Light ring images of thin accretion disk in regular compact objects

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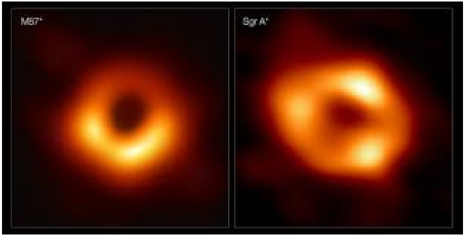
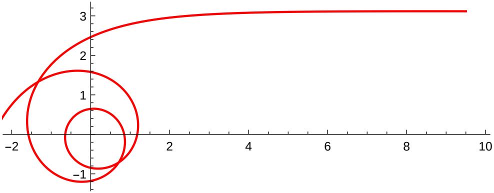
- The multimessenger era (astronomy with different carriers: light, neutrinos, and GWs) is already here with us.
- In particular, the Event Horizon Telescope (EHT) results provides a new stream of info to both feed and test our theoretical models of the gravitational interaction and of alternative compact objects.



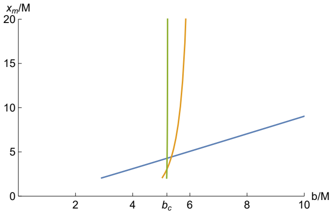
EHT observations of the center of the galaxy M87 (left) and Sgr A*.
Credit: Event Horizon Telescope Collaboration

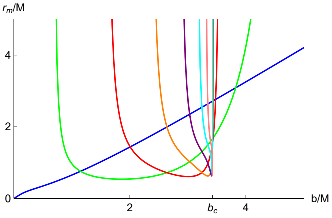
- The Ray Tracing is the first step to study the optical appearance of a compact object. It consists of a bunch of curves covering the relevant range of impact factor values above and below that of the critical curve.
- We orientate our setup in order to locate the observer at the asymptotic infinity



- The method traces back the light rays arriving to our screen with a certain impact parameter region b using the geodesic equation until we find the place they were originated from.

- Depending on the number of turns around the compact objects (or, alternatively, of intersections with the plane containing the accretion disk) we can classify the light rays as:
  - Direct emission
  - Lensed emission
  - Photon ring emission
- After three intersections,the corresponding light rings are expected to be so demagnified[1] that their contribution to the total luminosity can be dismissed.

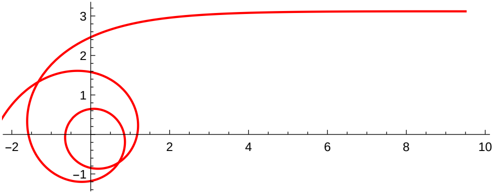




[1] S. Gralla *et al.* Phys. Rev. D 101.4(2020).

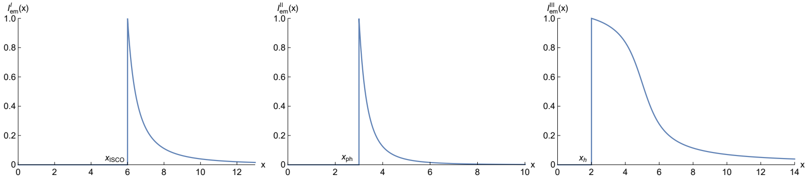
Accretion disk

- The received luminosity depends on the emission profile of the accretion disk.
- To find an analytic solution of this equation (avoiding GRMHDs), one can neglect absorption effects, which corresponds to an optically thin disk.
- Assume that the disk emits isotropically, and monochromatically.
- Another assumption is considering it geometrically thin (we assumed it to be optically thin from the onset).



For the purpose of simulating different stages in the temporal evolution of the accretion disk we employ three canonical toy models with different inner edges, smoothly falling off asymptotically with different tails.

- Model I: The emission starts at the innermost stable circular orbit for time-like observers (ISCO).
- Model II: The emission stars at the critical curve itself.
- Model III: The emission starts right off the event horizon (in the black hole case) or to the throat (in the wormhole case).



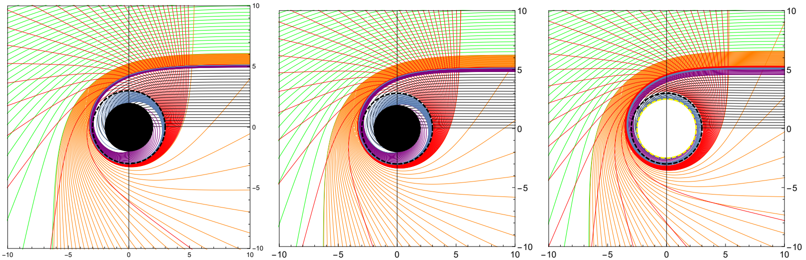
- The observed intensity is the emited corrected by two factors; the gravitational redshift and the additional luminosity picked on each interaction with the accretion disk,

$$I^{ob}(b) = \sum_m A^2 I\big|_{x=x_m(b)} \, , \tag{1}$$

with A being the time metric component and $x_m(b)$ the radius where a given light ray with impact parameter b will have its m^{th}-intersection with the disk (in the coordinate x).

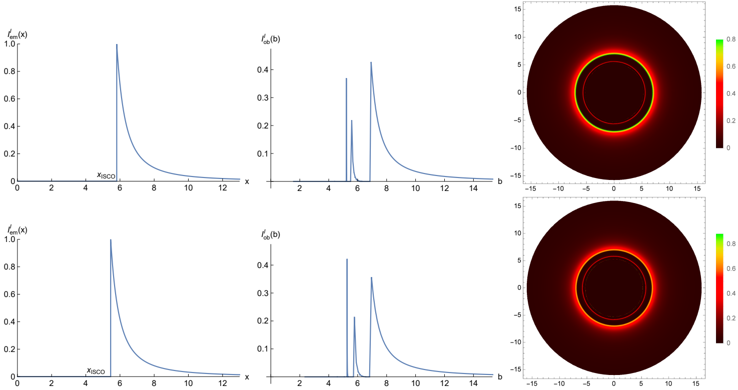
- The black bounce (BB) solution is a uniparametric family of solutions given by metric components [2]

$$A(x) = 1 - \frac{2M}{r(x)} \ ; \ r^2(x) = x^2 + a^2 \ , \tag{2}$$



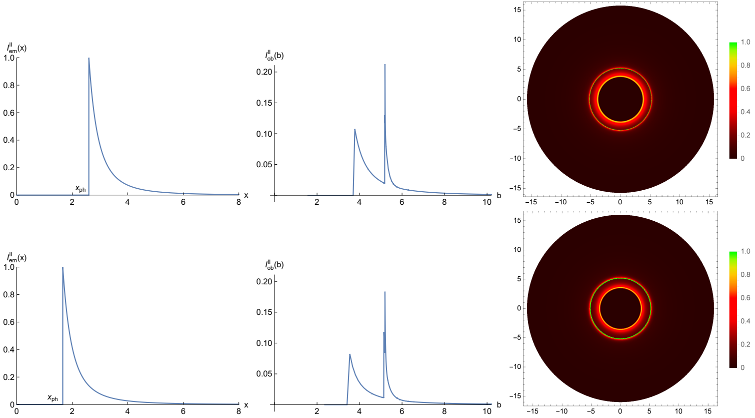
Ray-tracing of Schwarzschild (left), one-horizon black hole (middle) and wormhole (right) for a range of relevant values of the impact factor.

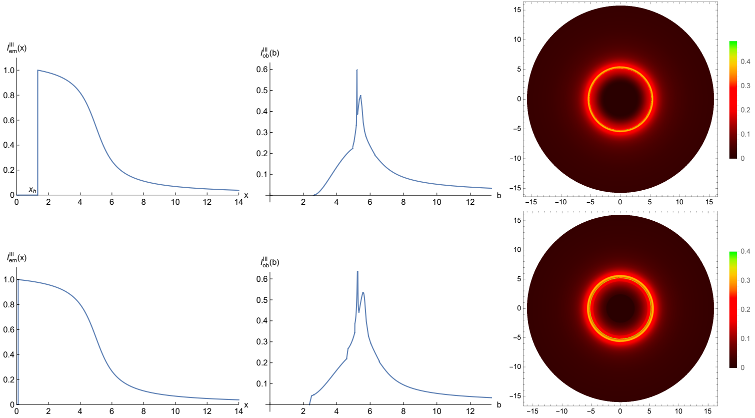
[2] A. Simpson *et al.*, JCAP 02 (2019) 042



The emitted intensity (left panel), the observed intensity (middle panel) and the optical appearance of the BH (top) and wormhole (bottom).

Black Bounce solution, Model II



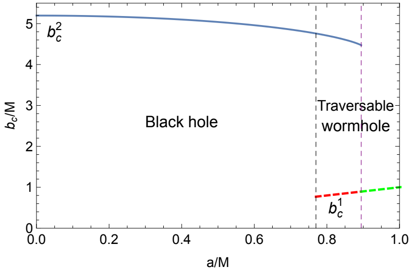


$I^{III}_{em}(x)$
x
x_h
$I^{III}_{ob}(b)$
b
$I^{III}_{em}(x)$
x
$I^{III}_{ob}(b)$
b

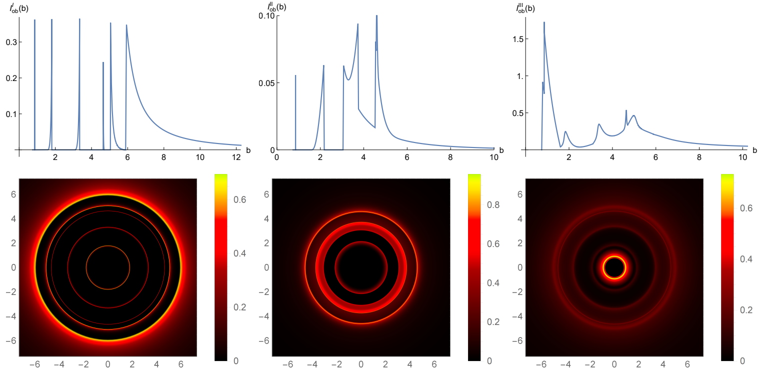
A generalized version of black bounce-type geometry[3], where the metric functions are given by

$$A(x) = 1 - \frac{2Mx^2}{(x^2 + a^2)^{3/2}}\,;\; r^2(x) = x^2 + a^2\;. \qquad (3)$$

As before, depending on the parameter a, the solution corresponds to a BH or a traversable wormhole with one or two critical curves.



[3] F. SN Lobo *et al.* Phys.Rev.D 103 (2021) 8, 084052

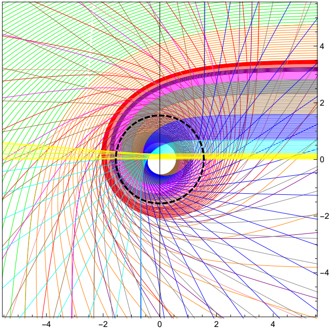


Observed intensity (top) for a two-critical curves wormholeand its optical appearance (bottom) with an accretion disk of model I (left), model II (middle) and model III (right).

The single metric function $A(r)$ is given by the non-rotating limit of the SV family of configurations [4] as

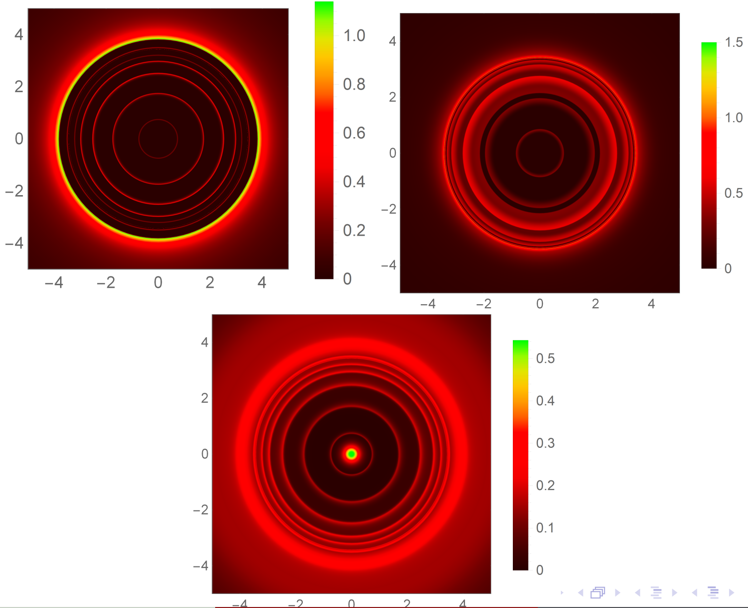
$$A(r) = 1 - \frac{2Me^{-l/r}}{r} \ , \tag{4}$$

where $l > 0$ is a new scale parameterizing the deviations with respect to the Schwarzschild solution.



[4] A. Simpson *et al.* JCAP 03 (2022) 03, 011

Eye of the storm, Light Rings



- A new playground for testing our favourite compact objects and alternative models to GR is currently at our disposal.
- Difficulty in finding new theoretically well-motivated and workable solutions of modified gravity and/of exotic/alternative compact objects.
- Difficulty in disentangling the contributions from the background geometry and the accretion disk in the image of an object, though some discriminators (e.g. size of the shadow) are already available.
- Difficulty in managing the numerics of GRMHD simulations to implement the points above. Resort to analytical approximations and/or toy models to get some glimpse on the new Physics that can be expected.
- Cross-tests with GW observations for better fittings of predictions to data.

Thank you!

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