WHAT'S NEW IN BLACK HOLE JETS?

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What's new in gravity? Workshop

Niels Bohr Institute @ Marienlyst

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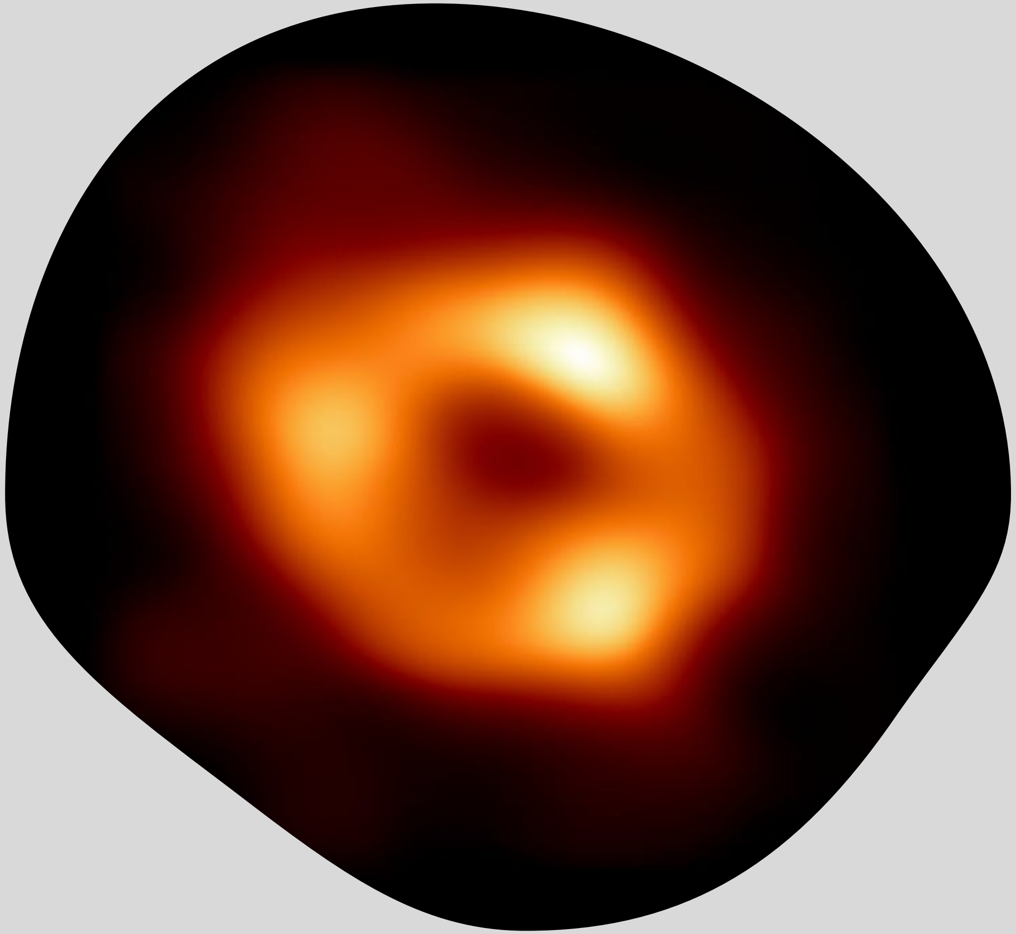
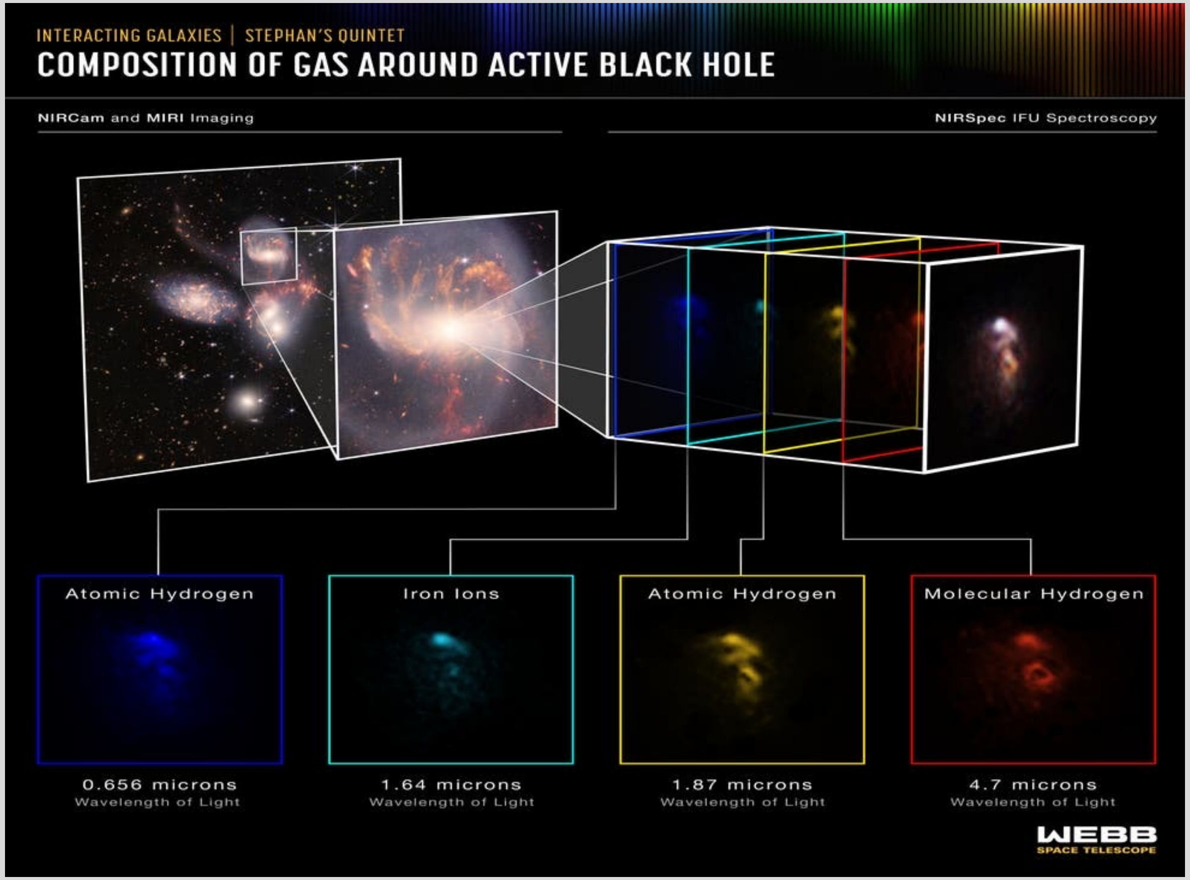
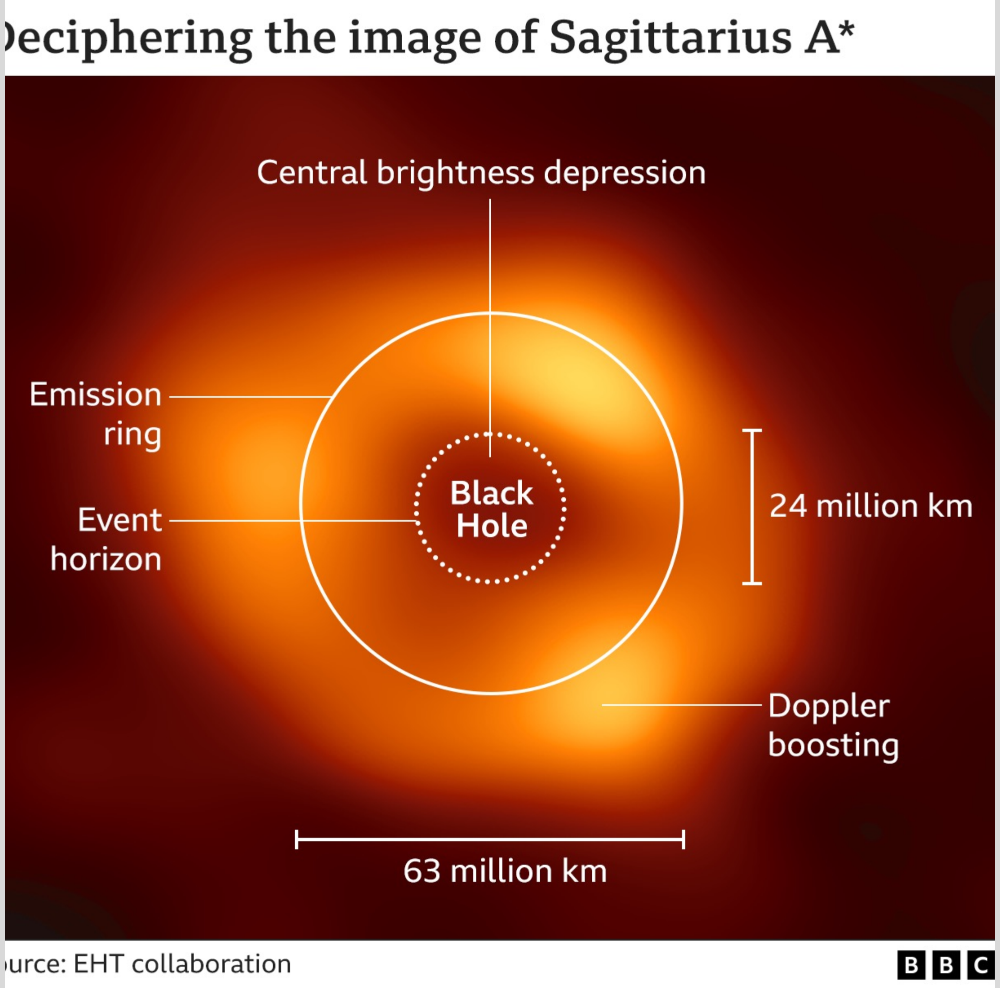



INTERACTING GALAXIES | STEPHAN'S QUINTET
COMPOSITION OF GAS AROUND ACTIVE BLACK HOLE
NIRCam and MIRI Imaging
NIRSpec IFU Spectroscopy
Atomic Hydrogen
Iron Ions
Atomic Hydrogen
Molecular Hydrogen
0.656 microns
Wavelength of Light
1.64 microns
Wavelength of Light
1.87 microns
Wavelength of Light
4.7 microns
Wavelength of Light
WEBB
SPACE TELESCOPE


eciphering the image of Sagittarius A*
Central brightness depression
Emission ring
Event horizon
Black Hole
24 million km
Doppler boosting
63 million km
urce: EHT collaboration
BBC

What’s new in black hole jets?

Black Holes are not new, but for decades to come we will have several experiments providing very precise data about the outflow processes in black holes.

SOME NEW INSIGHTS IN BH JETS:

What is the effect in black hole jet models of the number of spacetime dimensions?

Can black holes in five space-time dimensions (5D) support energy extracting magnetospheres?

Do higher dimensions introduce an even steeper scaling on the spin parameter in the jet power ?

Electro-Magnetic Energy Extraction from Rotating 5D black holes

We will present new electro-magnetic energy extracting solutions from rotating black holes in 5 space-time dimensions.

The aim is to show the applicability of this mechanism in higher dimensions to gain insights into the effect of these (e.g. in jet power scaling).

We will work in asymptotically flat space-times.

Based on
2206.10644 [hep-th] by A. Chanson and MJR

Black hole jets

The sky contains a variety of objects (like pulsars and quasars)
that produce extravagantly energetic signals
and form collimated jets of electromagnetic radiation.
These may be powered by black holes.

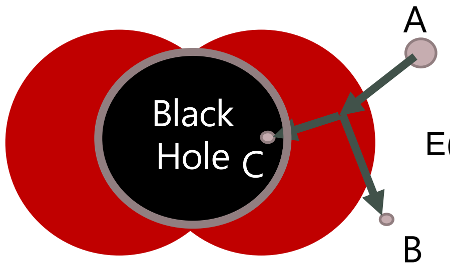
Black Hole Jets

The image shows the nearby galaxy Centaurus A. The lowest-energy X-rays Chandra detects are in red, while the medium-energy X-rays are green, and the highest-energy ones are blue.

Introduction :
Energy extraction from black holes

Energy extraction is made possible due to the rotational kinetic energy of the black hole that winds up not inside the **event horizon** of the black hole, but in its **ergosphere** (a region in which a particle is necessarily propelled in locomotive concurrence with the rotating spacetime)

This energy can be extracted by the Penrose process

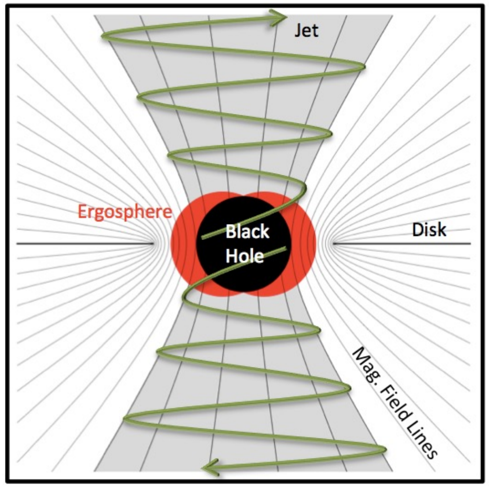


$E(A)=E(B)+E(C)$ and say $E(C)<0$, then $E(B)>E(A)$

Positive energy flows away and negative energy flows into the black hole

Blandford- Znajek process

When a black hole is threaded by a magnetic field and surrounded by plasma there is another type of Penrose process : Blandford-Znajek (BZ) process



As the ergosphere causes the magnetosphere inside it to rotate, the outgoing flux of angular momentum results in extraction of energy from the black hole.

Extravagant energy signals in the sky

How is the mechanism described ?

The Blandford-Znajek process is described by the highly nonlinear equations of force-free electrodynamics (FFE)

$$F_{\mu\nu}\mathcal{J}^{\nu} = 0.$$

Supported by Maxwell's equations

$$\nabla_{[\alpha}F_{\mu\nu]} = 0$$
$$\nabla_{\nu}F^{\mu\nu} = J^{\mu}$$

Force-free equations

The full stress-energy tensor

$$T^{\mu\nu} = T^{\mu\nu}_{\text{EM}} + T^{\mu\nu}_{\text{matter}}$$

is always conserved

$$\nabla_\nu T^{\mu\nu} = 0.$$

(1) $\nabla_\nu T^{\mu\nu}_{\text{EM}} = -F_{\mu\nu}\mathcal{J}^\nu.$

the relativistic form of the Lorentz force density

Force-free electrodynamics (FFE) describes systems in which most of the energy resides in the electrodynamical sector of the theory, so that

$$T^{\mu\nu} \approx T^{\mu\nu}_{\text{EM}}.$$

$$\nabla_\nu T^{\mu\nu}_{\text{EM}} = 0.$$

This approximation is known as the "force-free" condition, since by (1) it is equivalent to the requirement that the Lorentz force density vanishes

$$F_{\mu\nu}\mathcal{J}^\nu = 0. \quad (2)$$

BZ models for black holes in 5D ?

Electro-Magnetic Energy Extraction from Rotating Black Holes in 5D

The background is a Myers-Perry black hole

$$ds^2 = -dt^2 + \frac{m}{\Sigma}\left(dt - a\sin^2\theta\, d\phi\right)^2 + \frac{\Sigma}{\Delta}dr^2 + \Sigma d\theta^2 + (r^2 + a^2)\sin^2\theta\, d\phi^2 + r^2\cos^2\theta\, d\psi^2\,, \qquad (5)$$

where

$$\Sigma = r^2 + a^2\cos^2\theta\,, \qquad \Delta = r^2 + a^2 - m\,. \qquad (6)$$

Here we defined the mass parameter m and spin parameter a.

The event horizon is $r \equiv r_H = \sqrt{m - a^2}$ and the angular velocities $\Omega_\phi^H = a/(r_H^2 + a^2)$ and $\Omega_\psi^H = 0$.

Electro-Magnetic Energy Extraction from Rotating Black Holes in 5D

For such a background

$$ds^2 = (g_1)_{ab}\, dx^a dx^b + (g_2)_{\alpha\beta}\, dx^\alpha dx^\beta$$

where $\{x^{a,b} = t, \phi, \psi\}$ and $\{x^{\alpha,\beta} = r, \theta\}$.

One can write a stationary and axisymmetric field strength of the form

$$F = d\Psi_\phi \wedge [d\phi - \omega_\phi\, dt] + d\Psi_\psi \wedge [d\psi - \omega_\psi\, dt] + I \sqrt{\frac{\det g_2}{-\det g_1}}\, dr \wedge d\theta\,.$$

Magnetic flux

current

field angular velocity

BZ jets solutions for black holes in 5D ?

We first start with finding solutions to the static (Tangherlini) black hole solutions in 5D.

$I = \omega_\phi = \omega_\psi = 0$ that the equations reduce to

$$\mathcal{L}_\phi \Psi_\phi \equiv r\,\partial_r \left[\left(\frac{r^2 - m}{r} \right) \partial_r \Psi_\phi \right] + \tan\theta\,\partial_\theta \left[\frac{1}{\tan\theta}\,\partial_\theta \Psi_\phi \right] = 0\,,$$

$$\mathcal{L}_\psi \Psi_\psi \equiv r\,\partial_r \left[\left(\frac{r^2 - m}{r} \right) \partial_r \Psi_\psi \right] + \cot\theta\,\partial_\theta \left[\frac{1}{\cot\theta}\,\partial_\theta \Psi_\psi \right] = 0$$

Note that the flux functions are separable

$$\Psi_\phi = 1 - \sum_{l=0}^{\infty} c_l\, R_l(r)\, T_l^\phi(\theta)\,, \qquad \Psi_\psi = 1 - \sum_{n=0}^{\infty} d_n\, R_n(r)\, T_n^\psi(\theta)\,.$$

The electromagnetic field solution is

$$F = d\Psi_\phi \wedge [d\phi - \omega_\phi\, dt] + d\Psi_\psi \wedge [d\psi - \omega_\psi\, dt] + I \sqrt{\frac{\det g_2}{-\det g_1}}\, dr \wedge d\theta\,.$$

$$\Psi_\phi = \begin{cases} 1 - c_0\, \log(\cos^2\theta) \\ 1 - c_0\, \log(r^2 - m)\log(\cos^2\theta) \\ 1 - c_0\, EllipticE[1 - r^2/m](EllipticE[\sin^2\theta] - EllipticK[\sin^2\theta]) \\ 1 - c_0\, r^2 \sin^2\theta \end{cases} ,$$

$$I = \omega_\phi = \omega_\psi = 0 \text{ t}$$

Exact solutions in static 5D BHs

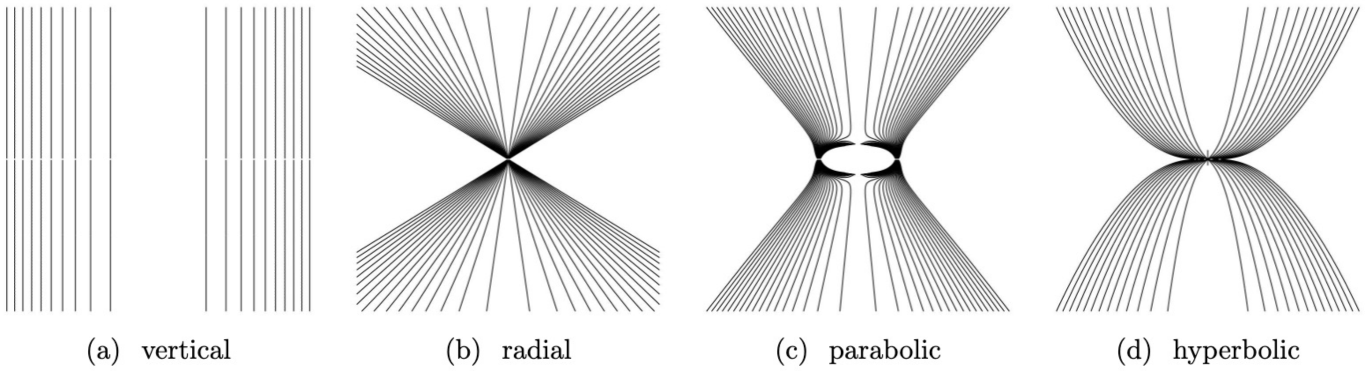


Figure 1: Field lines of families of exact force-free magnetospheres in 5-dimensional static black hole backgrounds. Our new solutions include the vertical, radial, parabolic, hyperbolic field geometries.

The FFE equations are highly nonlinear, hence our strategy to find a collimated cylindrical shape twisted field solutions is to perturb the non- rotating black holes by allowing small spin black hole perturbation. To leading orders in rotational parameter α namely, the corresponding solution can be expressed

$$\Psi_\phi = \Psi_\phi^{(0)}(r,\theta) + \alpha^2\,\Psi_\phi^{(2)}(r,\theta) + O(\alpha^3)\,,$$

$$r_0\,\omega_\phi = \alpha\,\omega^{(1)}(r,\theta) + O(\alpha^2)\,,$$

$$I = \alpha\,I^{(1)}(r,\theta) + O(\alpha^2)\,.$$

where $r_0 = \sqrt{m}$ and reduced spin parameter $\alpha = a/\sqrt{m}$.

$$\omega^{(1)} = \omega^{(1)}(\Psi_\phi^{(0)}) \qquad I^{(1)} = I^{(1)}(\Psi_\phi^{(0)})\,.$$

Boundary conditions

For the 5D singly rotating black hole the relevant conditions for the fluxes $\Psi\varphi,\psi$ on the black hole event horizon yield a relation between the field functions

$$I^H(\Psi^H) = (\omega_\phi^H - \Omega_\phi^H)\, \frac{(r_H^2 + a^2)\, r_H \sin\theta \cos\theta}{r_H^2 + a^2 \cos^2\theta}\, \partial_\theta \Psi_\phi^H\, .$$

Notably the smoothness condition obey a similar structure to its 4D analog in Kerr.

At infinity $r \to \infty$ setting boundary conditions is more subtle, but as argued in [10], we resort to match the fields to solutions of flat space. The regularity condition in the region far from the black hole is

$$I^\infty(\Psi^\infty) = \pm\, \omega_\phi^\infty r \sin\theta \cos\theta\, \partial_\theta \Psi_\phi^\infty\, .$$

Energy and angular momentum fluxes

The expression for the energy flux is given by

$$P \equiv \int T^{r\nu}_{EM}(\xi_t)_\nu \, dV = -2\,(2\pi)^2 \int (\omega_\phi\, \partial_\theta \Psi_\phi + \omega_\psi\, \partial_\theta \Psi_\psi)\, I\, d\theta\,,$$

and the angular momentum fluxes

$$L_\phi \equiv -\int T^{r\nu}_{EM}(\xi_\phi)_\nu \, dV = -2\,(2\pi)^2 \int I\, \partial_\theta \Psi_\phi \, d\theta\,,$$

$$L_\psi \equiv -\int T^{r\nu}_{EM}(\xi_\psi)_\nu \, dV = -2\,(2\pi)^2 \int I\, \partial_\theta \Psi_\psi \, d\theta\,.$$

where

$T^{\mu\nu}_{EM} = F^{\mu\alpha} F^{\nu}_{\alpha} - (1/6)\, g^{\mu\nu} F_{\alpha\beta} F^{\alpha\beta}$ is the electromagnetic energy momentum tensor,

$\xi^\nu_t = (1,0,0,0,0)$, $\xi^\nu_\phi = (0,0,0,1,0)$ and $\xi^\nu_\psi = (0,0,0,0,1)$ respectively.

Solution

Among the exact solutions we derived in the previous section, in the non-rotating 5-dimensional black hole background there exists a collimated, uniform, vertical magnetic field solution

$$\Psi_\phi^{(0)}(r,\theta) = r^2 \sin^2\theta\,.$$

The FFE equations are highly nonlinear, but we can solve the first order current perturbation setting the smoothness condition on the horizon

$r = r_H = r_0$

$$I^{(1)}(r_0^2 \sin^2\theta) = 2\, r_0^2 \sin^2\theta \cos^2\theta \,(1 - \omega^{(1)})\,.$$

Likewise

$$r_0^2\, I^{(1)}(\Psi_\phi^{(0)}) = 2\,\Psi_\phi^{(0)} \left(r_0^2 - \Psi_\phi^{(0)}\right) (1 - \omega^{(1)}(\Psi_\phi^{(0)}))$$

On the surface $r_0^2 - \Psi_\phi^{(0)} = 0$ both energy and angular momentum fluxes vanish.

In this way we aim to construct a highly-collimated and magnetically-dominated jet solution in the vicinity of spinning 5D (singly spinning) black hole. An interior region $r\sin\theta < r_0$ with a current and field angular velocity

$$I \neq 0\,, \qquad \text{and} \qquad \Omega \neq 0 \qquad (r\sin\theta < r_0) \tag{40}$$

and exterior region where we choose

$$I = 0\,, \qquad \text{and} \qquad \Omega = 0 \qquad (r\sin\theta > r_0) \tag{41}$$

The global solution across the interface at r sin θ = r0 will be required to be continuous. Our choice naturally imposes this smoothness condition from the FFE quations

$$\mathcal{L}_\phi \Psi^{(2)}_\phi = \begin{cases} S_{out}, & \text{if } r\,\sin\theta > r_0. \\ S_{in}, & \text{otherwise.} \end{cases}$$

Here the source term in the outer region $(r \sin\theta > r_0)$ yields

$$S_{out} = \frac{4\, r_0^2 \sin^2\theta\, (r^4 + (r_0^4 - 3r^2 r_0^2)\cos^2\theta)}{r^2(r^2 - r_0^2)}\,,$$

and in the inner region $(r \sin\theta < r_0)$ is

$$\begin{aligned} S_{in} \quad = \quad & \frac{r^2 (I^{(1)})(I^{(1)})'}{(r^2 - r_0^2)\,\cos^2\theta} + \frac{4r^2 \sin^4\theta\,\left(r^2 - r_0^2 \sin^2\theta\right)\left(r_0^4 - r^4\omega^{(1)}\right)(\omega^{(1)})'}{r_0^2 (r^2 - r_0^2)} \\ & - \frac{4\; r^4 \sin^2\theta\,\left(r^2 - 2\, r_0^2 \sin^2\theta\right)(\omega^{(1)})^2}{r_0^2 (r^2 - r_0^2)} + \frac{8\; r^2 r_0^2 \sin^2\theta\; \cos 2\theta\, \omega^{(1)}}{(r^2 - r_0^2)} \\ & + \frac{4\; r_0^2 \sin^2\theta\, (r^4 + (r_0^4 - 3r^2 r_0^2)\cos^2\theta)}{r^2 (r^2 - r_0^2)}\,. \end{aligned}$$

If we assume that the convergence condition is true, then we can specify a second relation between ω(1) and I(1), thus determining the outgoing energy flux.

given a Green's function solution of the differential equation

$$\mathcal{L}_\phi G = \delta(r - r_i)\delta(\theta - \theta_i),$$

this tells us that we can write down the solution to

$$\Psi_\phi^{(1)} = \int r_i \int d\theta_i \, G(r, \theta, r_i, \theta_i) S(r_i, \theta_i)$$

if, and only if

$$\int_{r_0}^{\infty} dr \int_{\delta}^{\pi-\delta} d\theta \, \frac{S_{in/out}}{r}$$

The contribution from all terms are convergent, assuming ω(1) ~ O(1), except

$$\frac{r^2 r_0^2 (I^{(1)})(I^{(1)})'}{\cos^2\theta} - 4 r^8 \sin^4\theta \, \omega^{(1)} (\omega^{(1)})' - 4 r^6 \sin^2\theta \, (\omega^{(1)})^2 = 0 \quad \longrightarrow \quad \omega^{(1)} = \frac{r_0^2 - x}{2 r_0^2 - x} .$$

where $x = r^2 \sin^2\theta$.

Properties of black hole jets in 5D

In this way were able to construct a highly-collimated and magnetically-dominated jet solution in the vicinity of spinning 5D (singly spinning) black hole

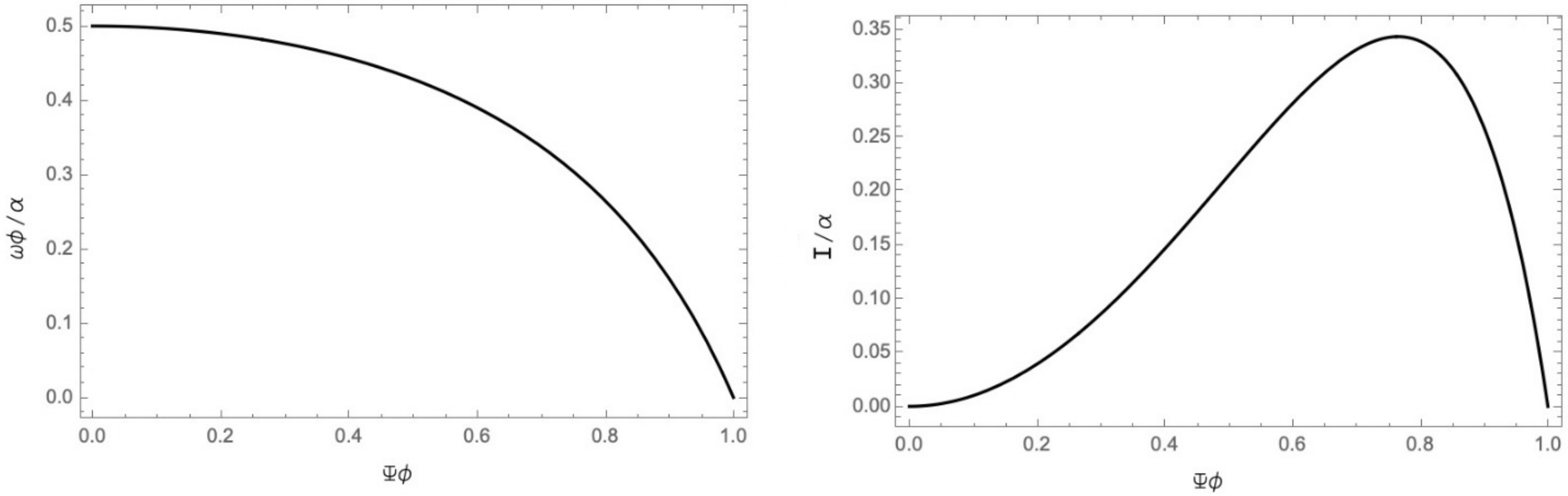


Figure 2: Variation of the angular velocity ω_ϕ and current I on the black hole horizon.

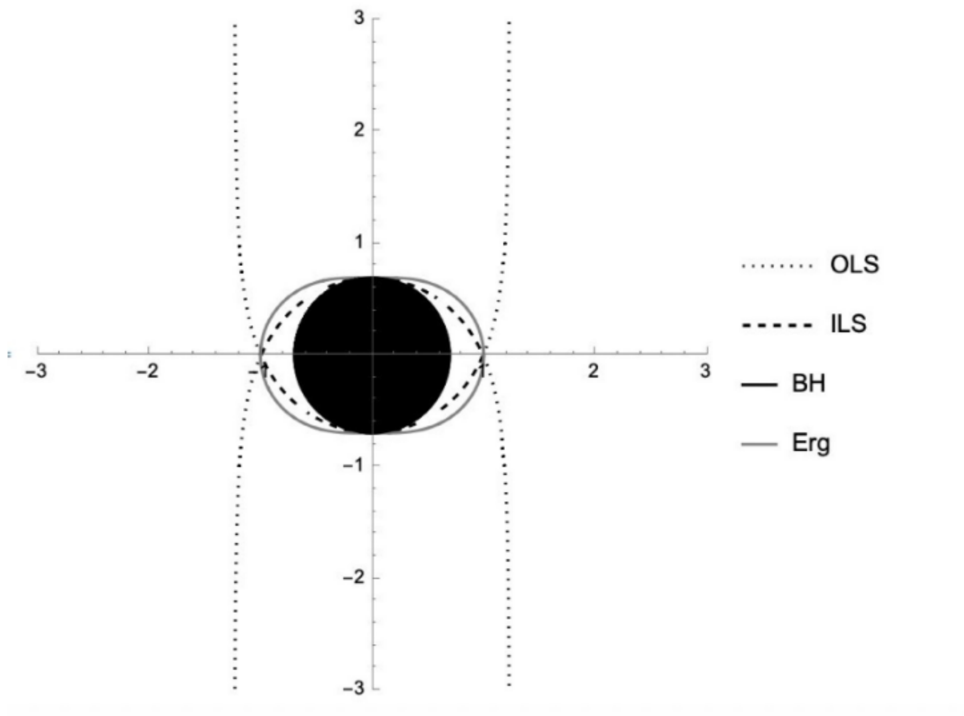


Figure 3: Regions in MP black hole: the central *black shaded* disk represent the single spinning MP black hole (BH), the *dotted* lines correspond to the outer (OLS), the *dashed* curve represents the inner light surfaces (ILS), and the ergosphere (Erg) *solid* curve for the mass $m = 1$ and the spin parameter $\alpha = 0.7$.

Energy Flux

The total energy flux is defined as (10) and the angular momentum fluxes as (11). Equivalently a direct integration leads to

$$P = -2\,(2\pi)^2 \int_0^{r_0^2} I\,\omega_\phi\, d\Psi_\psi \sim 0.137\,(2\pi)^2\, r_0^4\, \alpha^2\,, \tag{53}$$

$$L_\phi = -2\,(2\pi)^2 \int_0^{r_0^2} I\, d\Psi_\psi \sim 0.455\,(2\pi)^2\, r_0^5\, \alpha\,. \tag{54}$$

The energy extraction efficiency can be employed for the comparison between analytic solutions for the collimated jet in 5D black holes that we derived and the 4D Kerr black hole. To keep the amount of magnetic flux crossing the horizon identical we defined the energy extraction efficiency as in [10] via

$$\bar{\epsilon} = \frac{\int I\,\omega_\phi\, d\Psi_\psi}{\int I\,\Omega_\phi^H\, d\Psi_\psi} \tag{55}$$

In 4D the BZ models for collimated jets [29] display an energy extraction efficiency

$$\bar{\epsilon} \sim 0.36 \text{ in 4D black holes} \tag{56}$$

For the collimated jet solution in Section 4 we obtain

$$\bar{\epsilon} \sim 0.30 \text{ in 5D black holes} \tag{57}$$

A direct comparison shows that the collimated jet power is reduced by a factor about 17% compared to the 4D collimated jet BZ model.

Final comments

One sees directly that for the vertical field configurations in higher dimensions does not introduce in the jet power an even steeper scaling on the spin parameter. Whether steeper behaviors in other field configurations are possible (such as in the monopole, parabolic, hyperbolic configurations) remains an open question.

More exciting things to be done….

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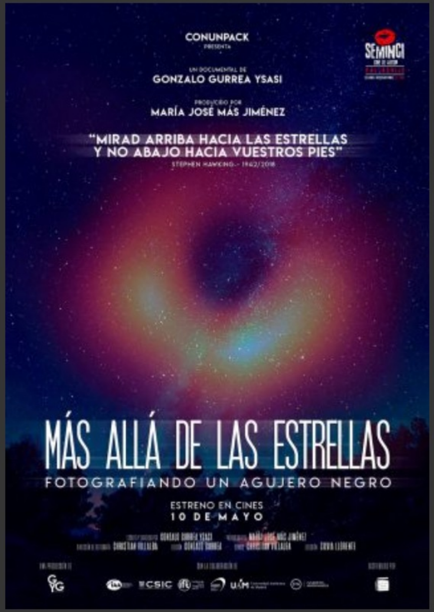

Más allá de las estrellas. Fotografiando un agujero negro

6 Candidaturas

EL 10 de abril de 2019 tuvo lugar uno de los acontecimientos científicos más impactantes del siglo: la obtención de la primera imagen de un agujero negro. Una fotografía que convulsionó al mundo ya que confirmaba la teoría de la relatividad de Einstein. Pero, ¿cómo se llega a un descubrimiento tan relevante? El documental conversa con los físicos más prestigiosos de España, incluyendo varios que intervinieron en la obtención de la imagen, e indaga en sus motivaciones personales con el objetivo de dar respuestas a estas preguntas tan fundamentales.

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Thank you!

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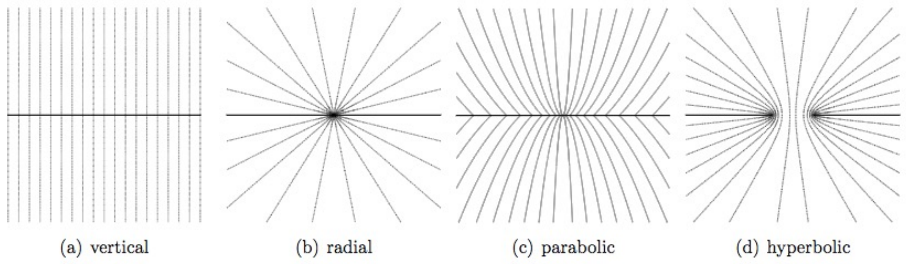
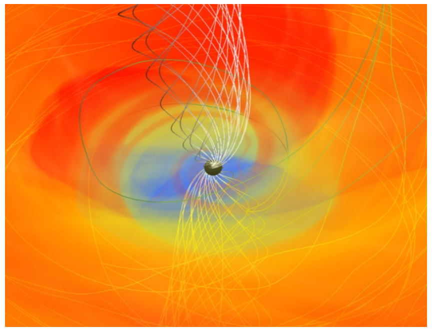
Solutions to Force-free equations

(A) Slowly rotating black holes : perturbative solutions



(B) Numerical solutions



(C) Extremally rotating black holes : exact solutions close to the black hole