Testing the Kerr hypothesis using the black hole shadow and gravitational lensing

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Several work in collaboration with: C. Herdeiro, E. Radu, L. Crispino, N. Sanchis-Gual, Haroldo Junior, J. Grover, E. Berti, A. Wittig, A. Pombo, H. Rúnarsson

First image (ever) of a BH candidate released on April 2019 by the EHT.

observed image M87*

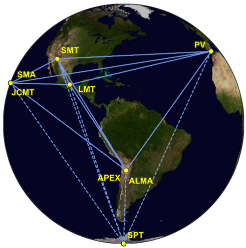
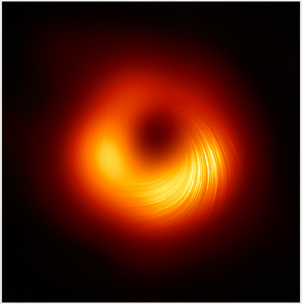


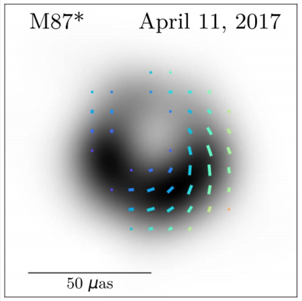
Figure 1. Eight stations of the EHT 2017 campaign over six geographic locations as viewed from the equatorial plane. Solid baselines represent mutual visibility on M87* (+12° declination). The dashed baselines were used for the calibration source 3C279 (see Papers III and IV).

(adapted EHT, AJ 875 L1 (2019))

- EHT combined an array of telescopes across the Earth in order to use VLBI.
- Consistent with an image of a Kerr BH surrounded by an accretion disk flow.

The EHT has released in March 2021 an image of polarized emission around M87*.

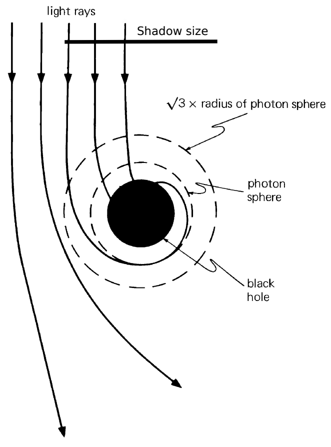




M87* image with polarization lines (adapted EHT, AJL 910 L13 (2021))

- Lines/ticks on image illustrate the observed direction of linear polarization.
- EHT data is consistent with *poloidal magnetic fields* in the M87* emission region.

Consider the scattering of light rays around a Schwarzschild BH:

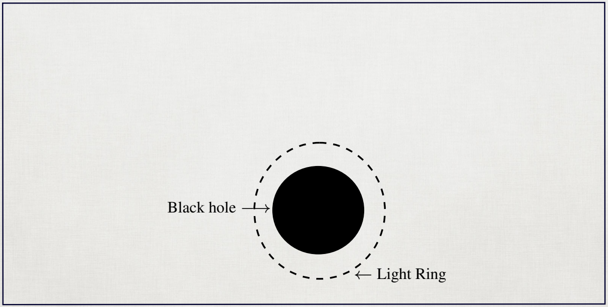


(adapted: *Cosmology*, E. Harrisson)

- Light rays need an impact parameter large enough to *escape* the BH.
- The shadow size corresponds to the bundle of rays that fall into the BH.

A scattering light ray around a BH can:

- *Escape* to infinity, *fall* into the BH, or *approach* a bound state orbit.



In spherical symmetry, the bound orbit is the *Light Ring* (LR), *a.k.a.* “photon sphere”: a *planar* photon orbit that encircles the BH forever.

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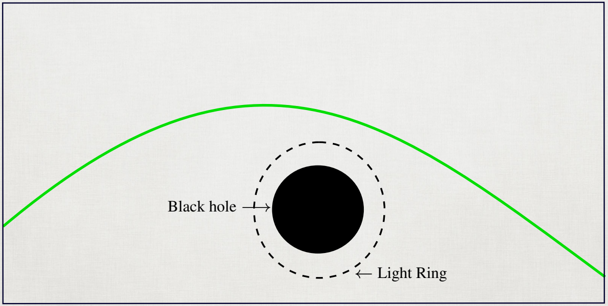

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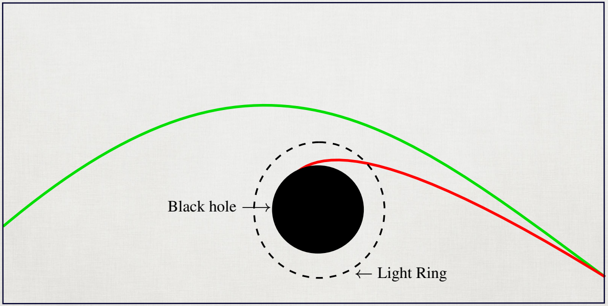

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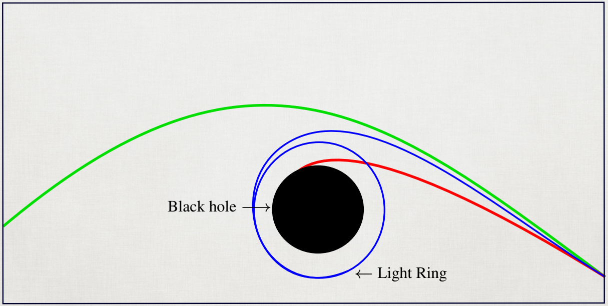

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Shadow rotating BH (Kerr)

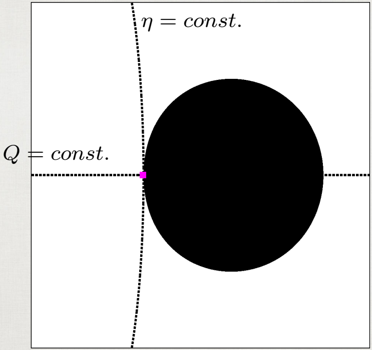
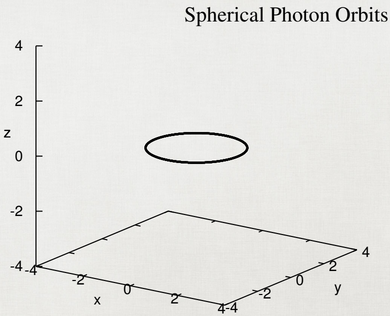


Image Kerr shadow



PRD 96 (2017) no.2, 024039

- Each point of the *Kerr* shadow edge is determined by "spherical" orbits.
- In contrast to Light Rings, the general family of null orbits is *not planar*.
- Each spherical orbit is uniquely identified by two impact parameters $\{\eta, Q\}$.

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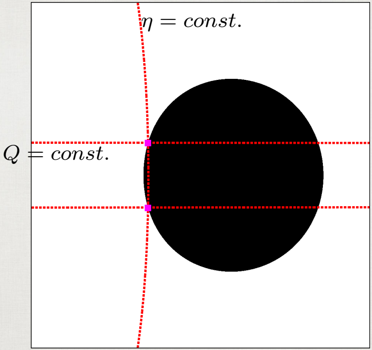

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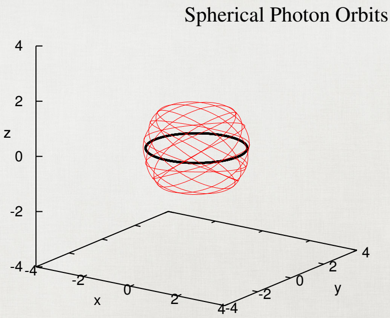

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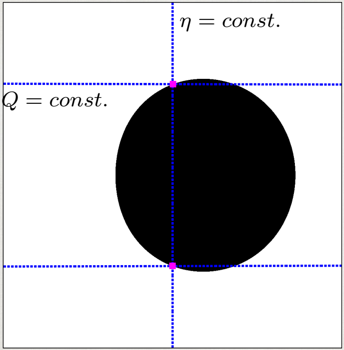

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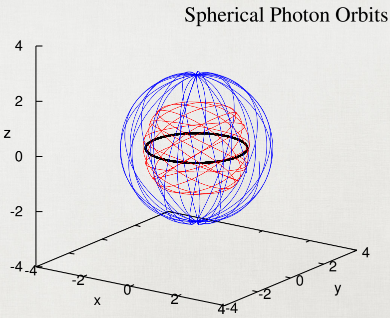

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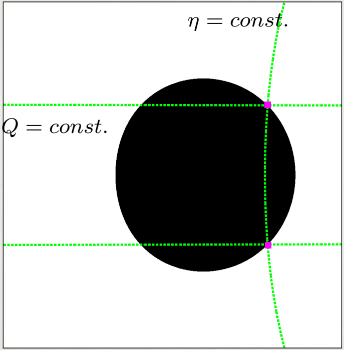
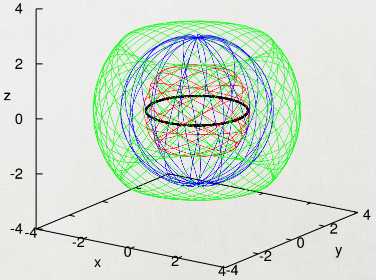


Image Kerr shadow

Spherical Photon Orbits



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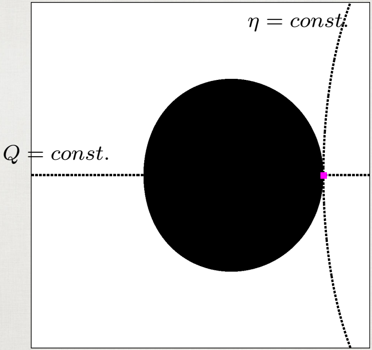

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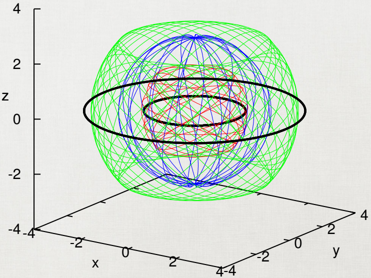
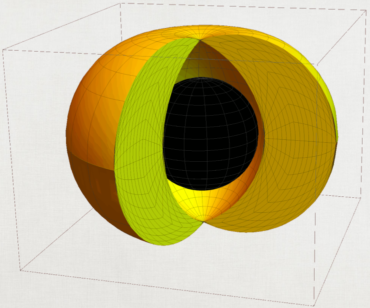
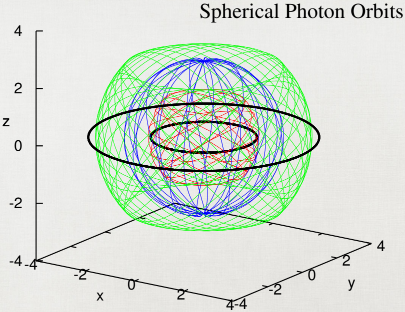


PRD 96 (2017) no.2, 024039

- Instead of a single "photon sphere", the shadow is determined by a ***photon region***.

Photon region (Kerr)

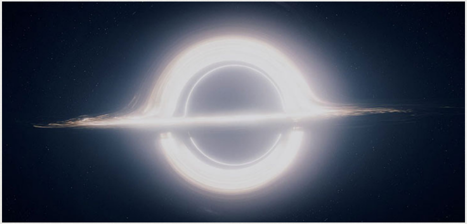


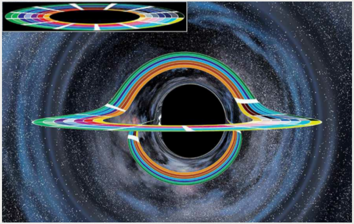


Photon region around a Kerr **Black Hole**

- The *collection* of Spherical Photon Orbits forms the *photon region*.

What is the BH image with a geometrically thin accretion disk?



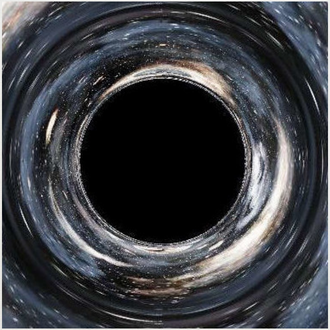


(adapted: *The Science of Interstellar*, K. Thorne)

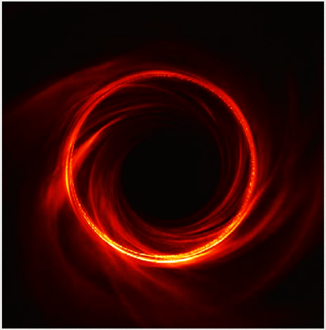
- BHs can be expected to have an accretion disk of orbiting (radiating) matter.
- The BH image in the film *Interstellar* (left) was generated with a simple disk.
- Due to lensing, the disk appears both *above* and *below* the shadow (right).

Kerr shadow (realistic)

What is the Kerr shadow in a more astrophysical setup?



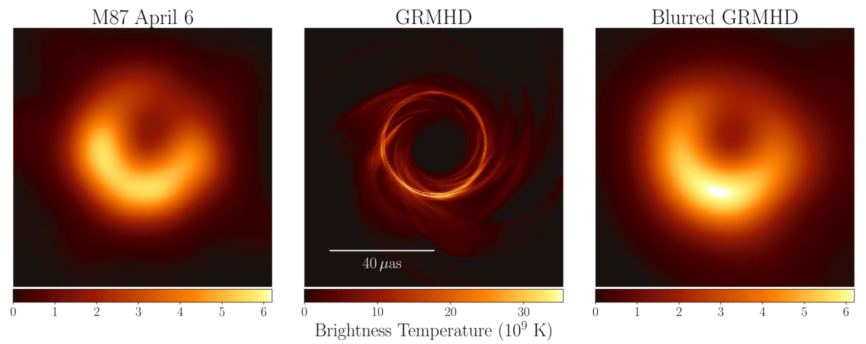
BH shadow (academic)



BH shadow (accretion disk)
(adapted EHT, AJ 875 L5 (2019))

- A *background light* is necessary to provide contrast for the BH shadow.
- In a astrophysical setup, it comes mainly from synchrotron radiation of *accretion flow*.
- Synthetic images (**right**) can be generated via GRMHD simulations of the flow.

Event Horizon Telescope



(adapted EHT, AJ 875 L5 (2019))

- To reproduce observation conditions → apply a Gaussian (blurring) filter.
- The blurred synthetic shadow image is remarkably similar to the data.
- The observed image is consistent with prediction for a Kerr shadow.

Relation to the image of Interstellar

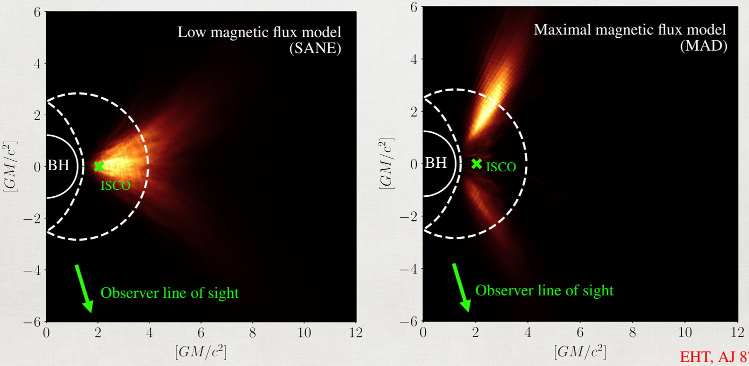
Video courtesy Double Negative:

https://www.dneg.com/new-black-hole-imagery/

https://www.youtube.com/watch?v=fKSa5aq_ae0&feature=emb_logo

The emission of the BH image comes from *which region?*

Source location of photons that make up the BH image (bright regions) :



EHT, AJ 875 L5 (2019)

Typical accretion emission models around a Kerr BH with spin $a = 0.94$.

Both models are consistent with EHT observed image.

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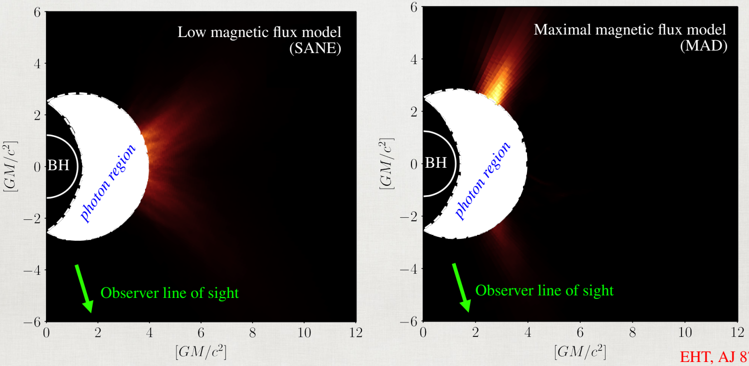
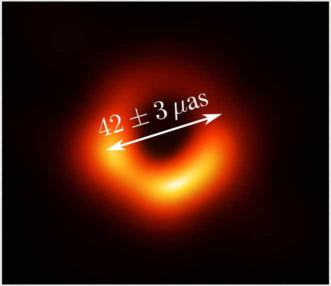


EHT, AJ 875 L5 (2019)

The *photon region* (highlighted in white) determines the BH shadow edge.

There is some contribution to the BH image from outside this region.

The image's *emission ring* does not have to coincide *exactly* with BH shadow edge.



EHT, AJ 875 L1 (2019)

From library of accretion flows one expects the shadow size to be $\sim 10\%$ *smaller than this ring*:

$$\boxed{\vartheta = 18.9 \pm 1.5\ \mu\text{as}}, \qquad \text{(M87* shadow radius)}$$

$\vartheta \rightarrow$ shadow (angular) radius

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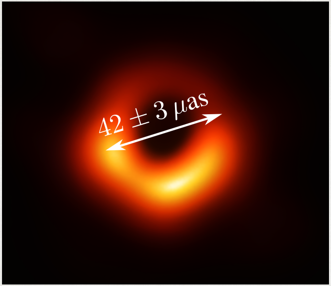

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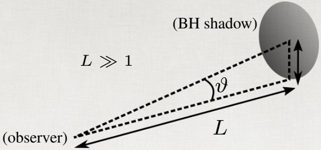

$$\vartheta = \mathcal{S}\,\frac{M}{L},$$

$\vartheta \rightarrow$ shadow (angular) radius

$L \rightarrow$ observer distance to BH

$M \rightarrow$ BH mass scale

$\mathcal{S} \rightarrow$ model dependent factor ($\simeq 5$)

Currently there is a lack of tension between observations and the Kerr hypothesis.

Kerr is likely a *fair approximation*, within current precision, rather than a fundamental truth.

The Kerr paradigm is motivated by multiple *uniqueness theorems*: equilibrium vacuum BHs of General Relativity (GR) are described by the *Kerr solution* (Israel 1967, Carter 1973, Robinson 1975).

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What could be an alternative to Kerr BHs?

- BHs in GR with matter fields, *e.g.* BHs with synchronized hair; Herdeiro, Radu PRL 112(2014) 221101
- Compact objects with no horizon, *e.g.* gravastars, Boson/Proca stars; Brito+ PLB 752 (2016) 291
- BHs in alternative gravity theories, *e.g.* scalarized BHs; Antoniou+ PRD 97 (2018) no.8, 084037

A simple way to circumvent the uniqueness theorems $\longrightarrow$ GR with *matter fields*.

A possible scenario is to consider hypothetical *scalar fields* (mass μ), which could be part of the dark matter content. Hui+ 2017 PRD **95** 4, 043541

Einstein-Klein-Gordon theory with a (complex) massive scalar field ϕ

$$\mathcal{S} = \int d^4x \sqrt{-g} \left[\frac{R}{16\pi G} - \nabla_\nu \phi \nabla^\nu \phi^* - \mu^2 \phi^* \phi \right].$$

One can find full BH solutions in equilibrium with ϕ. Herdeiro, Radu PRL **112** (2014) 221101

These solutions are known as *BHs with synchronized scalar hair*.

Properties of BHs with synchronized scalar hair:

Metric Ansatz

$$ds^2 = e^{2F_1}\left(\frac{dr^2}{N} + r^2 d\theta^2\right) + e^{2F_2} r^2 \sin^2\theta (d\varphi - W dt)^2 - e^{2F_0} N dt^2$$

where $N = 1 - r_H/r$.

Herdeiro, Radu PRL **112** (2014) 221101

- The metric is *stationary*, *axially symmetric* and *asymptotically flat*.
- A $\mathbb{Z}_2$ reflection symmetry around the plane $\theta = \pi/2$ is assumed.
- These solutions are regular on/outside horizon, and satisfy all energy conditions.
- The metric possesses two Killing vectors $\{\partial_t, \partial_\varphi\}$, with all metric functions $g_{\mu\nu}(r, \theta)$.

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- The metric possesses two Killing vectors $\{\partial_t, \partial_\varphi\}$, with all metric functions $g_{\mu\nu}(r, \theta)$.

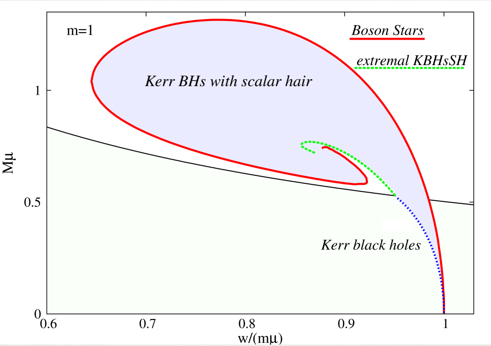
However, these Killing vectors are not symmetries of the *full solution*:

$$\phi = \psi(r,\theta) e^{i(m\varphi - \omega t)}, \qquad \omega \in \mathbb{R}^+, \quad m \in \mathbb{Z}.$$

Due to the harmonic ansatz, the t, φ dependence does not appear at the level of the geometry.

Herdeiro, Radu PRL **112** (2014) 221101

total BH mass (ADM) ⟶

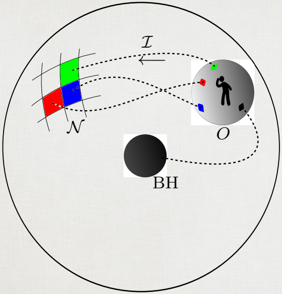


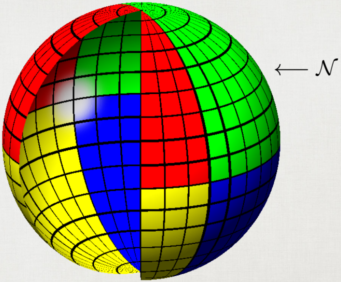
(horizon angular velocity)

The solution space of BHs with synchronized scalar hair (here $m = 1$) interpolates between:

- The Kerr solution + scalar test field.
- Extremal hairy BH solutions.
- Rotating Boson Stars (solitonic limit). These are regular *horizonless* solutions.

What is the image of a hairy BH in the electromagnetic channel?





Setup from: Bohn+ CQG 32 (2015) no.6, 065002

- Null geodesics are emitted from a far-away source $\mathcal{N}$, $e.g.$ colored sphere.
- $\mathcal{N}$ encloses both the BH and the observer.
- Light rays that reach the observer are perceived in a local sky O (a S^2 sphere).

An observation image defines a *map* $\mathcal{I} : O \to \mathcal{N}$.

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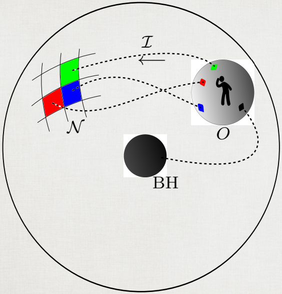
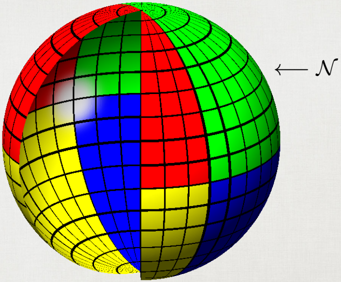




Setup from: Bohn+ CQG 32 (2015) no.6, 065002

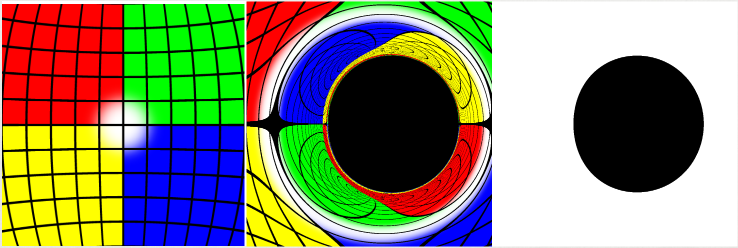
We can now define the *shadow* of a BH:

- set of points in the local sky O that are not mapped to $\mathcal{N}$, but rather to the BH.

Light rays from this set asymptotically fall into the BH when propagated backwards.

Shadows of Kerr BHs

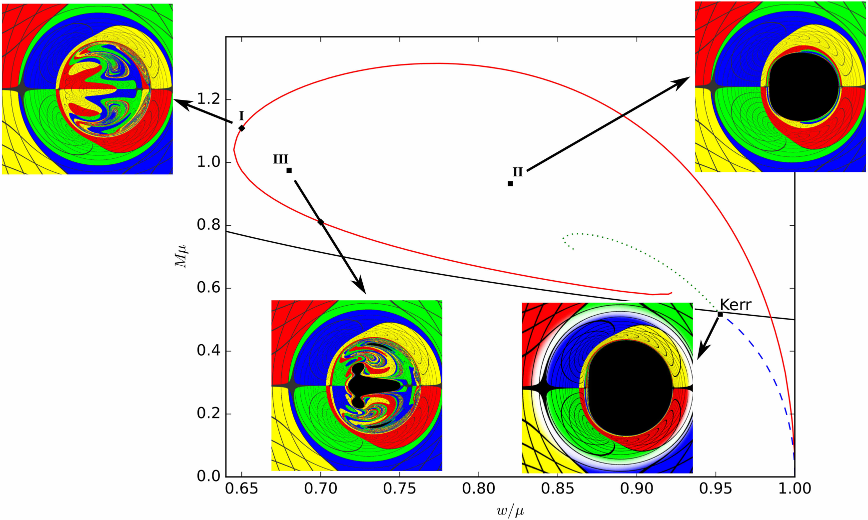
The Kerr observation image is displayed below (shadow represented in black).



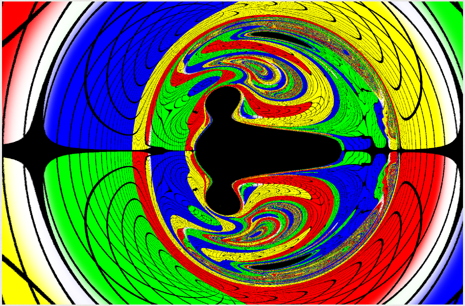
Flat spacetime   Kerr ($a = 0.82$)   Kerr (shadow only)

- The image center is always pointing to the center of the coordinate system.
- The Kerr shadow is simply connected, with a smooth edge.
- It is mostly circular, even for large spin a (with $a \leqslant 1$).

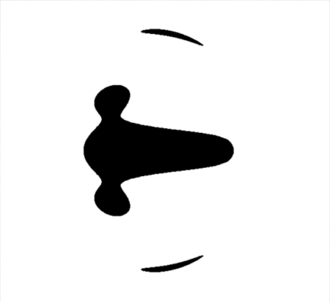
Summary of images in solution space



Cunha+ PRL 115 (2015) no.21, 211102



solution III (lensing)



(shadow only)

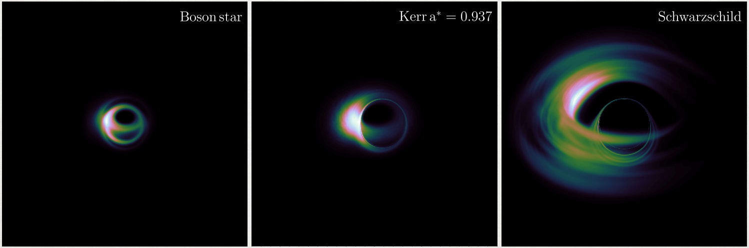
One can find hairy BHs with non-Kerr like phenomenology:

- Shadows can strongly deviate from a circular shape, $e.g.$ hammer-like.
- The shadow can become disconnected, $i.e.$ with a non-trivial topology.
- Chaotic-like lensing features appear in the image.

Cunha+ PRL **115** (2015) 21, 211102

Is it possible to distinguish an accreting Boson Star from a Kerr BH?

Adapted from: Olivares *et. al.*, Mon. Not. Roy. Astron. Soc. **497** (2020) 1, 521-535



Spherical Boson Star | Kerr BH | Schwarzschild BH

The authors analyse synthetic images of Spherical Boson Star with a realistic accretion flow.

Despite having no shadow, the Boson Star image can *mimic a BH shadow*.

Given comparable conditions, the image size was *smaller* than Kerr (detectable by EHT).

For other recent work, see also: Vincent+ CQG **33** (2016) 10 105015 and Vicent+ Astron.Astrophys. **646** (2021) A37.

How it is possible for a Bosonic Star to *mimic* a BH shadow?

- The BH shadow is linked to the existence of light ring orbits.

- But an *effective* shadow can arise if the object produces a stalled accretion flow torus. The torus scale is connected to a **maximum** of the angular velocity Ω of circular time-like geodesics outside the rotation axis. Olivares+ Arxiv:1809.08682

How it is possible for a Bosonic Star to *mimic* a BH shadow?

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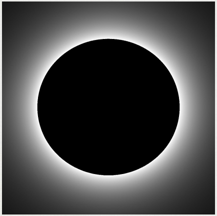
- But an *effective* shadow can arise if the object produces a stalled accretion flow torus. The torus scale is connected to a **maximum** of the angular velocity Ω of circular time-like geodesics outside the rotation axis. Olivares+ Arxiv:1809.08682

- This scale has been observed to determine the torus inner edge in simulations, with the Magneto-Rotational Instability (MRI) quenched inside. Olivares+ Arxiv:1809.08682

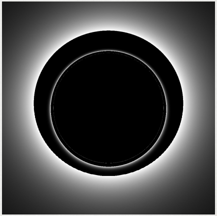
- There are *stable*, *spherical* Proca (vector) field stars that have a $\Omega_{\rm max}$ at a radius comparable to a Schwarzschild ISCO with the same mass. These Proca stars might be able to mimic the shadow of a Schwarzschild BH. Herdeiro et.al., JCAP **04** (2021) 051

We can obtain the image of Schwarzschild and a Proca star with a simplistic thin disk profile.
Herdeiro et.al., JCAP **04** (2021) 051

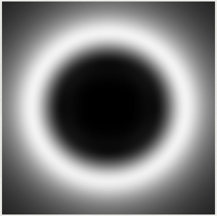
$\theta_o = 17^o$
(observation angle)



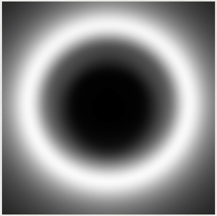
Proca star (disk stops at Ω max.)



Schwarzschild (disk stops at ISCO)



Proca star (blurred)



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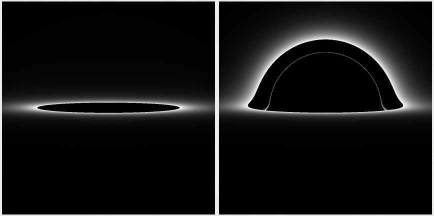
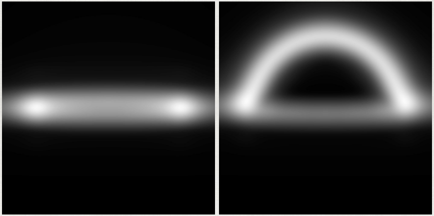


Proca star (disk stops at Ω max.)   Schwarzschild (disk stops at ISCO)

$\theta_o = 86^o$
(observation angle)



Proca star (blurred)   Schwarzschild (blurred)

Is it possible to *grow* a hairy BH starting from a Kerr BH?

- The energy of spinning BHs can be classically mined by a bosonic field through the phenomenon of *superradiance*. Brito+ Lect. Notes Phys. **2015** 906

- An appropriate small seed of such field will grow into a macroscopic condensate of bosonic particles storing a non-negligible fraction of the original BH mass.

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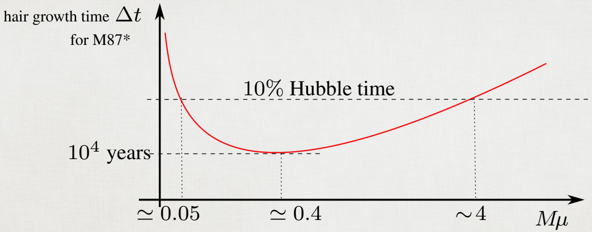
- In any case, thermodynamic sets a limit of $\simeq 29\%$ to the rotational energy that can be extracted from a Kerr BH.
- BHs with synchronised hair are not absolutely stable. They are themselves prone to their own superradiant instabilities. Ganchev, Santos PRL **120** (2018) 171101; Degollado+ PLB **781** (2018) 651

Formation of scalar hair:

The maximum superradiant efficiency to extract energy is at $M\mu \simeq 0.4$ (near-extremal Kerr).



Degollado+ 2018 PLB **781**, 651
Detweiler+ 1980 PRD **22**, 2323
Zouros+ 1979 Annals Phys. **118**, 139

Instability of scalar hair:

Leading superradiant instability timescale is *larger than Hubble time* if $M\mu \lesssim 0.25$.

Degollado+ 2018 PLB **781**, 651

M87* can grow (effectively stable) hair in an astrophysical timescale if $\boxed{0.05 \lesssim M\mu \lesssim 0.25}$.

The supermassive BH candidate M87* (the EHT target) has a mass $M \sim 10^9\, M_\odot$.

At the sweet spot $M\mu \sim 0.1$, this BH is sensitive to a boson mass scale $\mu \sim 10^{-20}$ eV.

Gebhardt+ 2011 AJ **729** 119

Cunha, Herdeiro, Radu, *Universe* 2019, **5** (12), 220

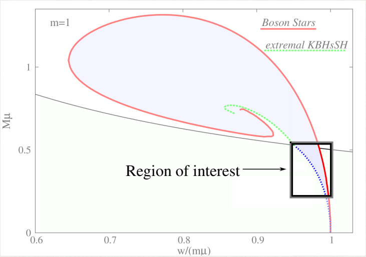
These scalar fields are thus *ultralight* and outside the scope of the standard model.

However, they are inspired by the QCD axion and they can find theoretical support as the low energy limit of string theory

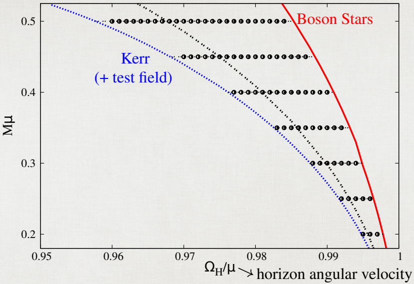
Peccei, Quinn PRL (1977) **38** 1440

Arvanitaki+ 2010 PRD **81** 123530

What is the region of interest to grow hairy BHs from Kerr?



Solution diagram of BHs with scalar hair



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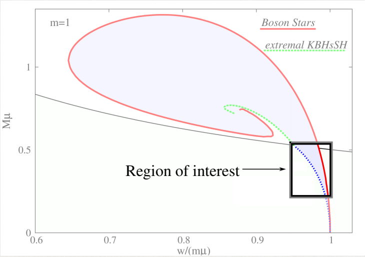

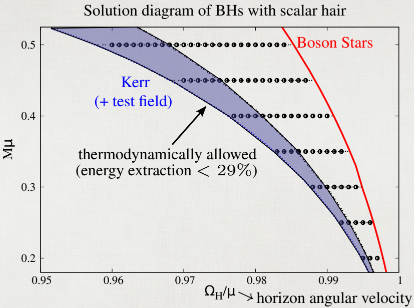

How does the shadow size changes for these hairy BHs?

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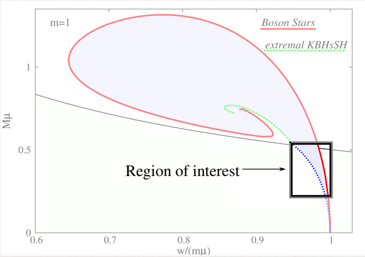
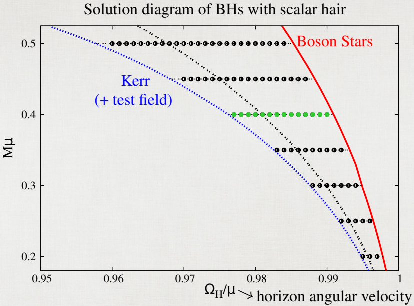


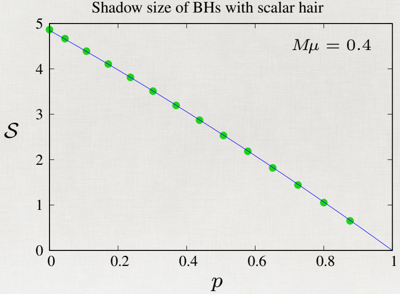


How does the shadow size changes for these hairy BHs?

$$p = \left(1 - \frac{M_H}{M}\right) \quad \rightarrow \quad \text{fraction of mass outside BH}$$

$(p = 0) \implies$ shadow is Kerr

$(p = 1) \implies$ shadow vanishes (solitonic limit)



Cunha, Herdeiro and Radu, *Universe* 2019, **5** (12), 220

How hairy could M87* be?

The shadow angular radius is $\vartheta = \mathcal{S}\,\frac{M}{L}$;   from M87* *star motion* measurements:

$$\frac{M}{L} = 0.369 \pm 0.022 \left(\frac{10^9 M_\odot}{\text{Mpc}}\right),$$

Gebhardt+ 2011 AJ **729** 119

Given the M87* uncertainties for $\frac{M}{L}$, how much can p (and $\mathcal{S}$) change such that ϑ also falls within EHT range $\vartheta_{\text{M87*}} = 18.9 \pm 1.5\,\mu$as?

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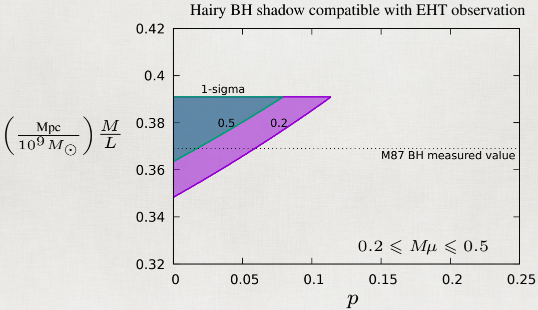

Cunha, Herdeiro and Radu, *Universe* 2019, **5** (12), 220

M87* could be compatible (within 1 sigma) with a hairy BH with $\simeq 12\%$ of mass in the scalar field.

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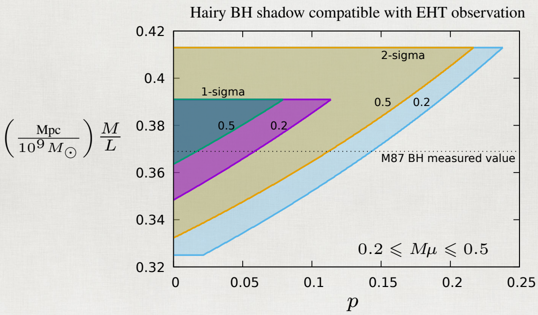


Cunha, Herdeiro and Radu, *Universe* 2019, **5** (12), 220

M87* could be compatible (within 2 sigma) with a hairy BH with $\simeq 24\%$ of mass in the scalar field.

Scalarized BHs in extended scalar-tensor GB gravity

Lovelock-like model (4D)

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

- In order to have spontaneous scalarization from a vacuum GR BH:

$$f'(\phi)\big|_{\phi=0} = 0, \qquad f''(\phi)\big|_{\phi=0} > 0$$

- One can make the following choice:

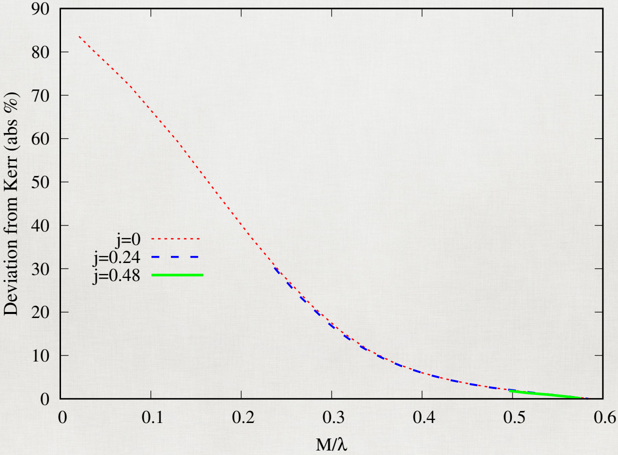
$$f(\phi) = \frac{\lambda^2}{2\beta}(1 - e^{-\beta\phi^2})$$

- BH solutions exist, but non-GR effects are only significant for low spin $j = J/M^2$.

Antoniou+ PRD 97 (2018) no.8, 084037, Cunha+ PRL 123 (2019) no.1, 011101

Plot of relative shadow size of scalarized BHs (SBHs) with respect to Kerr:

Cunha, Herdeiro, Radu PRL 123 (2019) no.1, 011101



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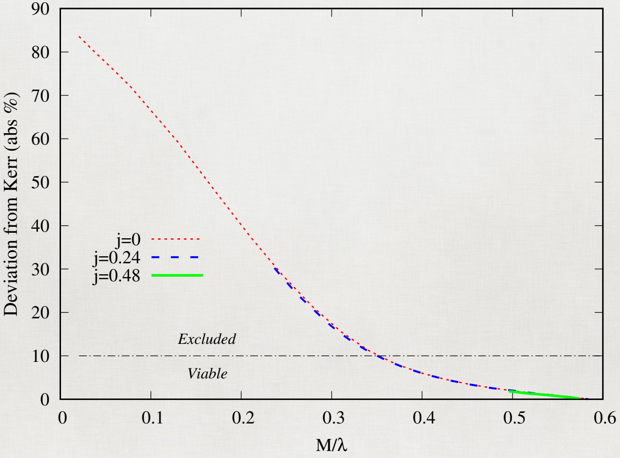
Cunha, Herdeiro, Radu PRL 123 (2019) no.1, 011101



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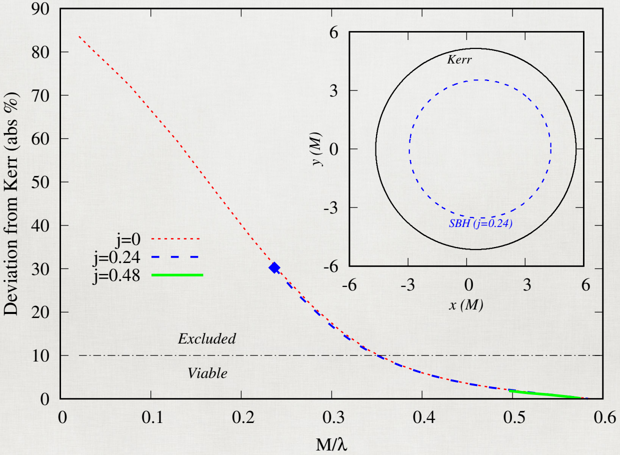

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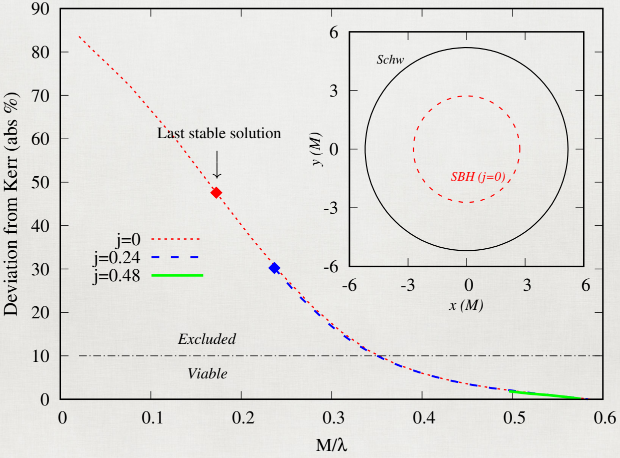
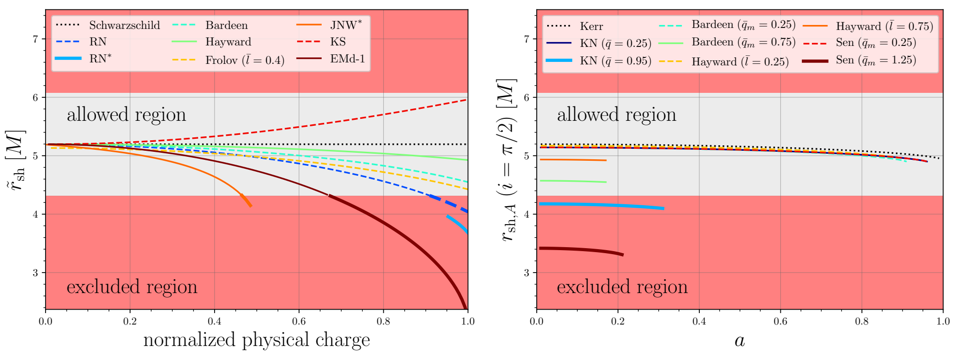


- Recent constrains by EHT collaboration on BH charges from M87* image:



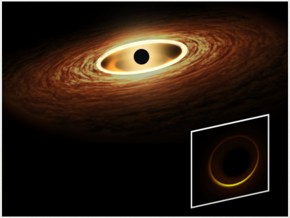
(adapted EHT collaboration, PRD **103** 104047 (2021))

- Testing GR beyond 1st PN order with the M87* shadow: EHTc, PRL **125** 141104

- Shadow images for a dilaton BH with GRMHD accretion: Mizuno+ Nature Astron. **2** (2018) 7, 585

Second part:

recent theorem shows that BHs must contain a Light Ring orbit.



Phys. Rev. Lett. **124** (2020) 18, 181101

(selected as Editors' Suggestion)

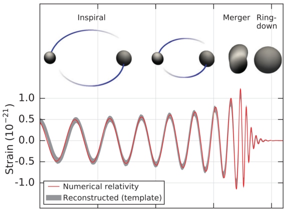
P. Cunha and C. Herdeiro

Strong gravity has entered the precision era:

- breakthroughs in gravitational wave astrophysics. LIGO/Virgo, PRL 116, 061102 (2016)
- unveiling of the first black hole (BH) shadow image. EHT, AJ 875 L1 (2019)

observed image M87*

EHT, AJ 875 L1 (2019)

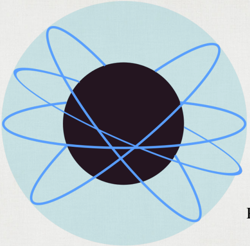


GW ringdown after BH merger

LIGO/Virgo, PRL 116, 061102 (2016)

A special class of null orbits are critical for these key observations: *Light Rings*.

A Light Ring (**LR**) is a (spatially closed) circular null geodesic orbit.



Photon Sphere as a collection of LRs

In spherically symmetry, the clustering of LRs forms a *Photon Sphere*.

LRs exist around Schwarzschild and Kerr BHs and very compact *horizonless* stars.

Question:

Does an equilibrium Black Hole always possess Light Rings (**LRs**)?

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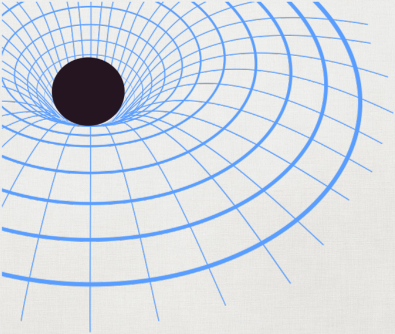
Previous results in restrictive setups, *e.g.* spherical symmetry.

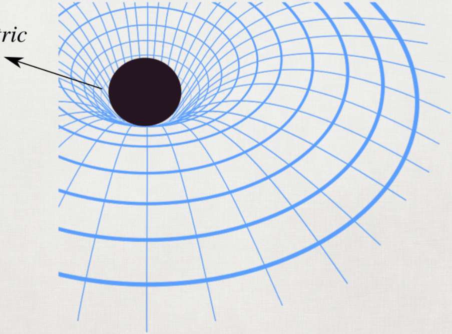
Hod, PLB **727** (1-3) 345-348 (2013)

Assume a 3+1 *Black Hole* (BH) spacetime $(\mathcal{M}, g)_{\rm BH}$:



Assume a 3+1 *Black Hole* (BH) spacetime $(\mathcal{M}, g)_{\mathrm{BH}}$:

stationary,
axially symmetric



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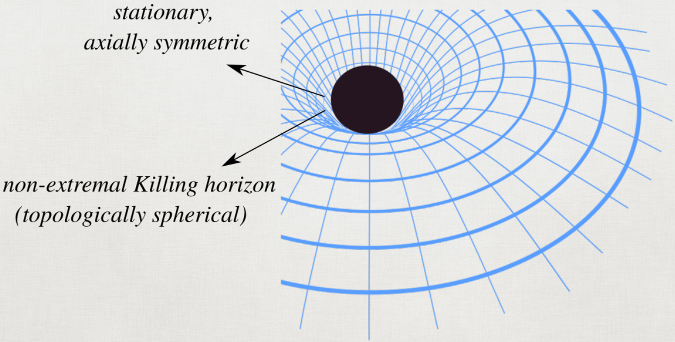

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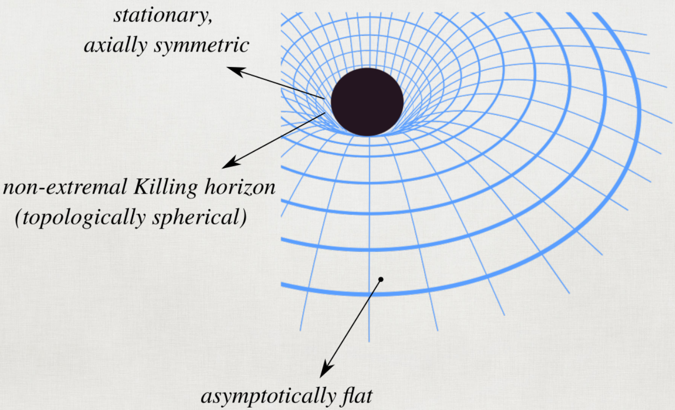

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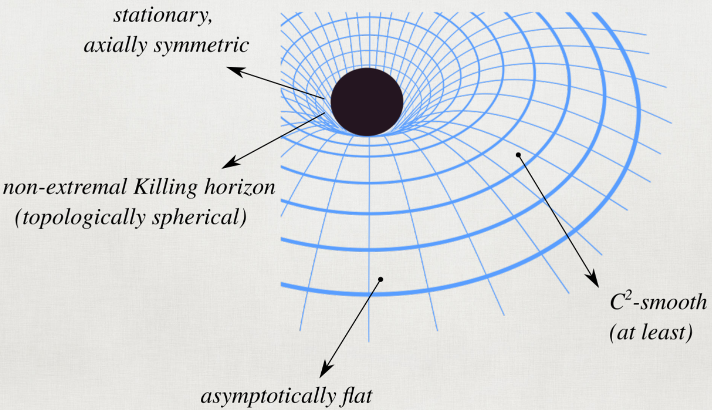

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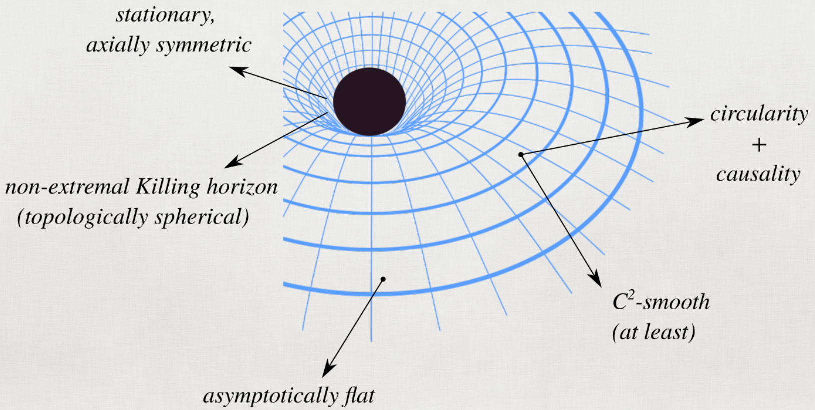


In the orthogonal 2-space we introduce spherical-like coordinates (r, θ)

Some gauge choices:

- (r, θ) reduce to standard spherical coordinates in the *asymptotically flat* limit $r \to \infty$.
- The polar coordinate $\theta = \{0, \pi\}$ at the rotation axis.
- The horizon is located at $r = r_{\rm H}$.
- The polar coordinate θ is chosen to be orthogonal to r.

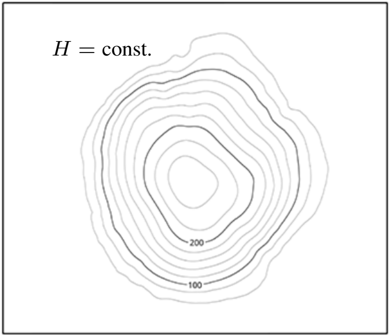
This means $g_{r\theta} = 0, \quad g_{rr} > 0, \quad g_{\theta\theta} > 0$ outside horizon.

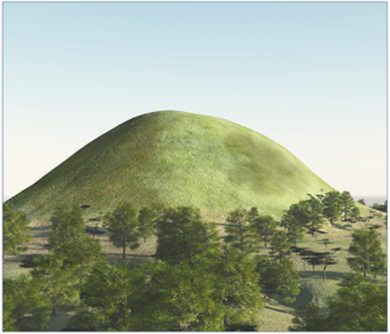
The null geodesic flow is determined by $\mathcal{H} = \frac{1}{2} g^{\mu\nu} p_\mu \, p_\nu = 0$.
It leads to the potential $H_\pm(r, \theta)$, that constrains motion.

At a *Light Ring*: $\Longrightarrow$ $\boxed{\nabla H_\pm(r, \theta) = 0}$

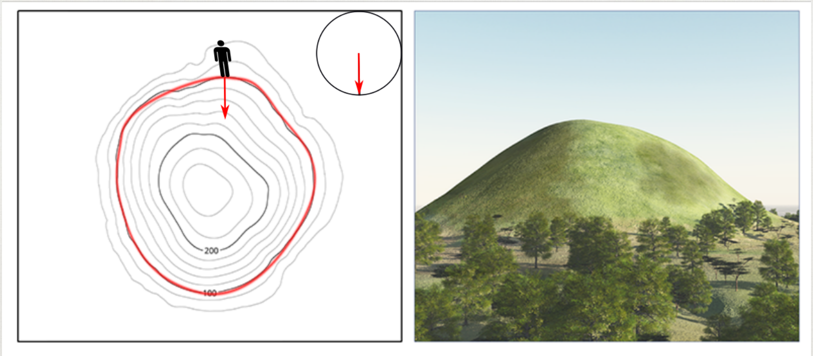
PRL 124 (2020) 18, 181101

The $\pm$ typically yields two different rotation directions.


$H = \text{const.}$
200
100



$\nearrow = \nabla H$



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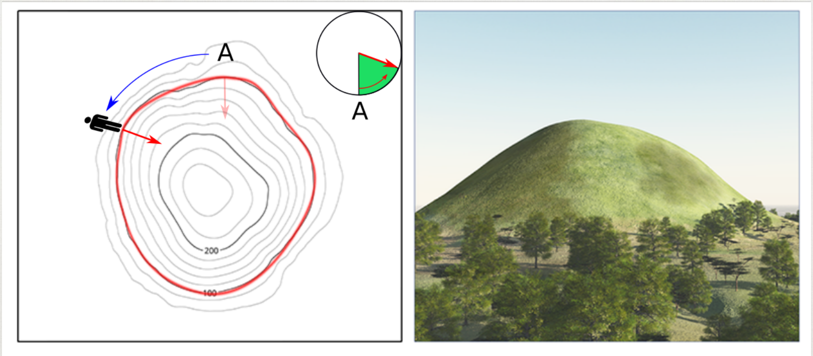

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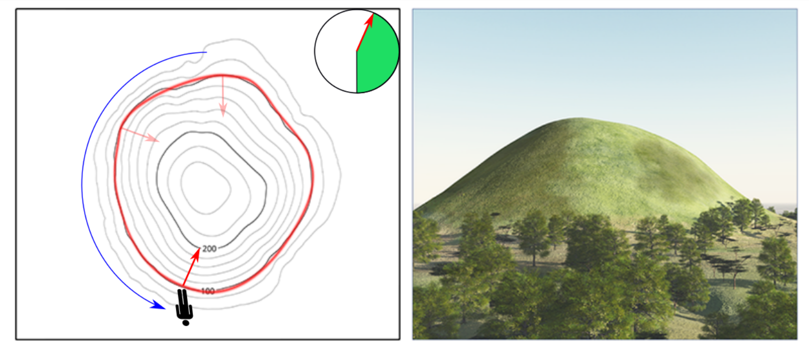

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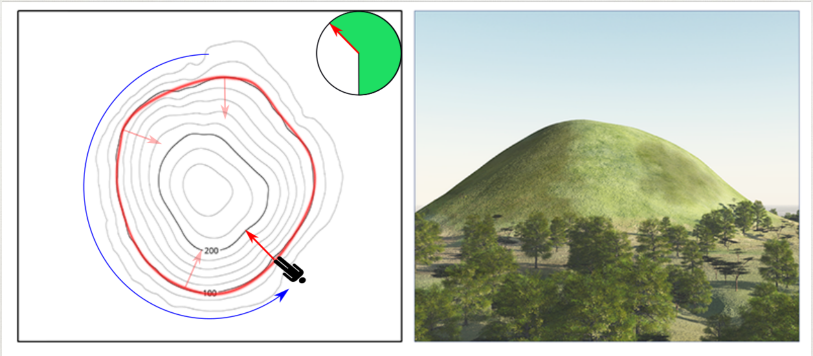

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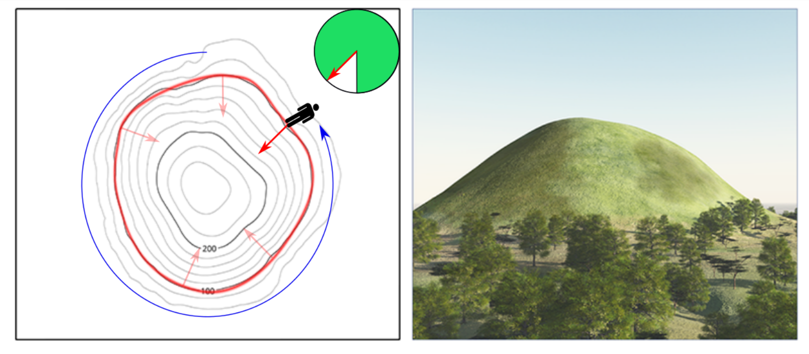

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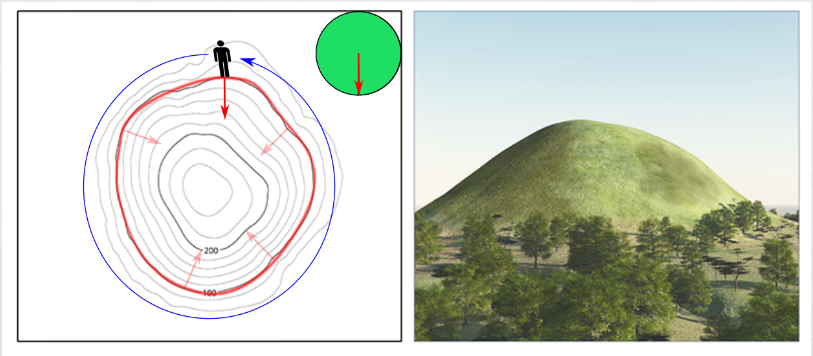
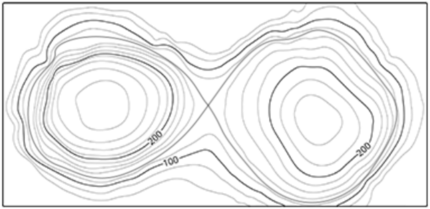


Rule 1 $\Longrightarrow$ a Maximum (or Min.) leads to $(+\mathbf{1})$ full turns of vector field.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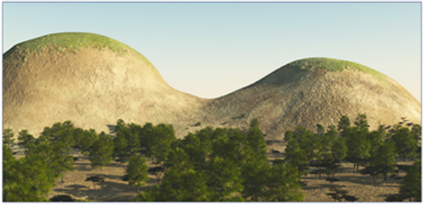
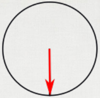
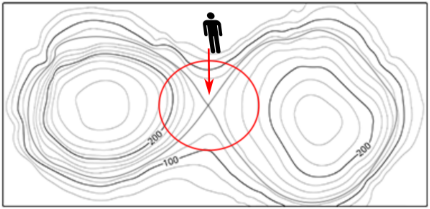
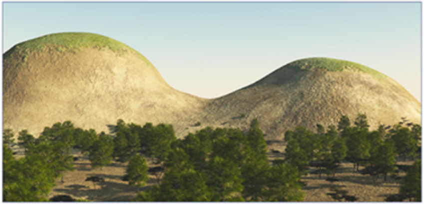
100
200



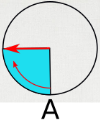
 $= \nabla H$

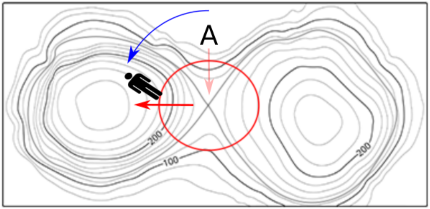


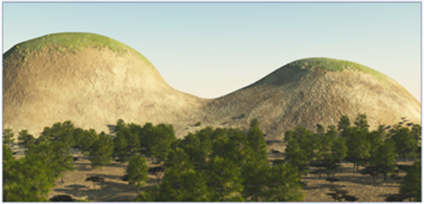




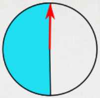
$= \nabla H$

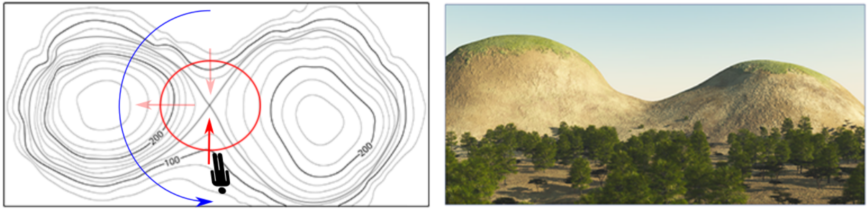




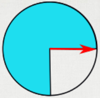


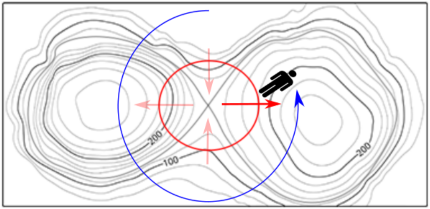
 $= \nabla H$

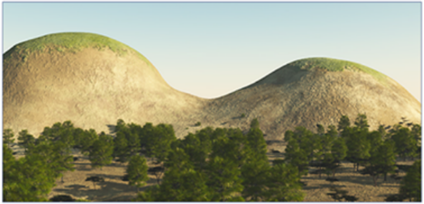




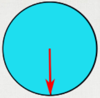
 $= \nabla H$

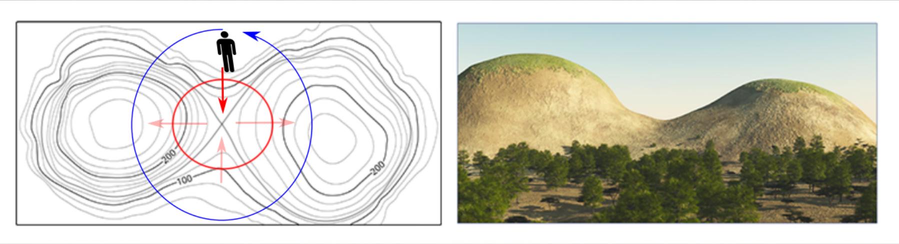






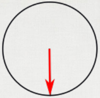
 $= \nabla H$

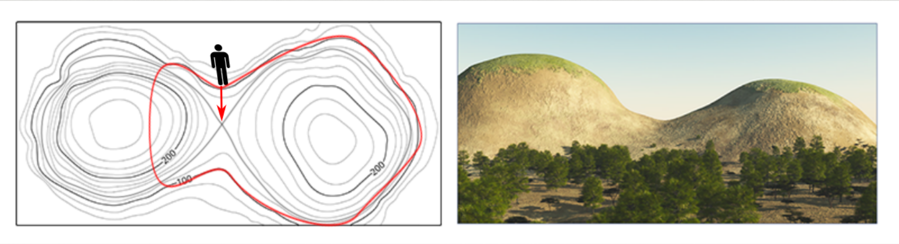




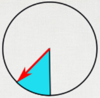
Rule 2 $\Longrightarrow$ Saddle point leads to $(-\mathbf{1})$ full turns of vector field ($i.e.$ inverse sense).

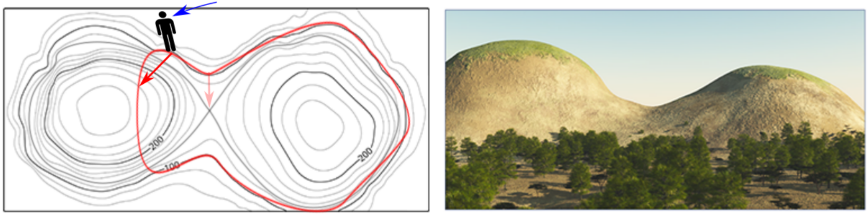
$= \nabla H$



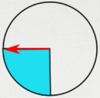


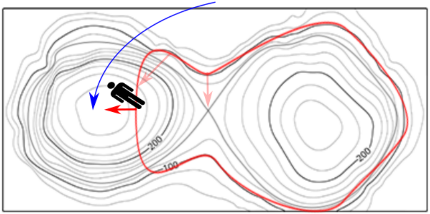
 $= \nabla H$

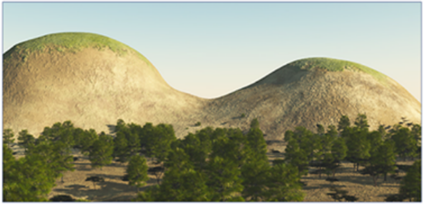




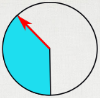
$= \nabla H$

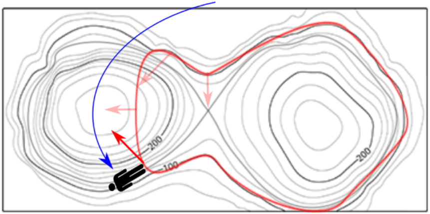


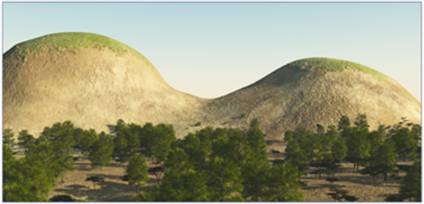




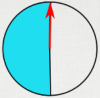
 $= \nabla H$

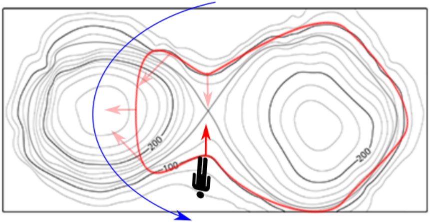


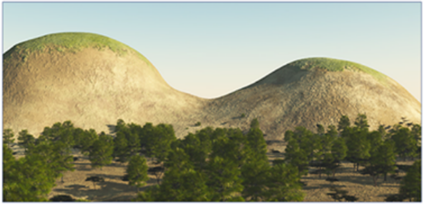




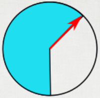
 $= \nabla H$

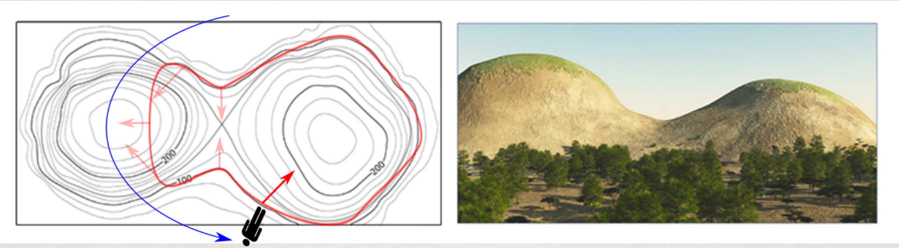






 $= \nabla H$





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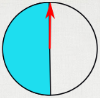
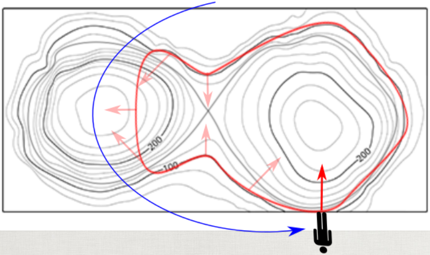
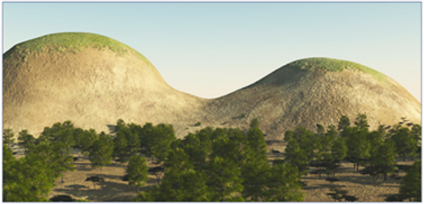
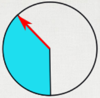
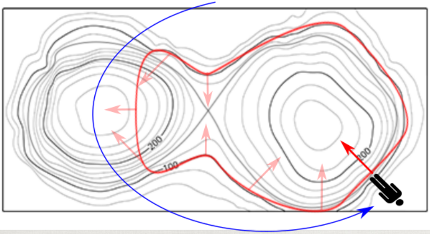


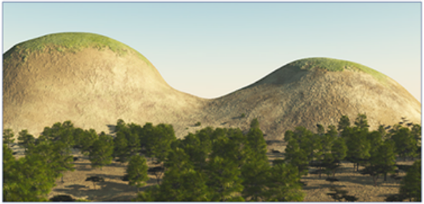




 $= \nabla H$







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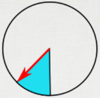
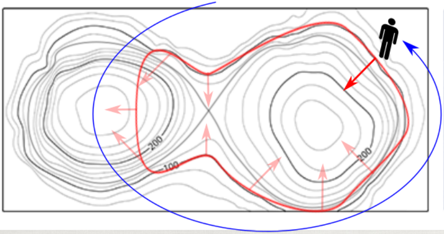
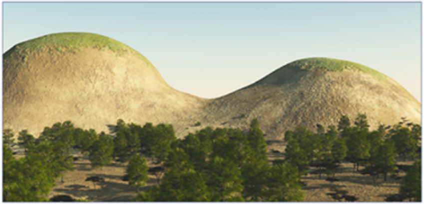
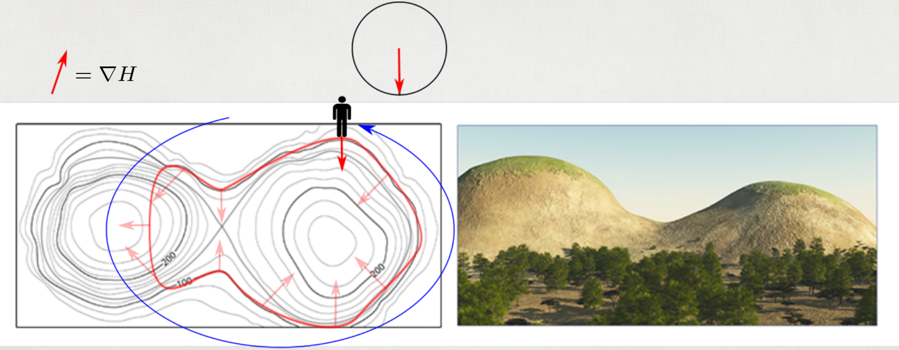


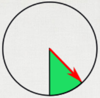


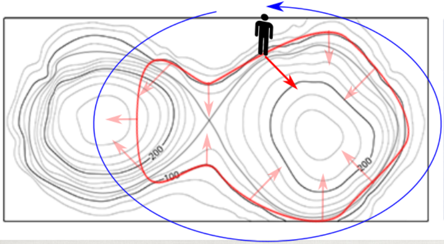


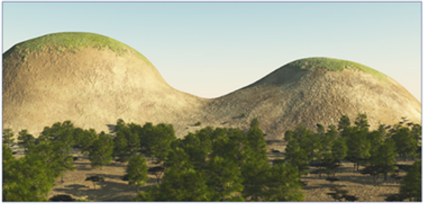
$= \nabla H$

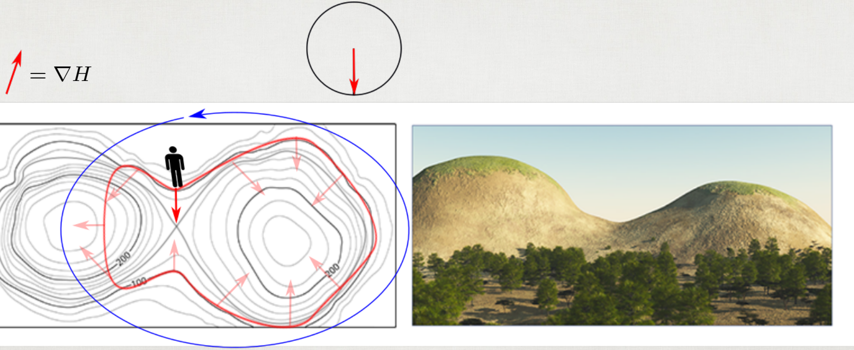


 $= \nabla H$

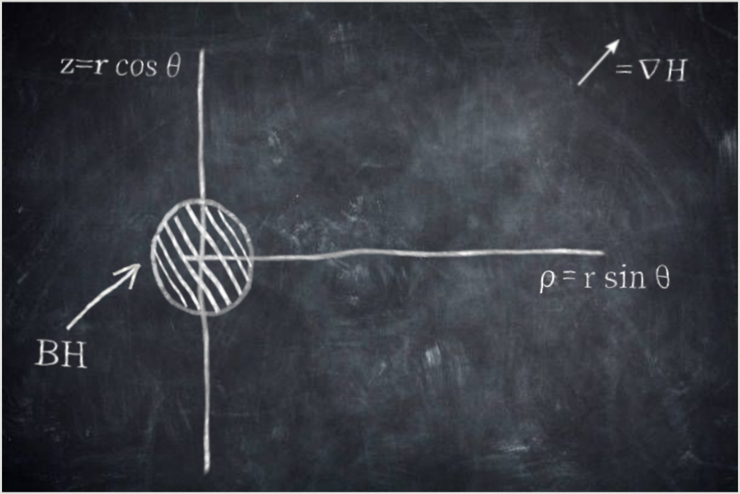


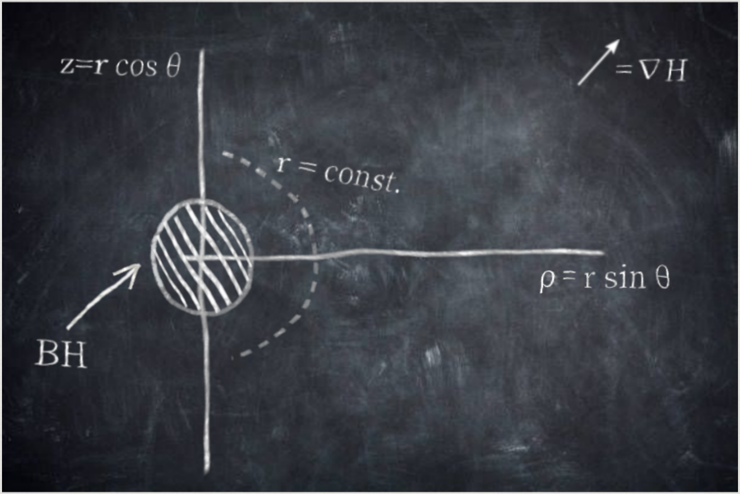


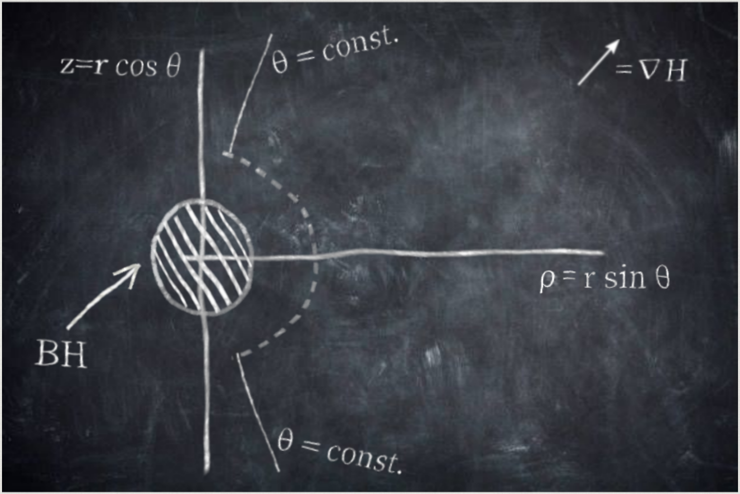


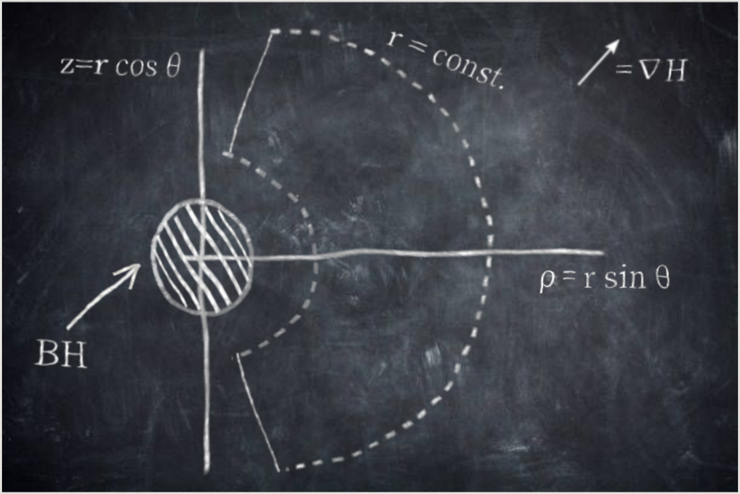


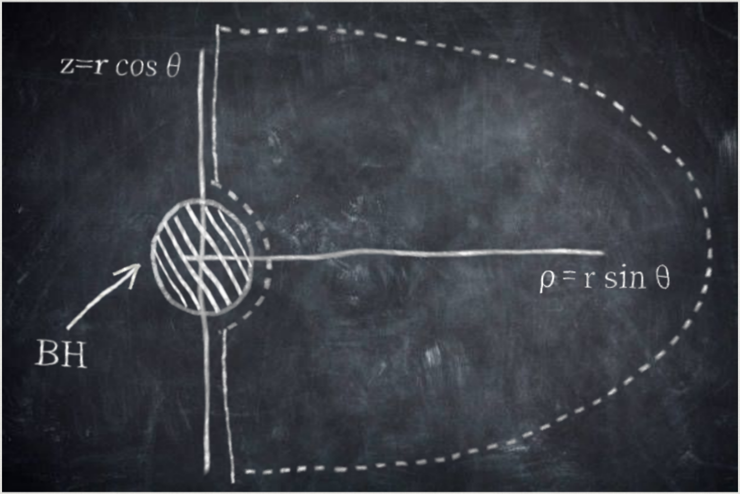
Rule 3 $\implies$ number of full turns is additive, *e.g.* Saddle point (-1) + Max (+1) = 0.

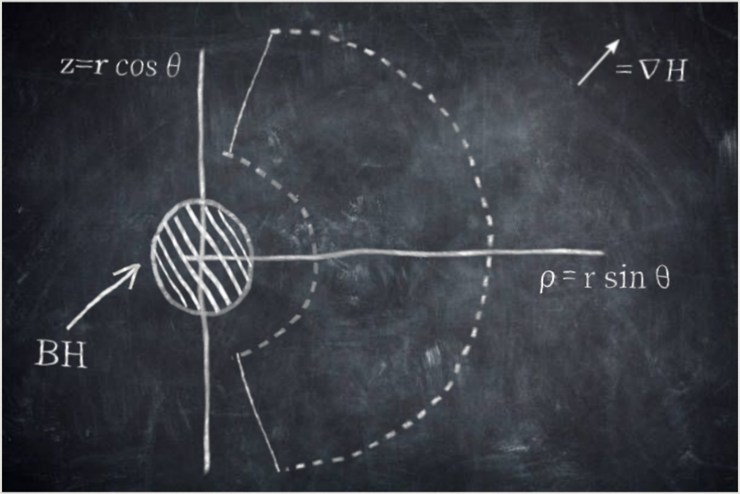

z=r cos θ
=∇H
BH
ρ = r sin θ

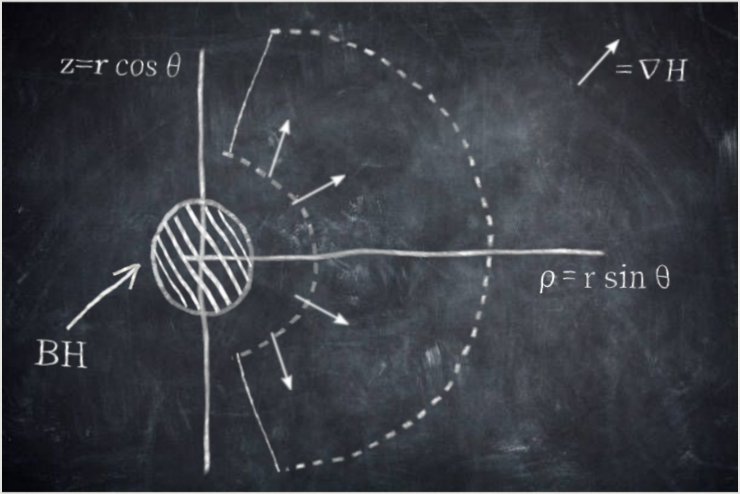

z=r cos θ
= ∇H
r = const.
ρ = r sin θ
BH


z=r cos θ
θ = const.
= ∇H
ρ = r sin θ
BH
θ = const.

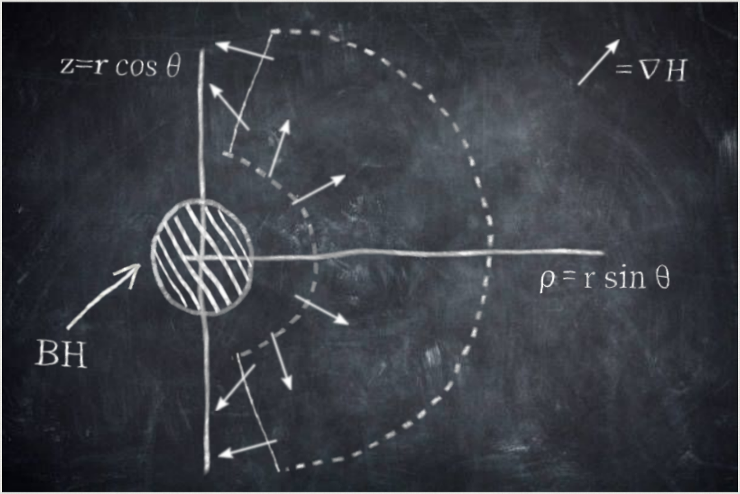

z=r cos θ
r = const.
= ∇H
ρ = r sin θ
BH


z=r cos θ
ρ = r sin θ
BH

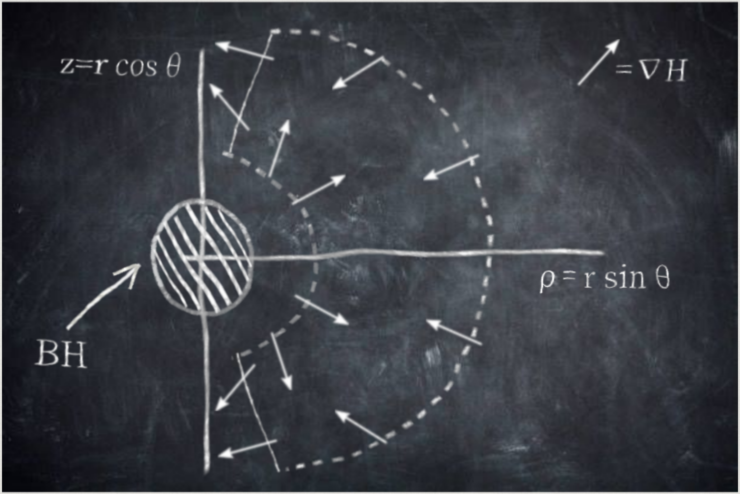

z=r cos θ
= ∇H
BH
ρ = r sin θ



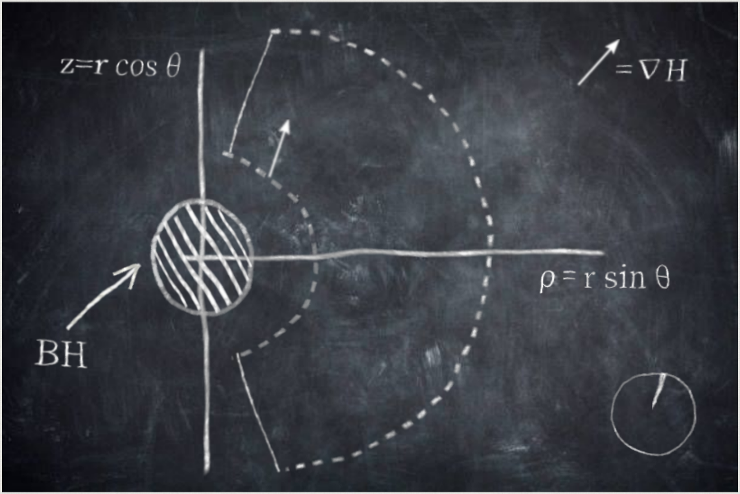
Horizon boundary $\implies$ *regular Ricci scalar* close to horizon. PRD **70**, 024009 (2004)



Axis boundary $\Longrightarrow$ *regular Ricci scalar* close to axis. PRL **124** (2020) 18, 181101



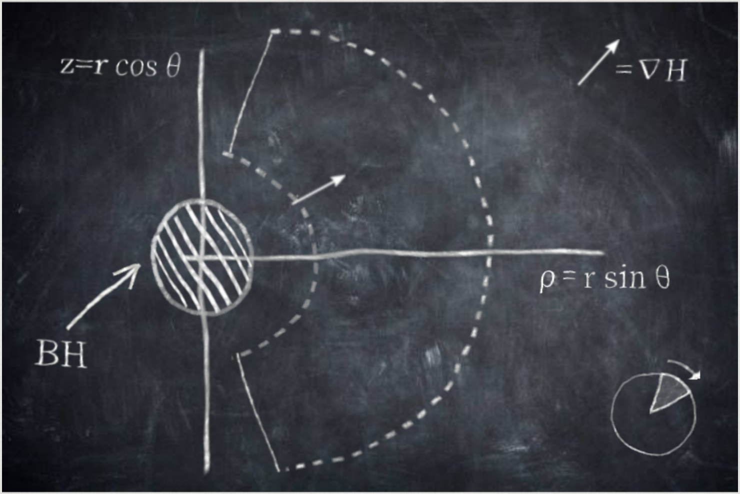
Asymptotic boundary $\Longrightarrow$ *flat* spacetime.



Horizon boundary $\Longrightarrow$ *regular Ricci scalar* close to horizon. PRD **70**, 024009 (2004)

Axis boundary $\Longrightarrow$ *regular Ricci scalar* close to axis. PRL **124** (2020) 18, 181101

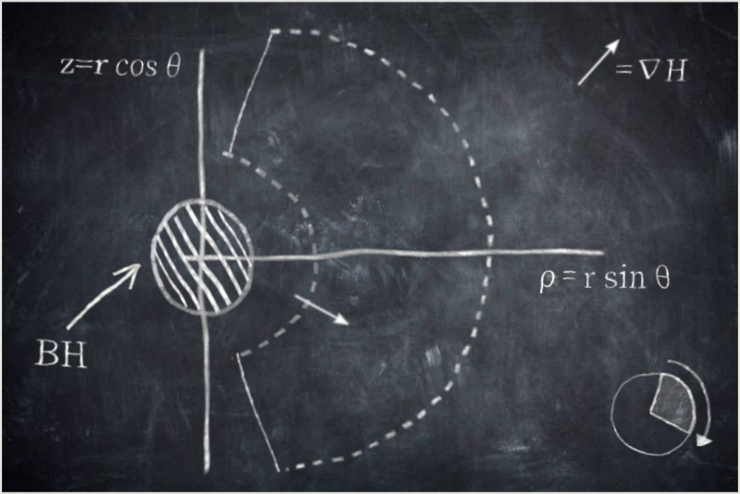
Asymptotic boundary $\Longrightarrow$ *flat* spacetime.



Horizon boundary $\Longrightarrow$ *regular Ricci scalar* close to horizon. PRD **70**, 024009 (2004)

Axis boundary $\Longrightarrow$ *regular Ricci scalar* close to axis. PRL **124** (2020) 18, 181101

Asymptotic boundary $\Longrightarrow$ *flat* spacetime.



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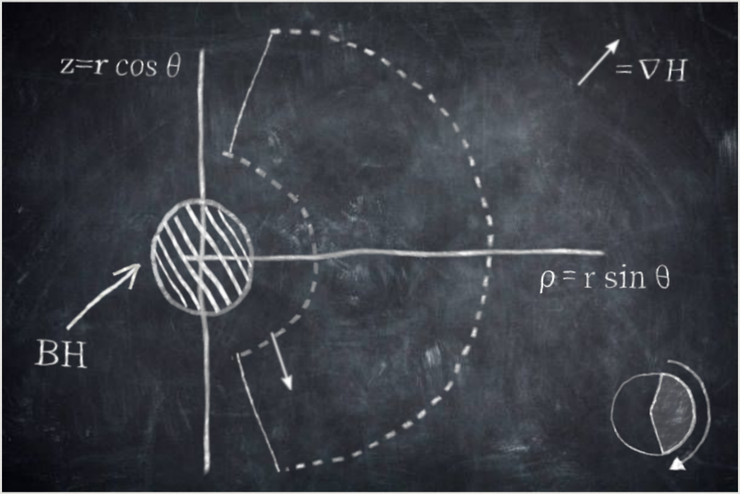

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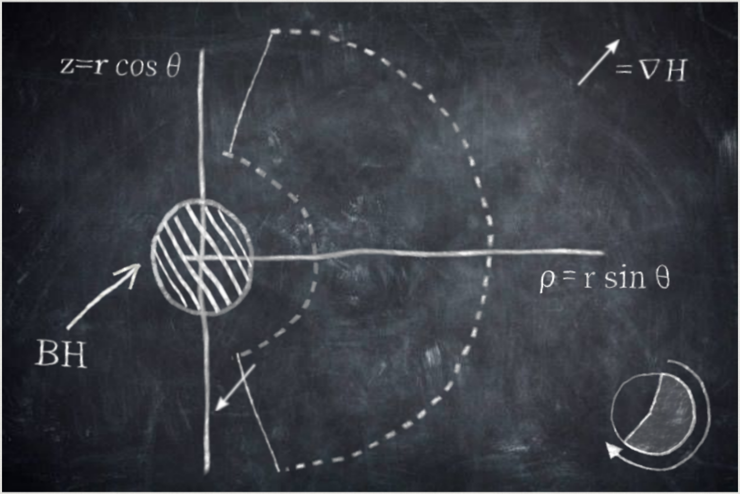

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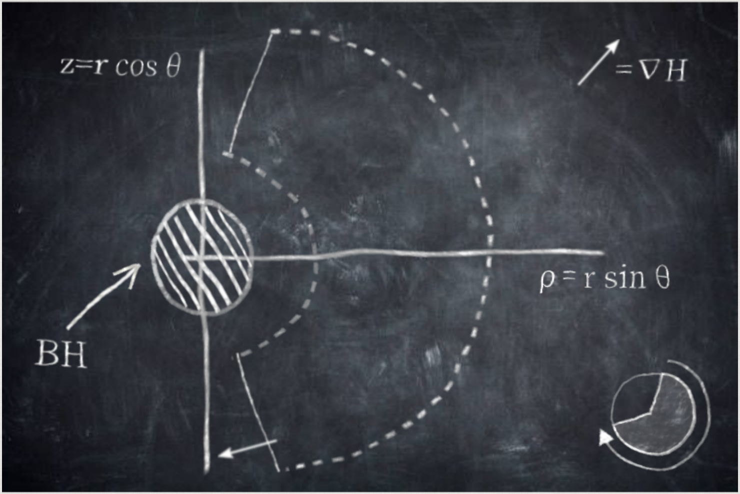

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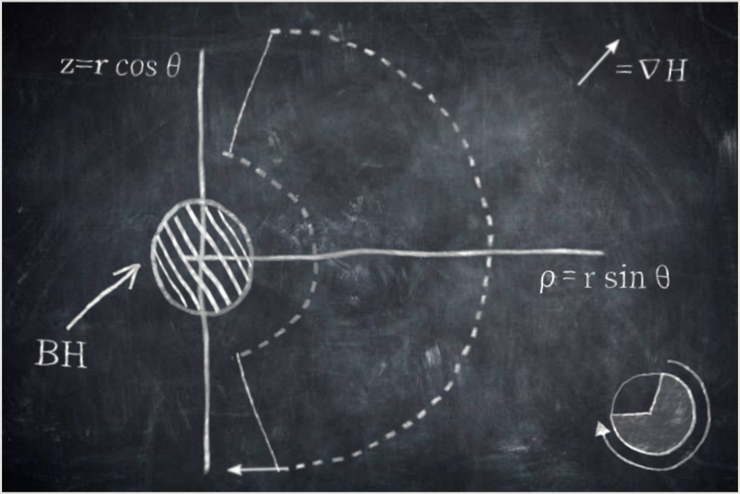

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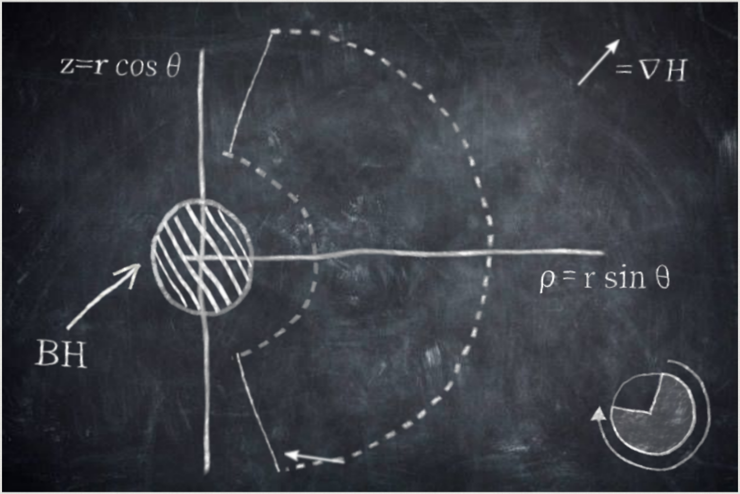

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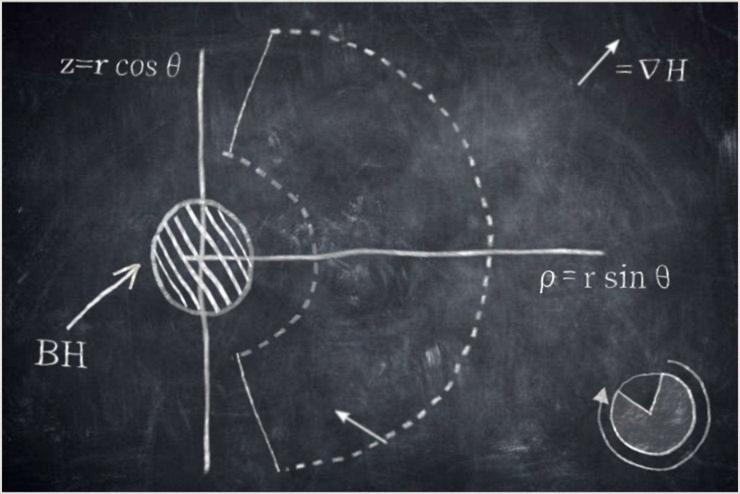

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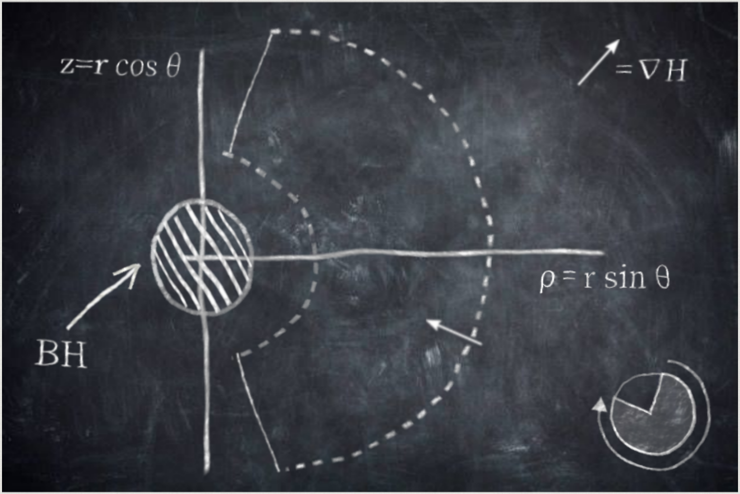

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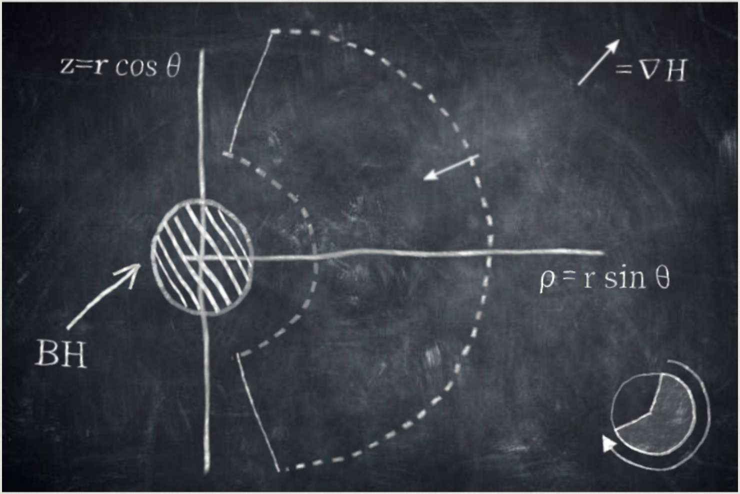

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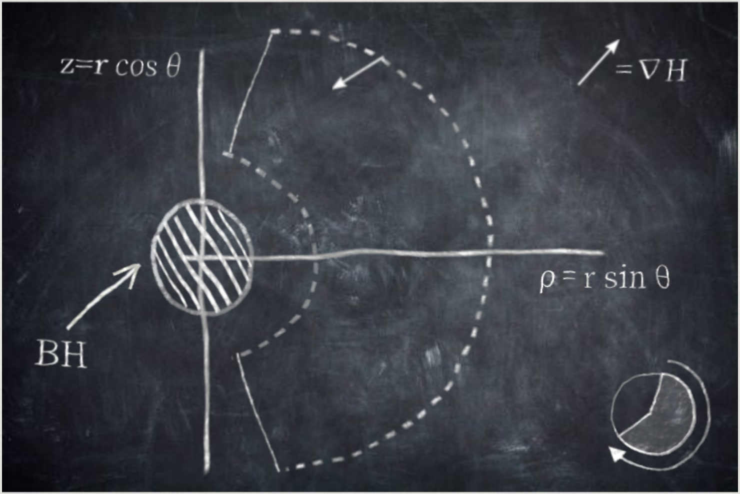

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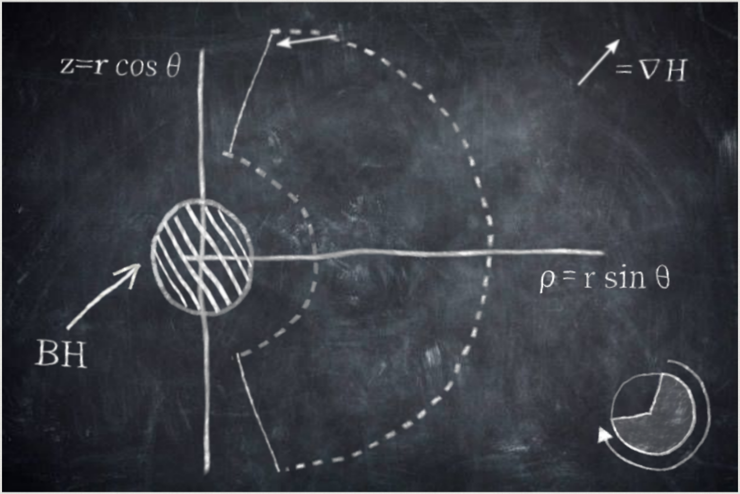

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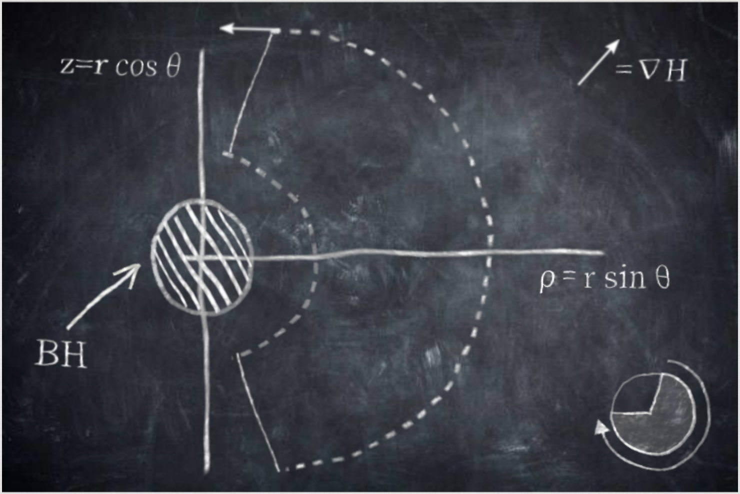

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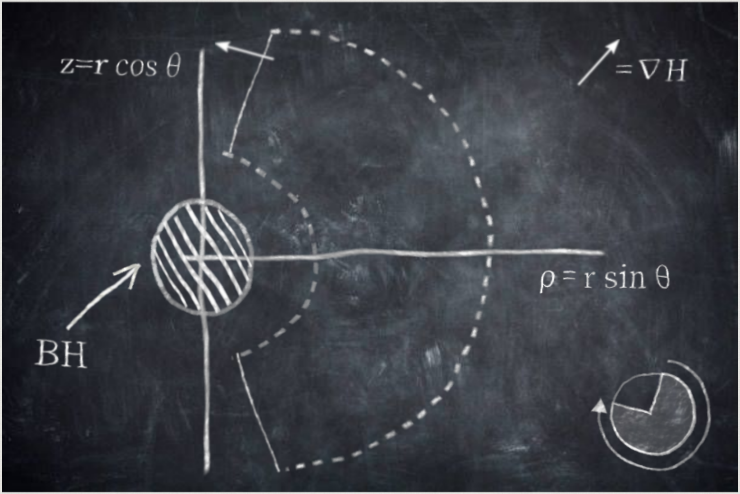

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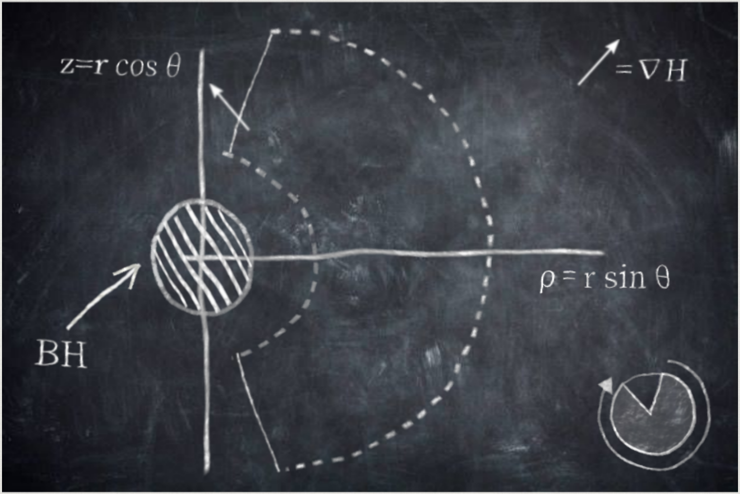
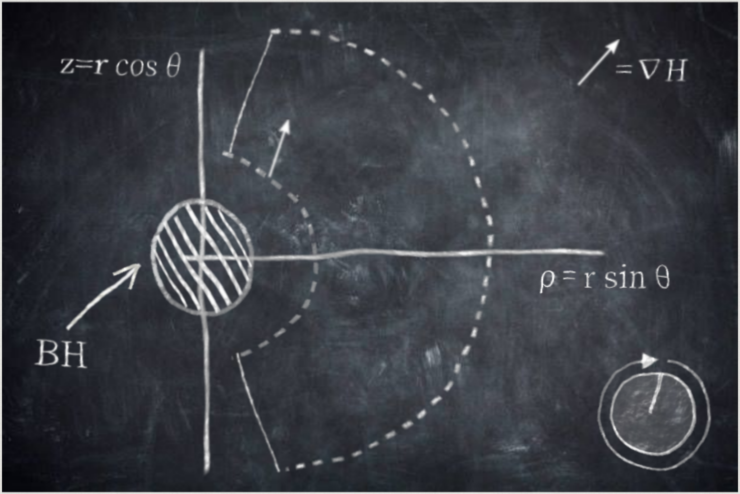


Horizon boundary $\Longrightarrow$ *regular Ricci scalar* close to horizon. PRD **70**, 024009 (2004)

Axis boundary $\Longrightarrow$ *regular Ricci scalar* close to axis. PRL **124** (2020) 18, 181101

Asymptotic boundary $\Longrightarrow$ *flat* spacetime.



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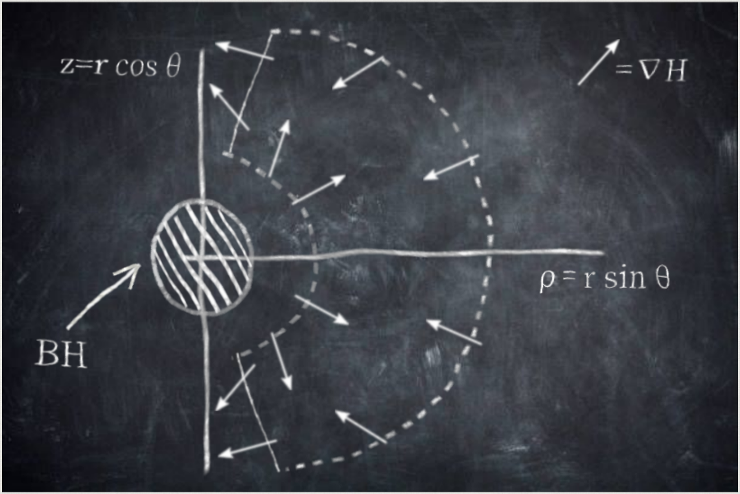
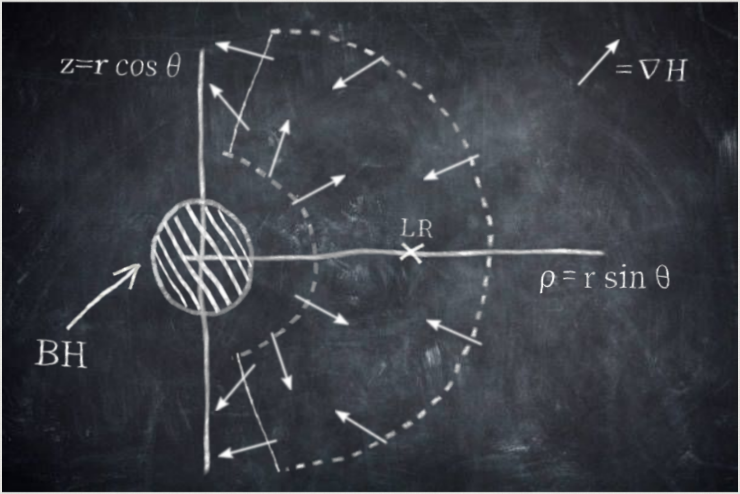
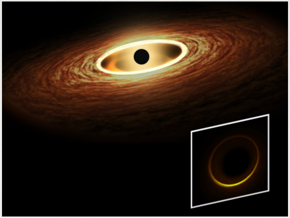


The vector circulation makes a $(-\mathbf{1})$ full rotation

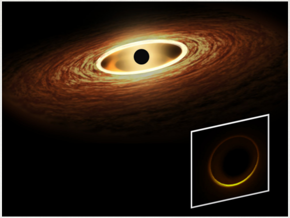


The vector circulation makes a $(-\mathbf{1})$ full rotation $\Longrightarrow$ LR exists! (saddle-point type)



Take home message:

- Equilibrium BHs admit one standard LR (at least) outside the horizon.
- The argument is topological and can be applied in gravity theories beyond GR.
- Asymptotic flatness is a critical boundary condition. Opportunity for generalizations!



Take home message:

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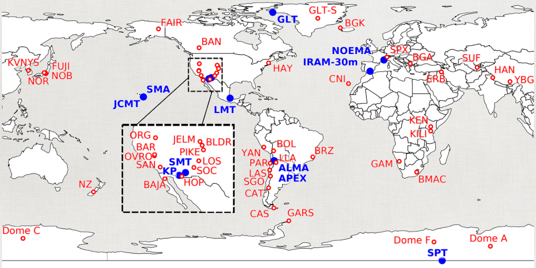
With other asymptotics, can BHs without LRs be possible?

Yes! Phys.Rev.D **104** 4, 044018 (2021)

The road ahead

- There are some bounds on deviations from Kerr, but the spacetime around M87* is still fairly unconstrained.

- With additional observations by the EHT and by the *next-generation* EHT (ngEHT), expected in 2024-2030, we will likely get much better constrains.



(Blue): EHT 2021 sites

(Red): ngEHT *potential new* sites

Adpated: Raymond+ 2021 ApJS **253** 5

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