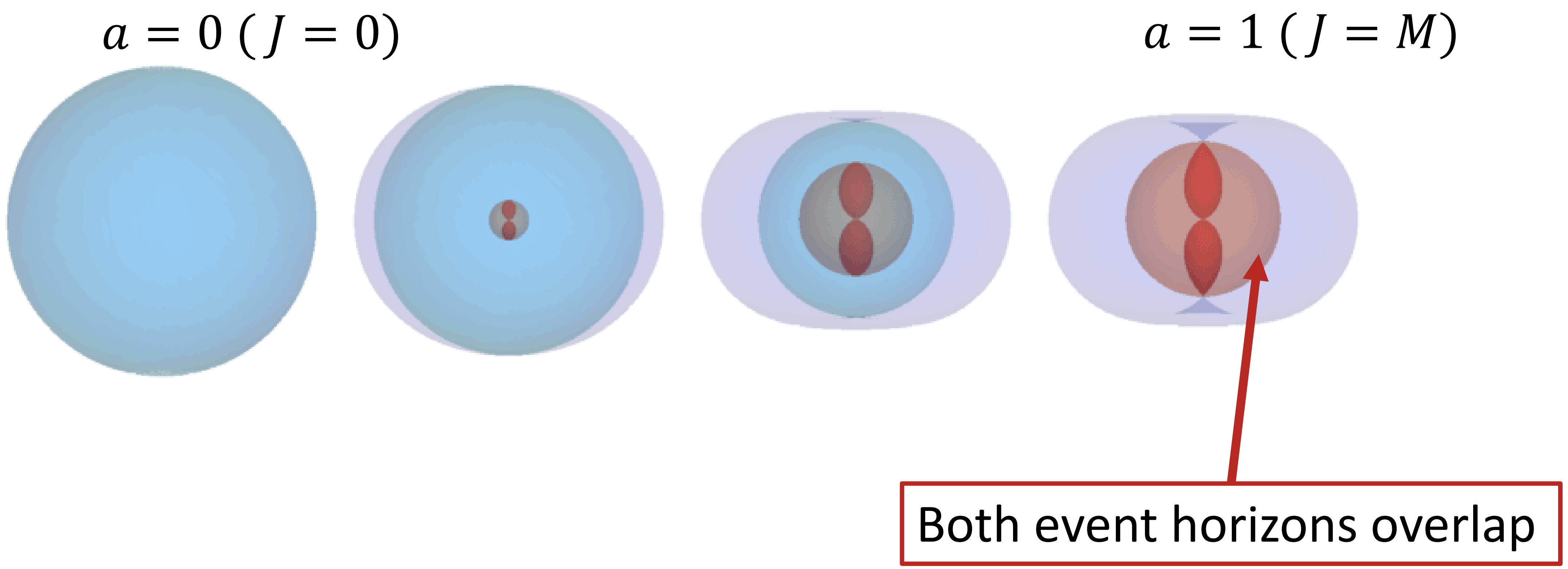


https://www.aei.mpg.de/1783615/Source_Modeling

1) Dafermos, Luk, The interior of dynamical vacuum black holes I: The C^0-stability of the Kerr Cauchy horizon. *submitted* **2017**.

Supercriticality and nakedness

Rotating, uncharged
(Kerr)



- $a^2 + Q^2 = 1$: GR breaks down at outer horizon
- $a^2 + Q^2 > 1$: naked singularity remains

→ problem: GR's determinism breaks down

→ conjecture: Naked singularities do not exist, i.e.

all singularities are hidden behind a null surface (Penrose, 1969)

http://notizblock.yukterez.net/viewtopic.php?p=426

Gedankenexperiments

- Wald (1974):
  Over-spinning a supercritical black hole, $a^2 + Q^2 = 1$

  → Plunge particles with

  1. angular momentum
  2. internal spin
  3. charge

Interstellar (2014)

1) Wald, Gedanken experiments to destroy a black hole. *Annals of Physics* **1974**, 82(2), 548-556.
2) Matsas, da Silva, Overspinning a nearly extreme charged black hole via a quantum tunneling process. *Phys. Rev. lett.* **2007**, 99(18), 181301.
3) Hod, Weak Cosmic Censorship: As Strong as Ever. *Phys. Rev. Lett.* **2008**, 100, 121101.

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  → Plunge particles with
    1. angular momentum
    2. internal spin
    3. charge

  → None of the particles get captured

    “[E]lectrostatic, centrifugal, and spin-spin repulsion have all conspired”

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Gedankenexperiments

- Matsas, da Silva (2007):
  Consider massless scalar particles

  → and find a violation!

- Hod (2008):
  Takes higher order backreactions into account

  → cosmic censorship save once more

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Simulations – black hole mergers

The configurations of two equal Kerr sources.—The family of two equal Kerr sources kept apart by a massless strut is described by the metric [8]

$$
\begin{aligned}
ds^2 &= f^{-1}[e^{2\gamma}(d\rho^2+dz^2)+\rho^2 d\varphi^2]-f(dt-\omega d\varphi)^2,\\
f &= \frac{A\bar{A}-B\bar{B}}{(A+B)(\bar{A}+\bar{B})}, \quad e^{2\gamma}=\frac{A\bar{A}-B\bar{B}}{16\lambda_0\bar{\lambda}_0 R_1R_2R_3R_4},\\
\omega &= \omega_0-\frac{2\mathrm{Im}[G(\bar{A}+\bar{B})]}{A\bar{A}-B\bar{B}},\\
A &= (R_1-R_2)(R_3-R_4)-4\sigma^2(R_1-R_3)(R_2-R_4),\\
B &= 2s\sigma[(1-2\sigma)(R_1-R_4)-(1+2\sigma)(R_2-R_3)],\\
G &= -zB+s\sigma[2R_1R_3-2R_2R_4-4\sigma(R_1R_2-R_3R_4)\\
&\quad -s(1-4\sigma^2)(R_1-R_2-R_3+R_4)], \qquad (1)
\end{aligned}
$$

where the functions R_i are defined by the expressions

$$
\begin{aligned}
R_i &= X_i\sqrt{\rho^2+(z-\alpha_i)^2},\\
X_1 &= -1/X_4=\phi(\mu+\sqrt{\mu^2-1}),\\
X_2 &= -1/X_3=\phi(\mu-\sqrt{\mu^2-1}),\\
\alpha_1 &= -\alpha_4=s\left(\frac{1}{2}+\sigma\right), \quad \alpha_2=-\alpha_3=s\left(\frac{1}{2}-\sigma\right),\\
\sigma &= -\frac{i\sqrt{\mu^2-1}}{\nu},\\
\mu &= \frac{(\phi^2+1)[\phi(\nu^2-4)+i\nu(\phi^2-1)]}{2[(\phi^2+1)^2-i\nu\phi(\phi^2-1)]}, \qquad (2)
\end{aligned}
$$

and the constants λ_0 and ω_0 have the form

$$
\begin{aligned}
\lambda_0 &= \frac{1}{\nu^2}(1-\phi^2)[(1+\phi^2)^2-\nu^2\phi^2],\\
\omega_0 &= \frac{2is(1-\phi^4-2i\mu\nu\phi^2)}{(1+\phi^2)^2-\nu^2\phi^2}. \qquad (3)
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B &= 2s\sigma[(1-\text{[illegible]}R_1-R_4)-(1+\text{[illegible]}R_2-R_3)],\\
G &= -zB + s\sigma[\text{[illegible]} - 2R_2R_4 \text{[illegible]} (R_1R_2-R_3R_4)\\
&\quad -s(1-4\sigma^2)(\text{[illegible]} R_2 - R\text{[illegible]}_4)], \qquad (1)
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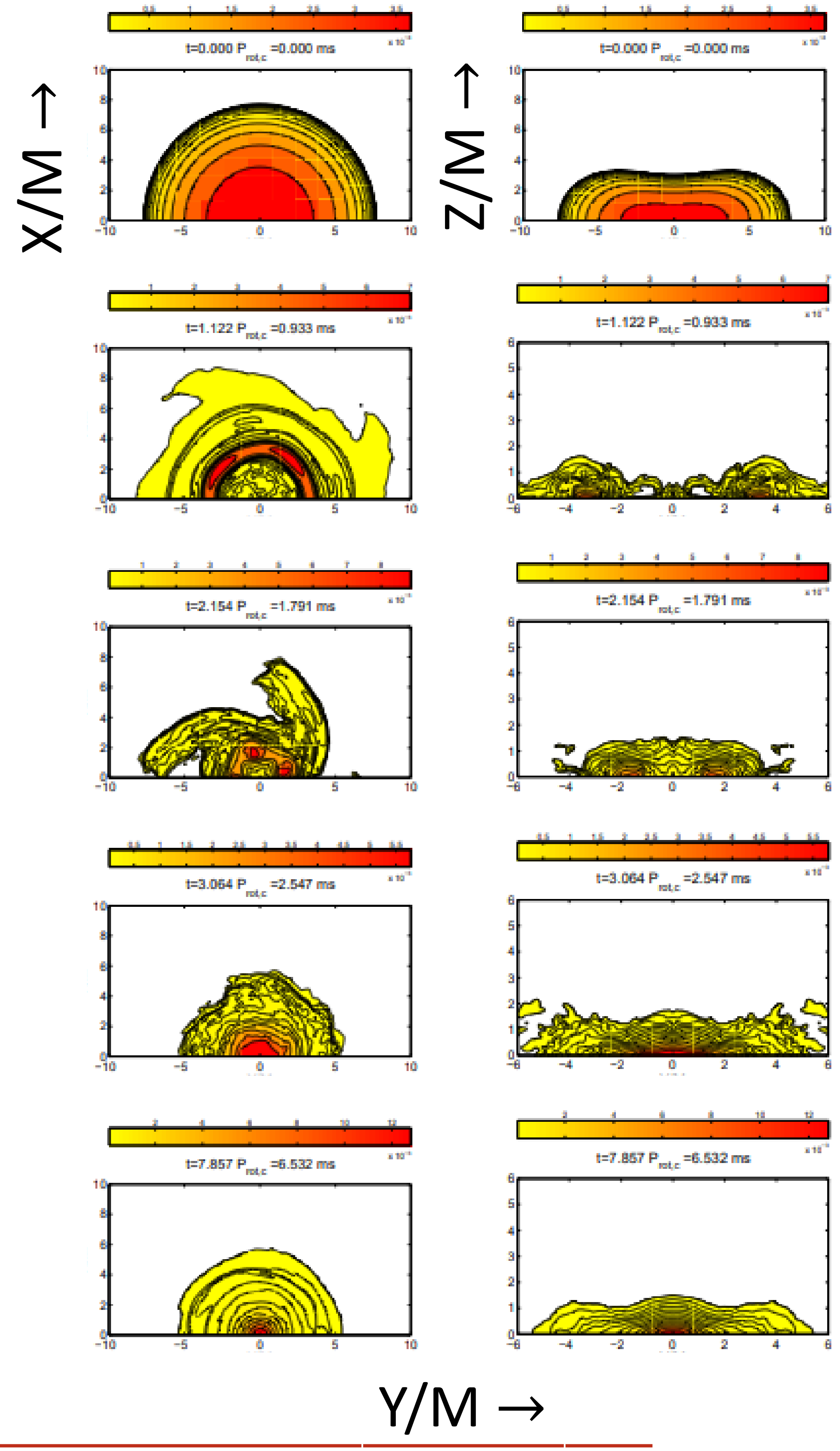
Simulations – black hole mergers

- Spin-spin interaction on cosmic scale (1,2)
- *"In all cases the collision results in a single BH plus gravitational radiation, i.e. there is no sign of any violation of cosmic censorship." (3)*
- supra-Kerr neutron star progenitors yield Kerr BH's (4) →

Densities: Axial Equatorial



1) Manko, Ruiz, "Black hole-naked singularity" dualism and the repulsion of two Kerr black holes due to spin-spin interaction. *arXiv preprint* **2018**, arXiv:1803.03301.

2) Campanelli, Zlochower, Loustó, Gravitational radiation from spinning-black-hole binaries: The orbital hang up. *Phys. Rev. D* **2006**, 74, 041501.

3) Sperhake, Cardoso, Pretorius, Berti, Gonzalez, High-energy collision of two black holes. *Physical review letters* **2008**, *101*(16), 161101.

4) Giacomazzo, Rezzolla, Stergioulas, Collapse of differentially rotating neutron stars and cosmic censorship. *Physical Review D* **2011**, *84(2), 024022.*

Simulations – black hole mergers

Densities: Axial

- Spin-spin interaction on cosmic scale (1,2)
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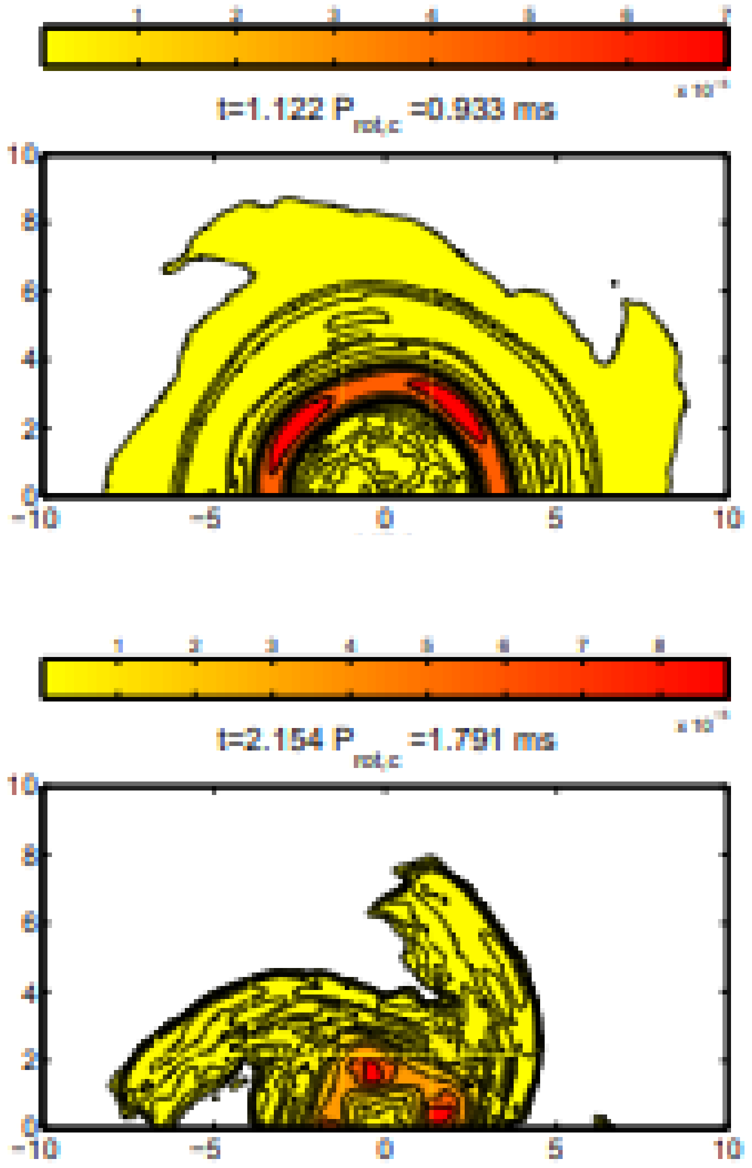
X/M ↑



Y/M →

1) Manko, Ruiz, "Black hole-naked singularity" dualism and the repulsion of two Kerr black holes due to spin-spin interaction. *arXiv preprint* **2018**, arXiv:1803.03301.

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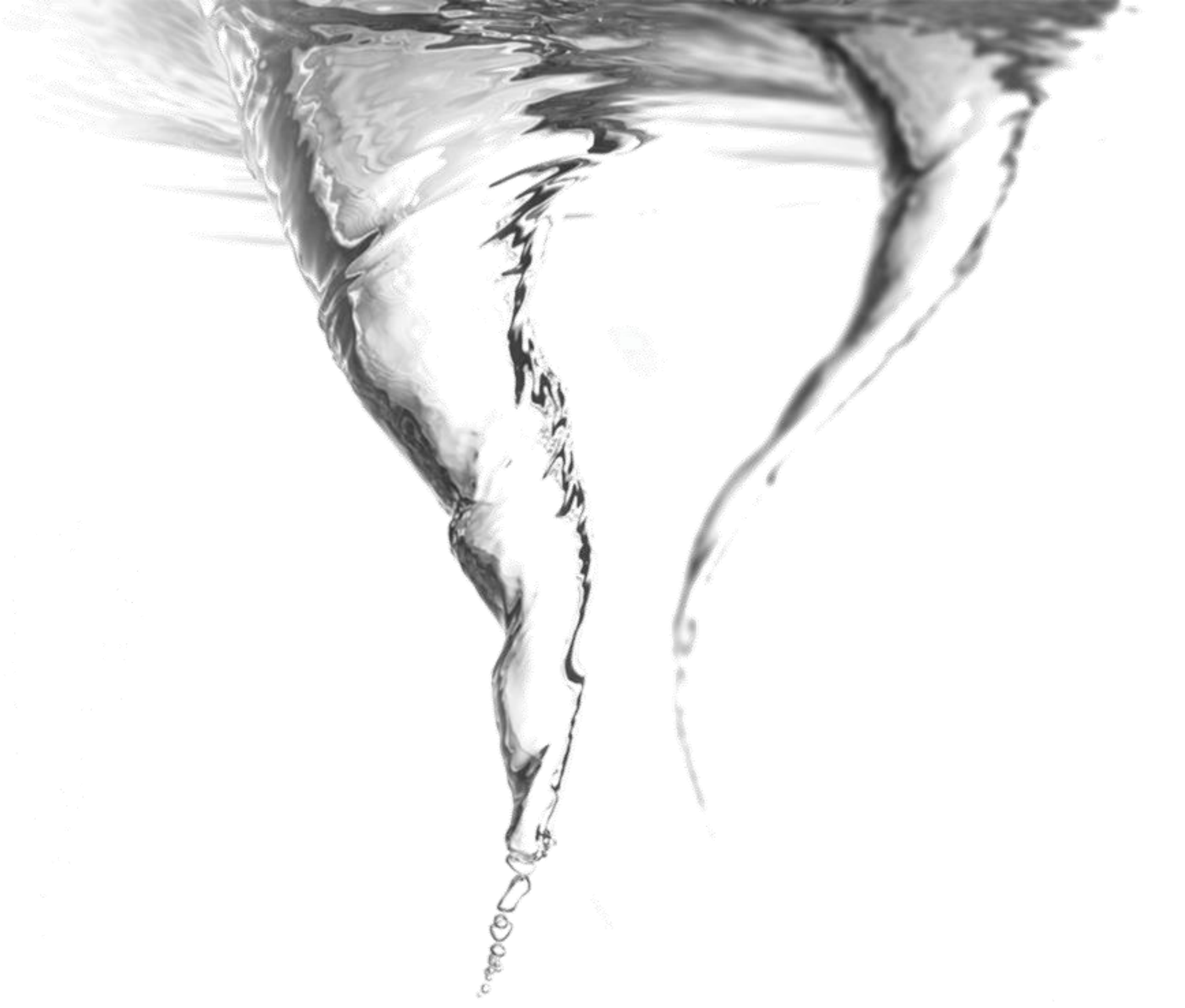
Experimental searches



- Square Kilometer array (1)
  → Looks for over-spinning BH pulsars

- Gravitational wave detectors (2)
  → Can measure orbital hang up

1) Kramer, Backer, Cordes, Lazio, Stappers, Johnston, Strong-field tests of gravity using pulsars and black holes. *New Astronomy Reviews* **2004**, *48*(11), 993-1002.

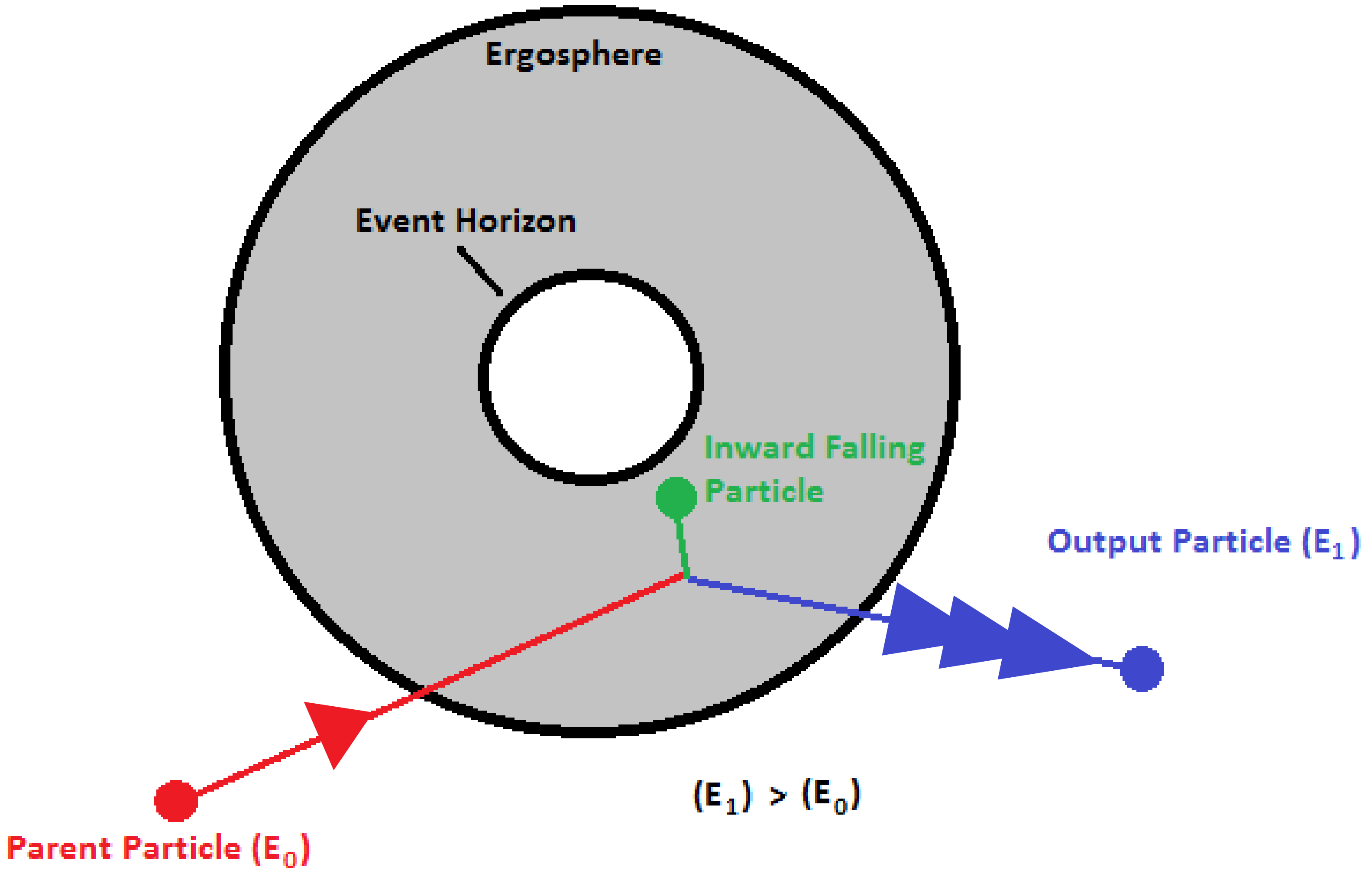
2) Dreyer, Kelly, Krishnan, Finn, Garrison, Lopez-Aleman, Black-hole spectroscopy: testing general relativity through gravitational-wave observations. *Classical and Quantum Gravity* **2004**, 21(4), 787.

What did we learn?

So we did not crack GR…

→ What can we do?

- Penrose process



- Black hole bomb https://youtu.be/ulCdoCfw-bY?t=323 (1:35 min)

1) Press, Teukolsky, Floating orbits, superradiant scattering and the black-hole bomb. *Nature* **1972**, 238(5361), 211.

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