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

Irene Urso

2nd year PhD student, LESIA (Paris Observatory) / LPENS (ENS)

Advisors: Frédéric Vincent (LESIA), Cédric Deffayet (LPENS)

Journées Théorie PNHE

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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

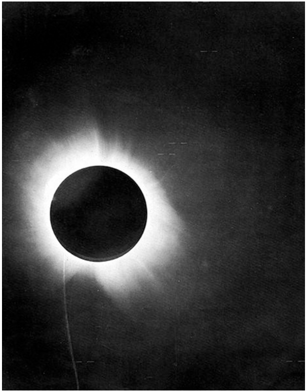

Figure: 1919 solar eclipse. Credits: Eddington

Black Holes

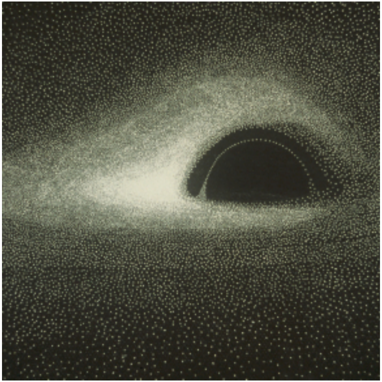

Figure: Simulated photograph of a BH.
Credits: Luminet

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

Black Holes

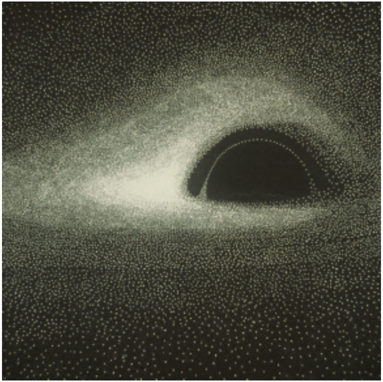

Figure: Simulated photograph of a BH.
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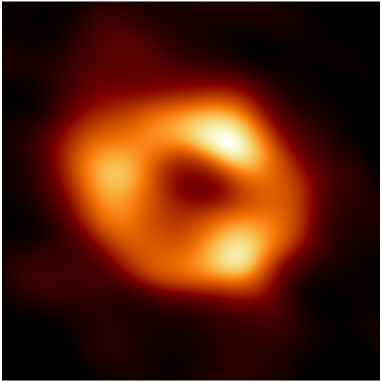


Figure: First image of SgrA*.
Credits: Event Horizon Telescope

Event Horizon Telescope

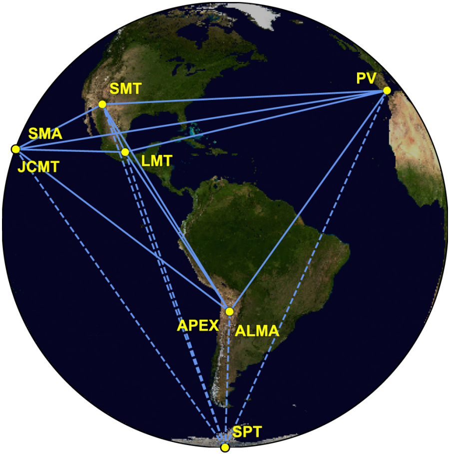


Figure: EHT array of the 2017 campaign.
Credits: Event Horizon Telescope

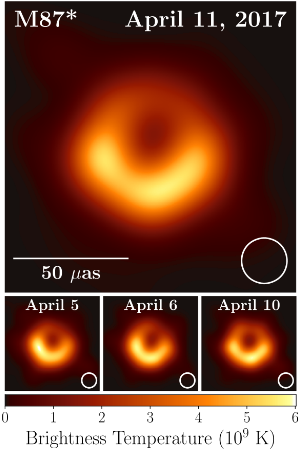


Figure: First image of a black hole.
Credits: Event Horizon Telescope

Project

Scientific question

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

Reasoning steps:

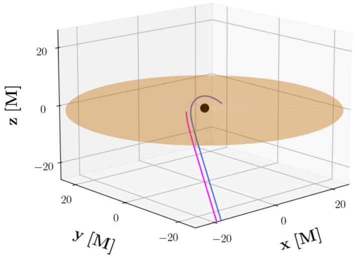
- Find distinctive **image features** induced by the spacetime properties
- Associate reliable electromagnetic **observable signatures**
- **Disentangle** between the **geometry** and the **astrophysics**

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**



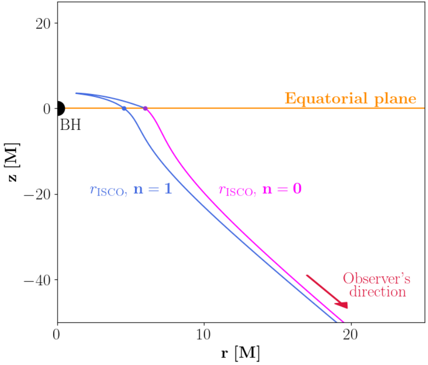


Figure: Geodesics of photons emitted at the innermost stable circular orbit

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 $n > 0$

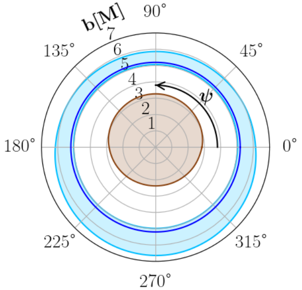


Figure: Horizon, critical curve and $n = 1$ lensing band on the observer's screen.

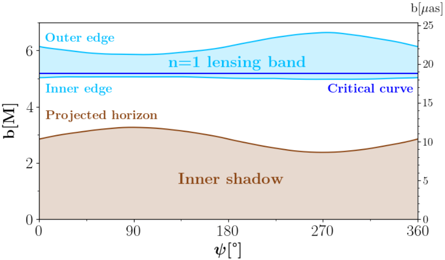


Figure: Impact parameters of the features along the polar angle on the screen.

Photon rings

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

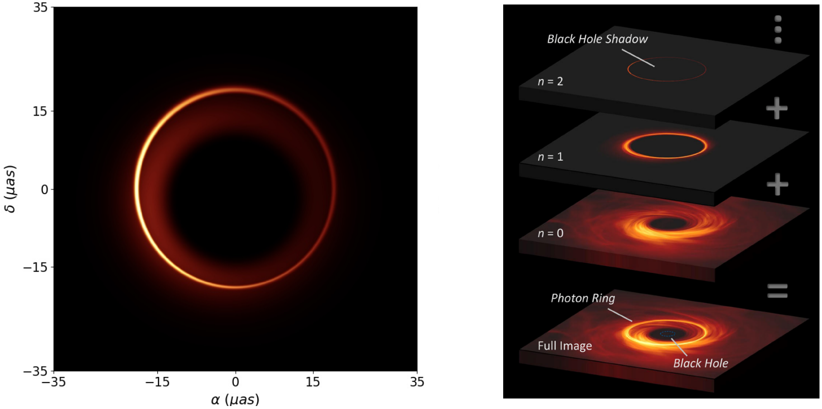


Figure:
Left panel: modeled image of the emission of an accretion disk observed at 230 GHz
Right panel: embedded rings. Credits: Wong, Johnson

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
- $j_\nu = j_\nu(\zeta, \nu_{\rm em}, \alpha, \beta, \gamma) \propto I_\nu$

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**

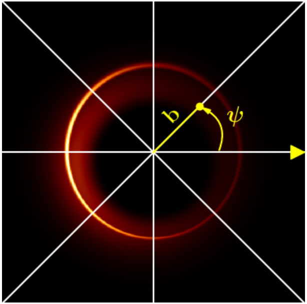


Figure: 1D intensity cuts

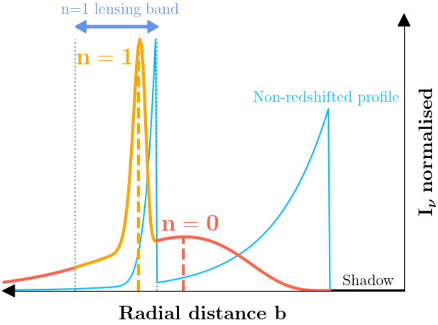


Figure: 1D intensity profile and peaks

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 $g = \frac{\nu^{\text{obs}}}{\nu^{\text{em}}} = \frac{\boldsymbol{p}^{\text{obs}} \cdot \boldsymbol{u}^{\text{obs}}}{\boldsymbol{p}^{\text{em}} \cdot \boldsymbol{u}^{\text{em}}}$

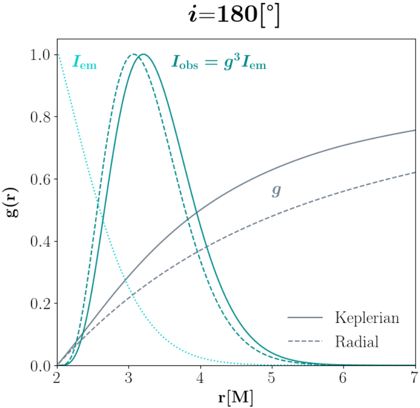


Figure: Redshifted profiles for a Schwarzschild black hole seen face-on

$n = 0$ image

Results

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

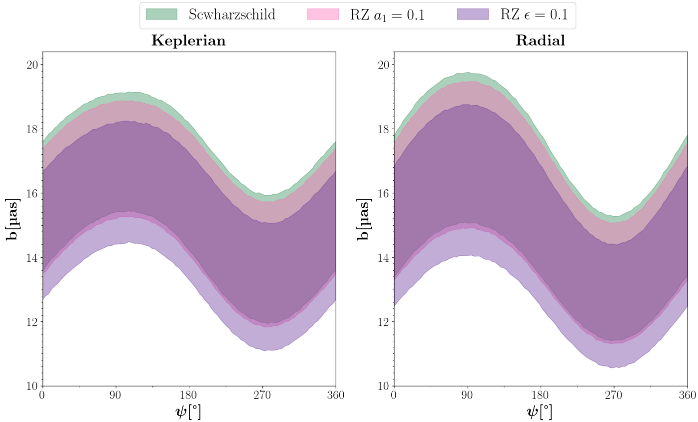


Figure: Impact parameters of the intensity's peaks along the polar angle on the screen

$n = 1$ photon ring

Results

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

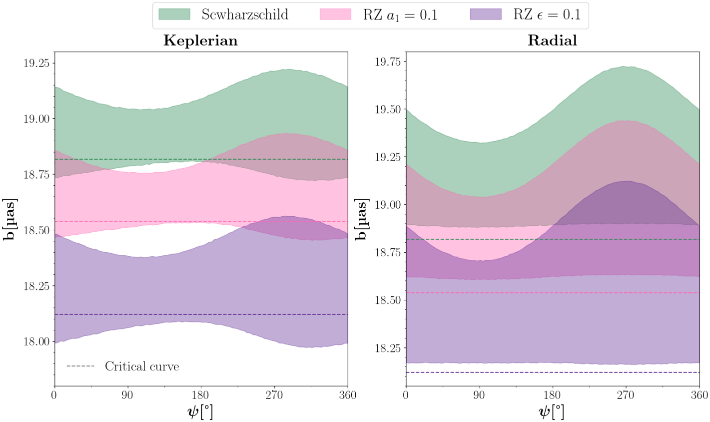


Figure: Impact parameters of the intensity's peaks along the polar angle on the screen

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

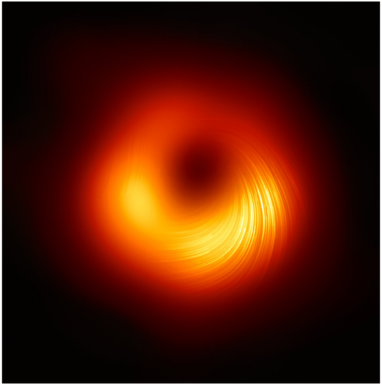


Figure: Polarised image of M87*.
Credits: Event Horizon Telescope

Références

[1] SE Gralla, A Lupsasca, and DP Marrone. "The Shape of the Black Hole Photon Ring: A Precise Test of Strong-Field General Relativity". In: *Physical Review D* 102.12 (2020), p. 124004.

[2] MD Johnson et al. "Universal interferometric signatures of a black hole's photon ring". In: *Science advances* 6.12 (2020), eaaz1310.

[3] L Rezzolla and A Zhidenko. "New parametrization for spherically symmetric black holes in metric theories of gravity". In: *Physical Review D* 90.8 (2014), p. 084009.

[4] FH Vincent et al. "Images and photon ring signatures of thick disks around black holes". In: *Astronomy & Astrophysics* 667 (2022), A170.

Backup slides

Very Long Baseline Interferometry

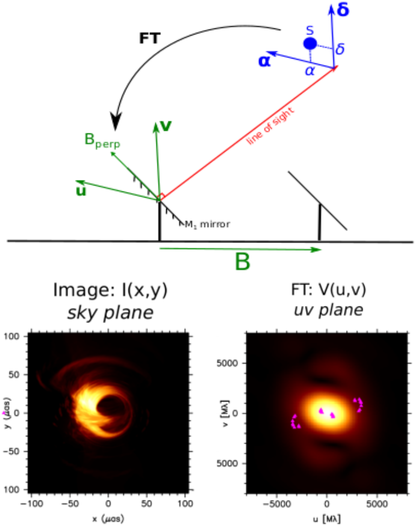


Figure: Relation between the planes of the sky and visibility. Credits: Frédéric Vincent

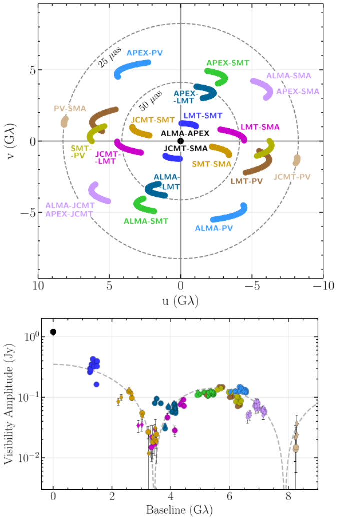


Figure: (u, v) plane coverage and visibility. Credits: EHT

Complex visibility

- **Spatial correlation** function: $\mathcal{V} = \mathcal{V}\left(\vec{B}_\perp/\lambda\right)$,
  with λ the wavelength and $\vec{B}_\perp$ the projection of the baseline
- **Fourier transform** of the **brightness distribution in the sky** I
- **Van Cittert-Kernike** theorem

$$\frac{\mathcal{V}\left(u,v\right)}{\mathcal{V}\left(0,0\right)} = \frac{\iint I(\alpha,\delta)e^{-2i\pi(u\alpha+v\delta)}d\alpha d\delta}{\iint I(\alpha,\delta)d\alpha d\delta},$$

with (α,δ) the usual right ascension and declination
and (u,v) their Fourier conjugate frequencies

Visibility amplitude

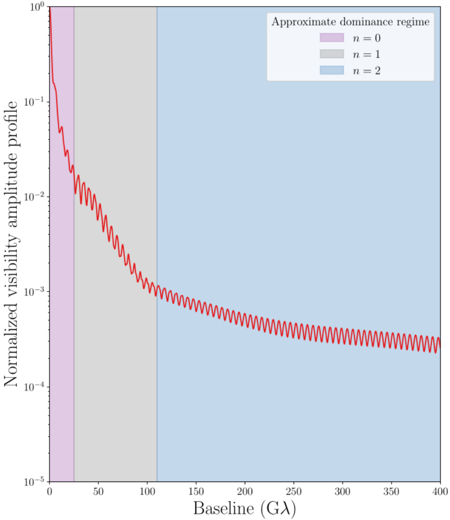


Figure: Visibility amplitude of a Gyoto simulated image. Credits: Paugnat et al. 2022

Photon ring detectability

EHT + **space telescope**: deviations of **0.1 mJy** detectable at 345 GHz

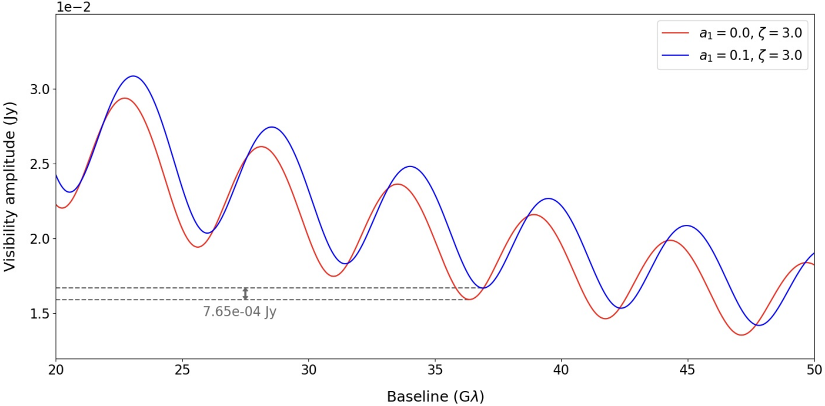


Figure: Visibility amplitude of the n=1 photon ring for $\zeta = 3$ and $a_1 = 0$ or $a_1 = 0.1$

Comapct object

- **Spherically symmetric** black hole
- Rezzolla-Zhidenko **parametrised** and **hierarchical metric**:

$$ds^2 = -\boxed{N(r)}^2 dt^2 + \frac{\boxed{B(r)}^2}{N(r)^2} dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2) \ ,$$

$$\begin{cases} N^2(x) = x[1 - \boxed{\epsilon}(1-x) + (\boxed{a_0} - \boxed{\epsilon})(1-x)^2 + \boxed{\tilde{A}(x)}(1-x)^3] \\ B(x) = 1 + \boxed{b_0}(1-x) + \boxed{\tilde{B}(x)}(1-x)^2 \end{cases} ,$$

$$\tilde{A}(x) = \cfrac{\boxed{a_1}}{1 + \cfrac{\boxed{a_2}\,x}{1 + \cfrac{\boxed{a_3}\,x}{1 + \boxed{\cdots}}}} \ , \quad \tilde{B}(x) = \cfrac{\boxed{b_1}}{1 + \cfrac{\boxed{b_2}\,x}{1 + \cfrac{\boxed{b_3}\,x}{1 + \boxed{\cdots}}}} \ ,$$

where we introduced the variable $x := 1 - r_{\mathcal{H}}/r$ and $1 + \epsilon = 2M/r_{\mathcal{H}}$, with $r_{\mathcal{H}}$ the radius of the horizon and M the mass of the black hole

Metric impact on image features

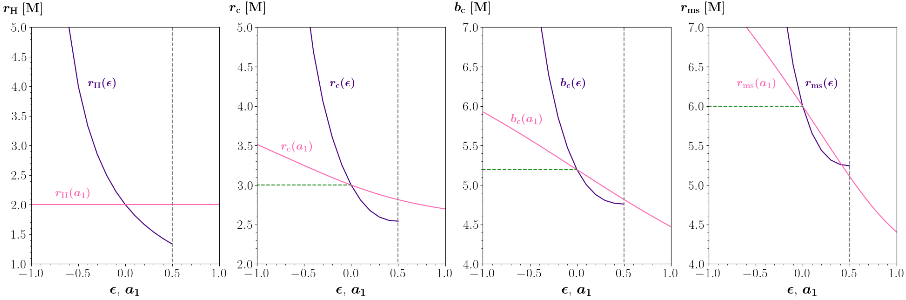


Figure: Dependence of the event horizon, photon shell, critical curve and ISCO on ϵ, a_1

Accretion disk

Set-up:

- **Geometrically thin** disk inclined at 163°

Dynamics:

- **Keplerian velocity** with the **Cunningham hypothesis**
- **Radially infalling velocity**

Emission:

- **Optically thin** disk
- **Thermal synchrotron emission**

Thermal synchrotron emission

- **Synchrotron power** emitted by an **ultrarelativistic electron**: P_ν
- Power of a **population** of electrons in **thermal equilibrium**:

$$j_\nu = \int_0^\infty \underset{\substack{\uparrow \\ B}}{P_\nu} \overset{\substack{\Theta_e, n_e \\ \downarrow}}{\frac{dn_e}{d\gamma}} \underset{\substack{\uparrow \\ v_e}}{d\gamma} \propto I_\nu$$

  with B the magnetic field, Θ_e the dimensionless temperature and n_e the density following a **Maxwell distribution** of speeds v_e

- **Hypotheses** of power-law fall-offs: $n_e \propto r^{-\alpha}$, $\Theta_e \propto r^{-\beta}$, $B \propto r^{-\gamma}$
- $i_1 = \alpha - 2\beta$ and $i_2 = \gamma + 2\beta$

Emissivity

- $j_\nu \approx \eta \frac{\nu_{\rm em}[\mathsf{GHz}]}{230} \left(\frac{r}{r_{\rm inner}}\right)^{-i_1} \exp\left[-\zeta \sqrt[3]{\frac{\nu_{\rm em}[\mathsf{GHz}]}{230}} \left(\frac{r}{r_{\rm inner}}\right)^{i_2/3}\right]$

  where $\zeta = \left(\frac{3.7\times10^5}{B_{\rm inner}\Theta^2_{e;{\rm inner}}\sin\theta}\right)^{1/3}$

  with $B_{\rm inner}$, $\Theta_{e;{\rm inner}}$ the values of B and Θ_e at the inner radius $r_{\rm inner}$ and θ the angle between the emission direction and the magnetic field

- **Various observing frequencies** of the ngEHT: 230, 345 GHz

- $I_\nu^{\rm em} \propto j_\nu$

Apparent shape of circular rings

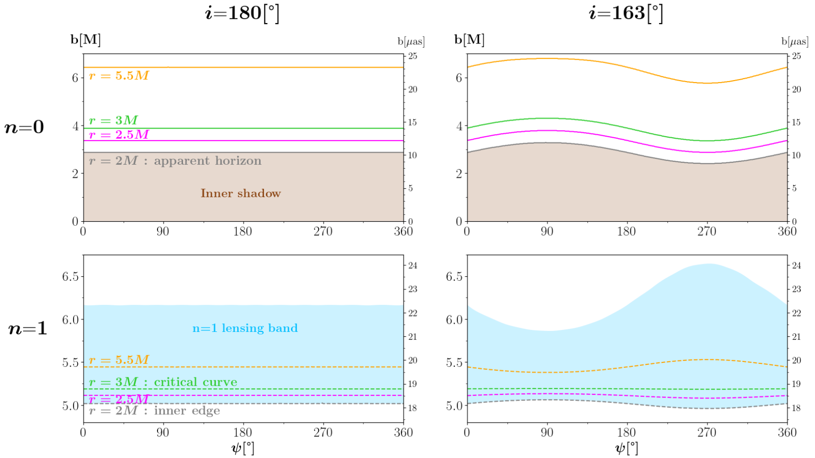


Figure: Direct and first-lensed apparent positions of rays emitted from isoradial distances

Null geodesics

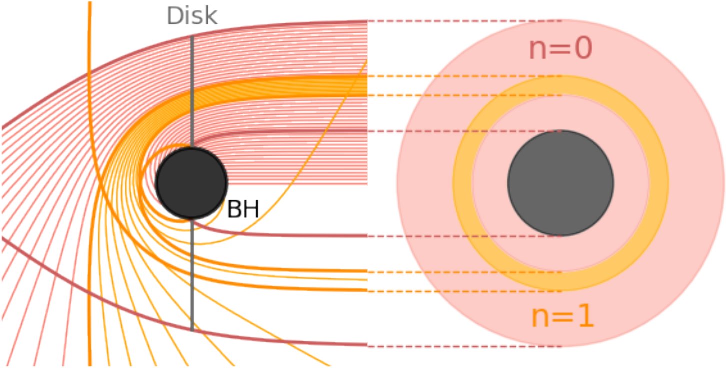


Figure: Geodesics of photons in the Schwarzschild spacetime and corresponding image at infinity of the black-hole seen face-on

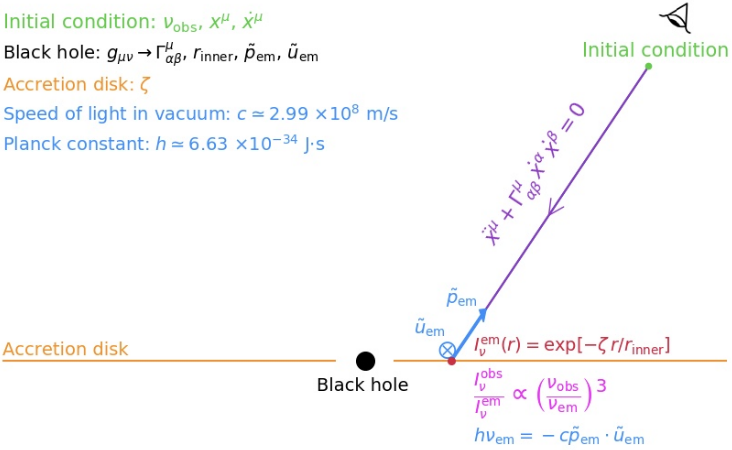


Figure: Scheme of the functioning of GYOTO

Adaptative ray-tracing

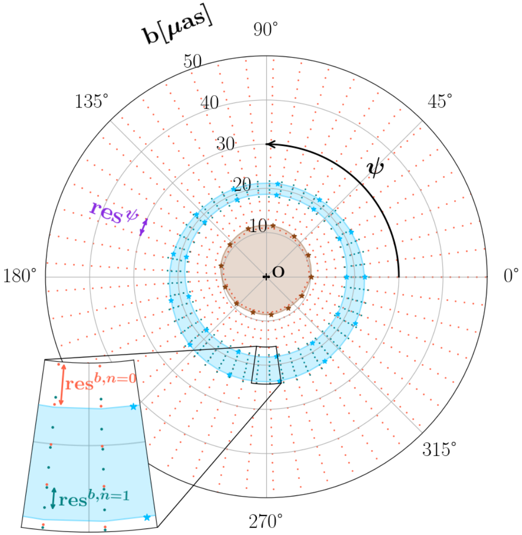


Figure: Adaptatively ray-traced points

Polarisation

- **Polarisation**: privileged orientation of the radiation
- Regular magnetic field
- **n** = number of **half turns**
- Even: same polarisation
- Odd: same polarisation
- Change of polarisation: dependence on the BH **spin**

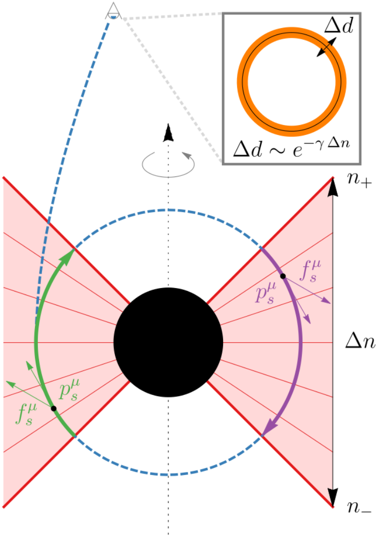


Figure: Ray-tracing in a thick disk.
Credits: Elizabeth Himwich