Black-hole metric and disc physics degeneracy on highly lensed observables in SMBH images

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LESIA Observatoire de Paris | PSL

LPENS LABORATOIRE DE PHYSIQUE DE L'ÉCOLE NORMALE SUPÉRIEURE

General Relativity

- Standard **theory** of **gravity** (1915)
- Gravity = **Curvature** of **spacetime**
- Gravitational **deflection** of **light**
- Eddington experiment (1919)
- Thorough **tests** in the Solar System

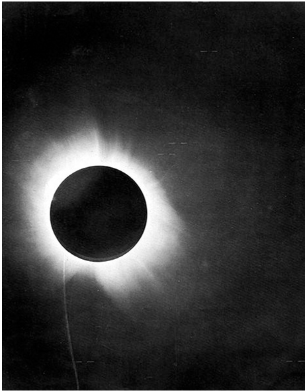

Figure: 1919 solar eclipse.
Credits: Eddington

Black Holes

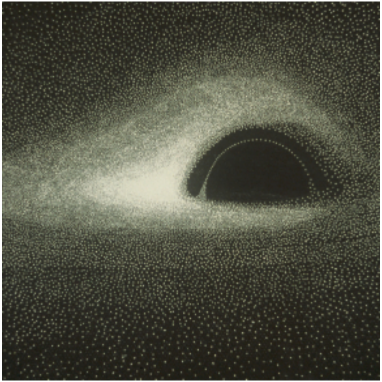

Figure: Simulated photograph of a BH.
Credits: Luminet

- **Black hole** $\leftrightarrow$ **Event horizon**
- No-hair theorem $\rightarrow$ **Kerr**
- **Spacetime singularity**
- Tests in the **strong field** regime
- **Event Horizon Telescope** (2019)

Black Holes

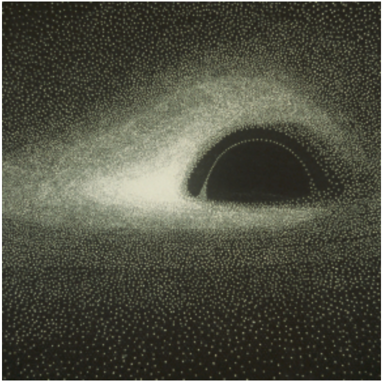

Figure: Simulated photograph of a BH.
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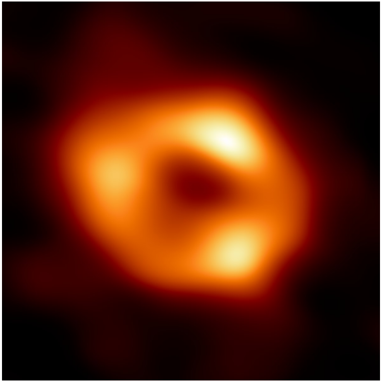


Figure: First image of SgrA*.
Credits: Event Horizon Telescope

Event Horizon Telescope

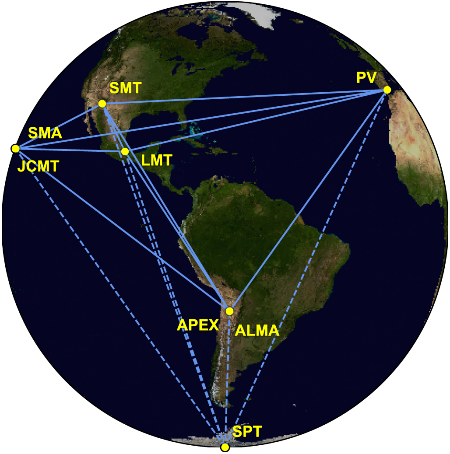


Figure: EHT array of the 2017 campaign.
Credits: Event Horizon Telescope

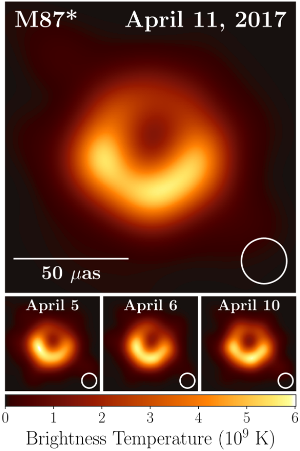


Figure: First image of a black hole.
Credits: Event Horizon Telescope

Project

Scientific question

Can we **detect** a **deviation** from the black-hole **standard model**?

Reasoning steps:

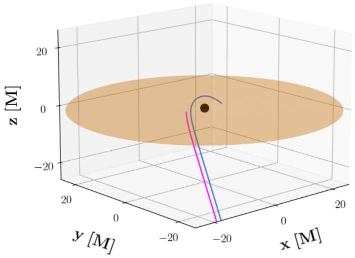
- Find distinctive **image features** induced by the spacetime properties
- Associate reliable electromagnetic **observable signatures**
- **Disentangle** between the **geometry** and the **astrophysics**

Methods:

- **Numerical simulations** via the ray-tracing code **GYOTO**

Trajectories of free photons

- **Photon sphere** = unstable circular orbits of light
- $\mathbf{n}$ = **half turns** around the black hole before leaving to infinity
- One point of the disk = **several images**



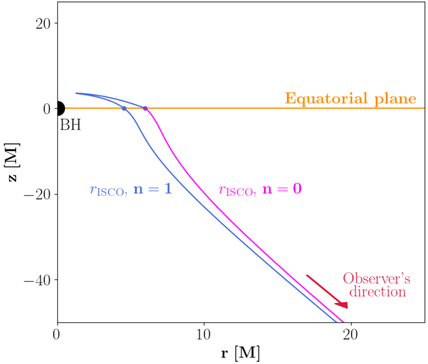


Figure: Geodesics of photons emitted at the innermost stable circular orbit

Image features

- **Critical curve** = projection of the **photon sphere**
- **Inner shadow** = region inside the projected equatorial **event horizon**
- n-th **lensing band** = impact points of light rays of order $n > 0$

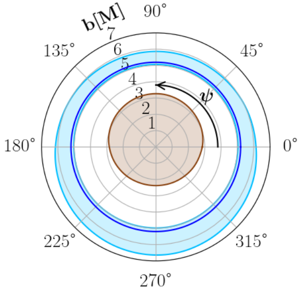


Figure: Horizon, critical curve and $n = 1$ lensing band on the observer's screen.

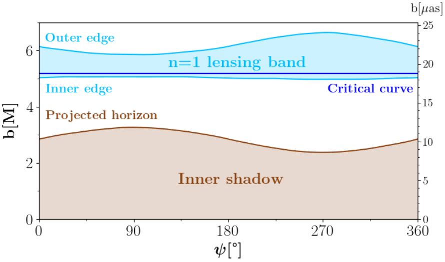
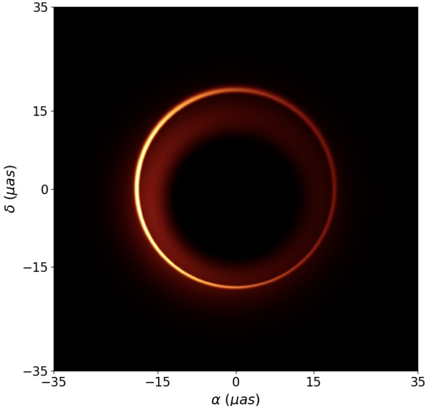


Figure: Impact parameters of the features along the polar angle on the screen.

Photon rings

- Critical curve, horizon, lensing bands = **mathematical regions**
- **Observable** photon rings = radiation of the accretion disk



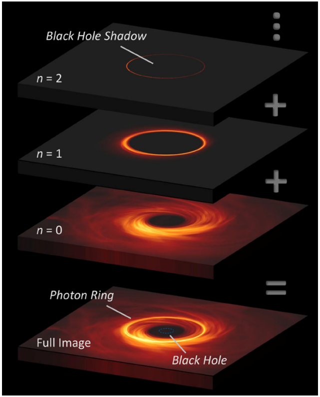


Figure:
Left panel: modeled image of the emission of an accretion disk observed at 230 GHz
Right panel: embedded rings. Credits: Wong, Johnson

Parametrised framework

Simulated Image

Compact Object

- Spacetime **geometry**
- Properties of **M87***
- RZ **spherically symmetric**
- $ds^2 = ds^2(\epsilon, a_i, b_i),\ i \in \mathbb{N}$

Thin Accretion Disk

- Astrophysical **emission**
- **Keplerian/Radial** velocity
- **Synchrotron** radiation
- $j_\nu = j_\nu(\zeta, \nu_{\mathrm{em}}, \alpha, \beta, \gamma) \propto I_\nu$

Parameters

Accretion disk:

- Emissivity $j_\nu(\zeta, \boxed{\nu_{\rm em}}, \alpha, \beta, \gamma)$
- $\boxed{n_e} \propto r^{-\alpha}$, $\boxed{\Theta_e} \propto r^{-\beta}$, $\boxed{B} \propto r^{-\gamma}$, $\zeta(B_{\rm inner}, \Theta_{\rm e;inner})$

Compact object:

- All **metric parameter** affect the **geodesic motion**
- Only **lower order** parameters affect **near-horizon** phenomena:

	Event horizon	Photon sphere	ISCO
$\boxed{\epsilon}$	✓	✓	✓
$\boxed{a_1}$	✗	✓	✓
b_1	✗	✗	✗

- a_0 and b_0 are constrained by observations in the Solar System

1D cross sections

- Separate intensity profiles: **n=0** image and **n=1** photon ring
- Measure the **radial position of the intensity peaks**

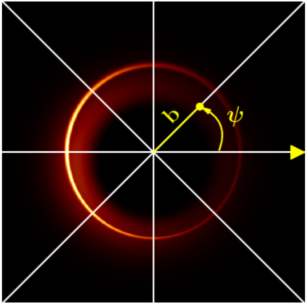


Figure: 1D intensity cuts

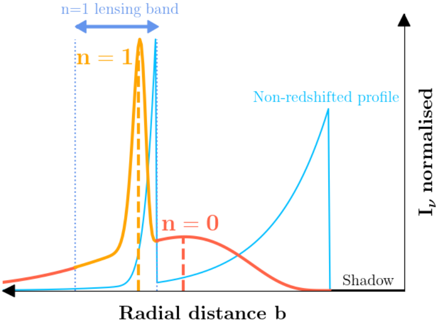


Figure: 1D intensity profile and peaks

Redshift effects

- All I_ν^{em} peak at the radial position of the equatorial event horizon
- Redshifted intensity: $I_\nu^{\text{obs}} = g^3 I_\nu^{\text{em}}$ with $g = \frac{\nu^{\text{obs}}}{\nu^{\text{em}}} = \frac{\boldsymbol{p}^{\text{obs}} \cdot \boldsymbol{u}^{\text{obs}}}{\boldsymbol{p}^{\text{em}} \cdot \boldsymbol{u}^{\text{em}}}$

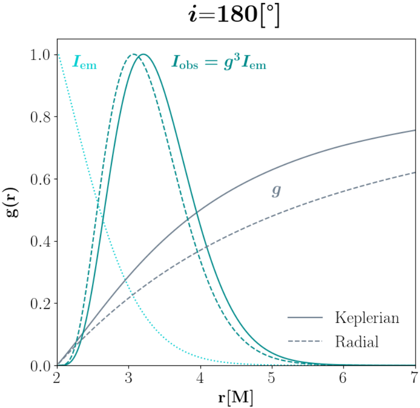


Figure: Redshifted profiles for a Schwarzschild black hole seen face-on

$n = 0$ image

Results

$n = 0$ peaks' position **degenerate** for every disc's dynamics

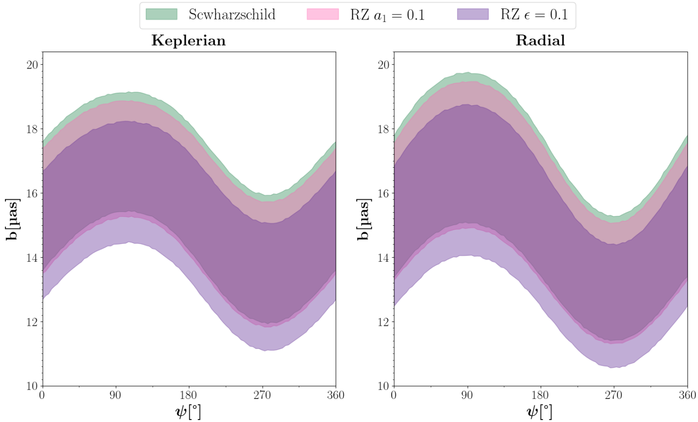


Figure: Impact parameters of the intensity's peaks along the polar angle on the screen

$n = 1$ photon ring

Results

$n = 1$ peaks' position **disentanglable** and always in the Keplerian case

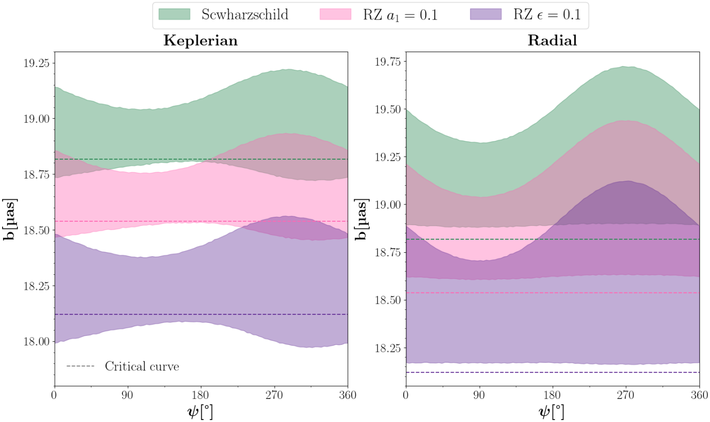


Figure: Impact parameters of the intensity's peaks along the polar angle on the screen

Detectability

- $n = 1$ photon ring not detectable with present instruments
- Angular **resolution** of an interferometer:

$$R \simeq \frac{\lambda}{B} \,,$$

with λ the observed **wavelength** and B the maximum **baseline**

- High-frequency ground array of the **ngEHT** (ongoing)
- **BHEX** space-based array (Small Explorer proposed to NASA)

Avenues

Astrophysics:

- **Geometrically thick** disk
- **Time variability**

Geometry:

- **Rotating** black hole

Methodology:

- **Interferometric signal**

Objects of study:

- **Polarised images**
- **n=2** photon ring

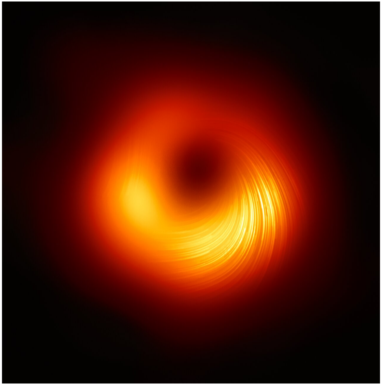


Figure: Polarised image of M87*.
Credits: Event Horizon Telescope