The optical appearance of spherical objects

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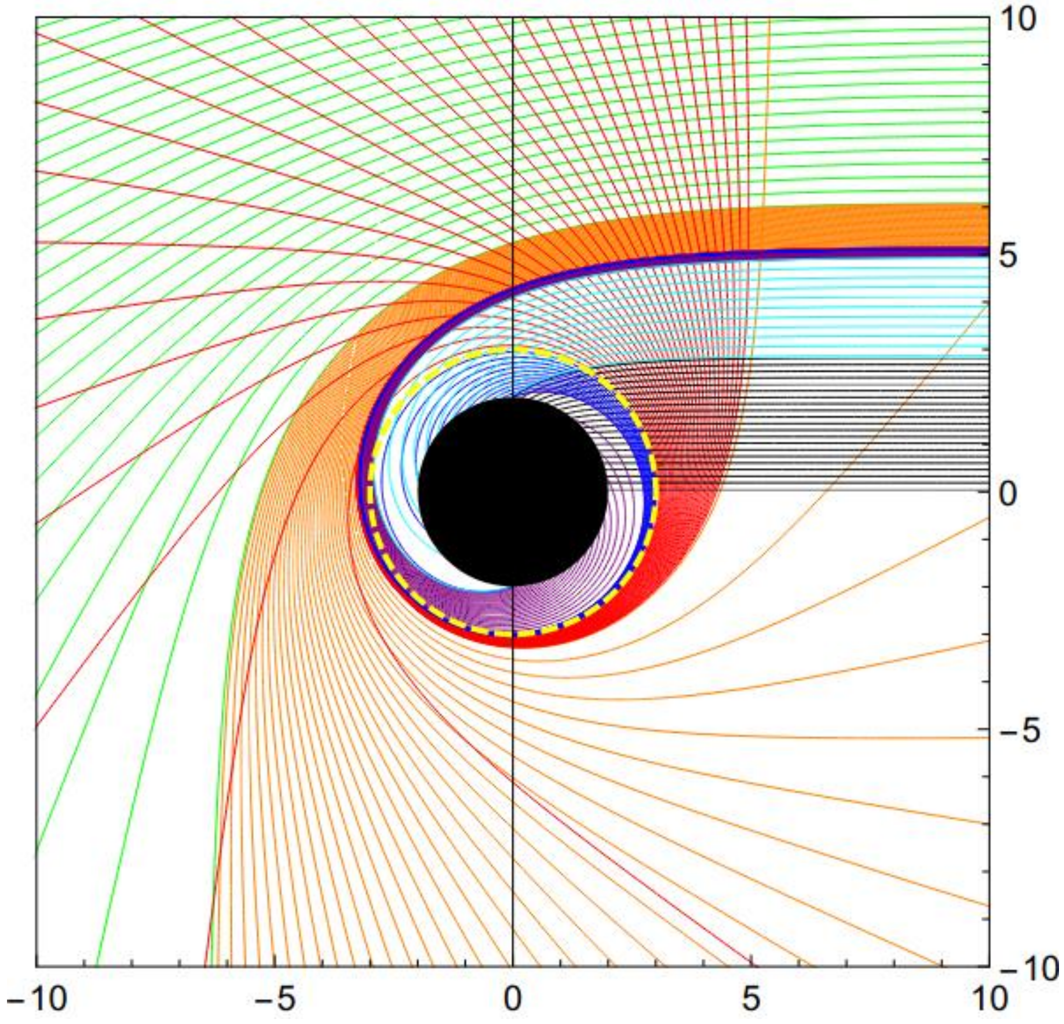
Introduction

- The optical appearance of the object is highly dependent on the optical and geometrical properties of the emission source illuminating it.
- The background geometry is the solely responsible for the critical curve (light ring).
- Disentangling the contributions from each other in such an image is one of the main challenges in the field.
- But is there a way to be able to disentangle?

Ray-tracing

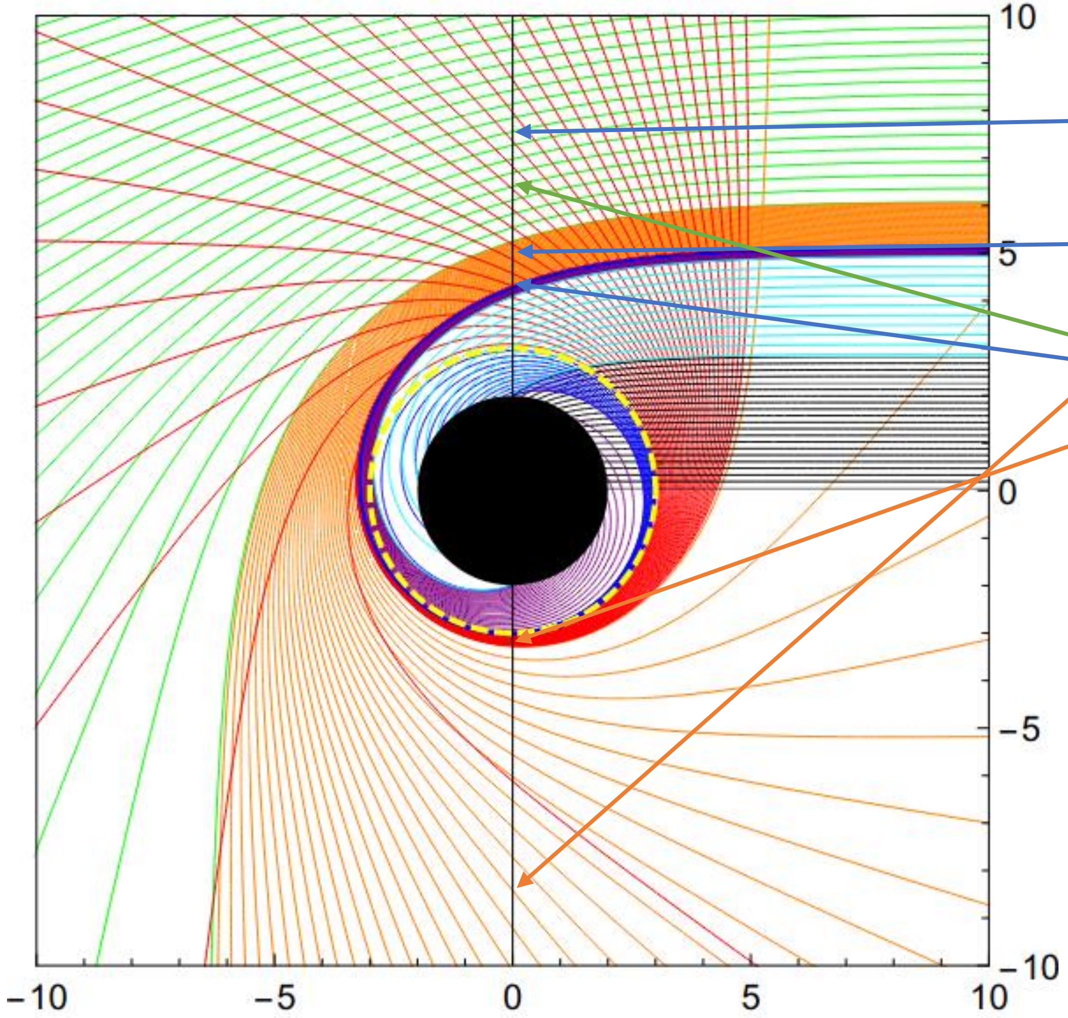
Ray-tracing



- Classifies the light-rays depending on the number of half-turns.
- Traces back the geodesic equation with an impact parameter, b, from our "screen" until reaching the compact object and leaving to the asymptotic infinity.

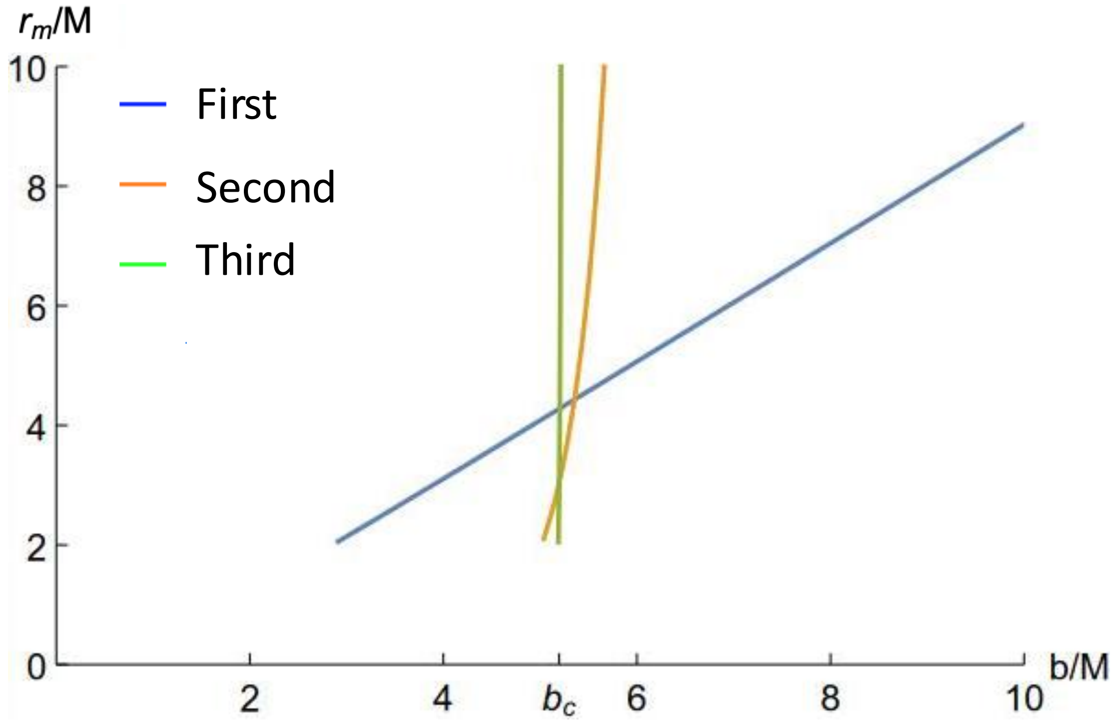
$$\frac{d\theta}{dr} = \mp \frac{b}{r^2\sqrt{1 - \frac{b^2 A(r)}{r^2}}}$$

Ray-tracing



First		Second		Third	
$\{b_1, r_1\}$					Direct
$\{b_2, r_1\}$	&	$\{b_2, r_2\}$			Lensed
$\{b_3, r_1\}$	&	$\{b_3, r_2\}$	&	$\{b_3, r_3\}$	Photon ring

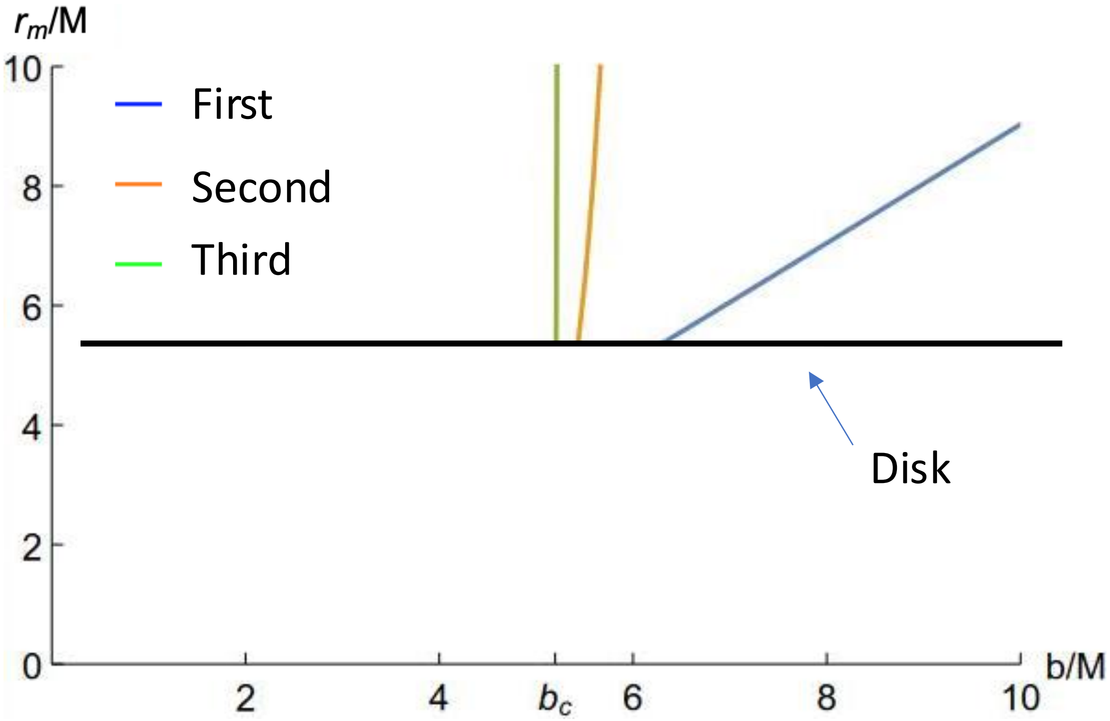
Ray-tracing



Transfer function in terms of the impact parameters for the Schwarzschild black hole

- The transfer function, r_m, is the radius at which a light ray with impact parameter, b, crosses the m-th time the vertical axis.
- The steeper the line is the more demagnified the corresponding ring will be.

Ray-tracing



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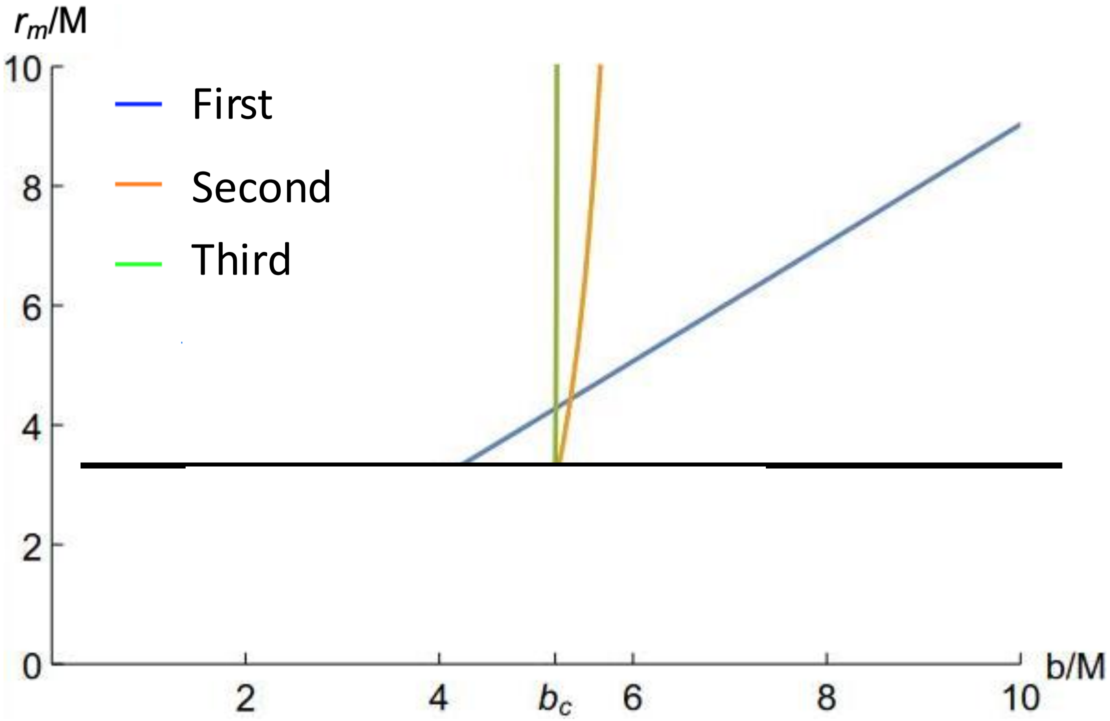

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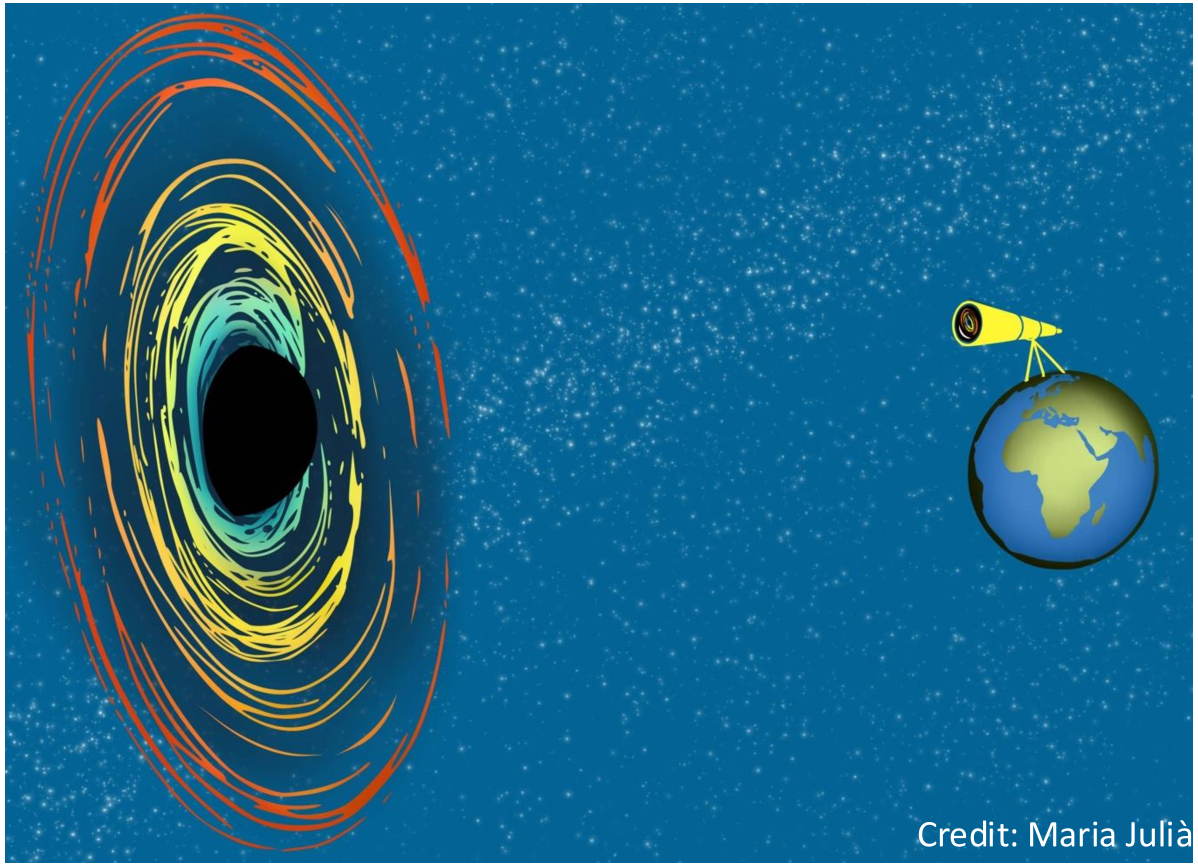
Accretion disk modelling

Accretion disk[1]



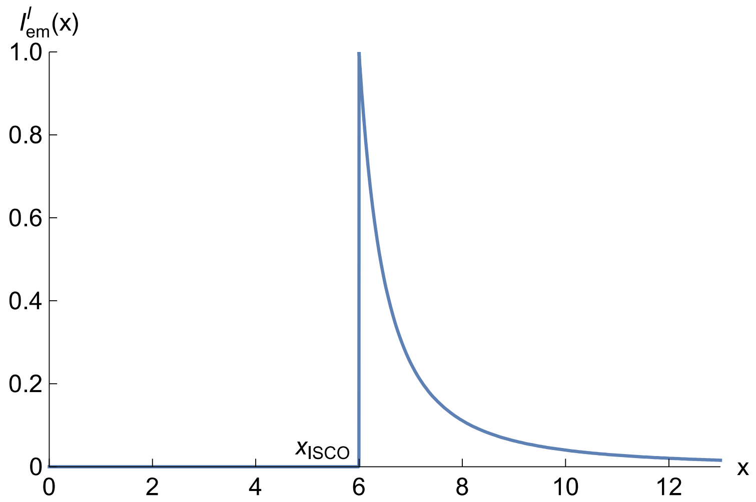
Schematic draw of the configuration black hole-Earth

- The received luminosity depends on the emitted by the accretion disk
- Assume that
  - Emits isotropically and monochromatically
  - Optically and geometrically thin
  - Placed perpendicular to us (face-on)

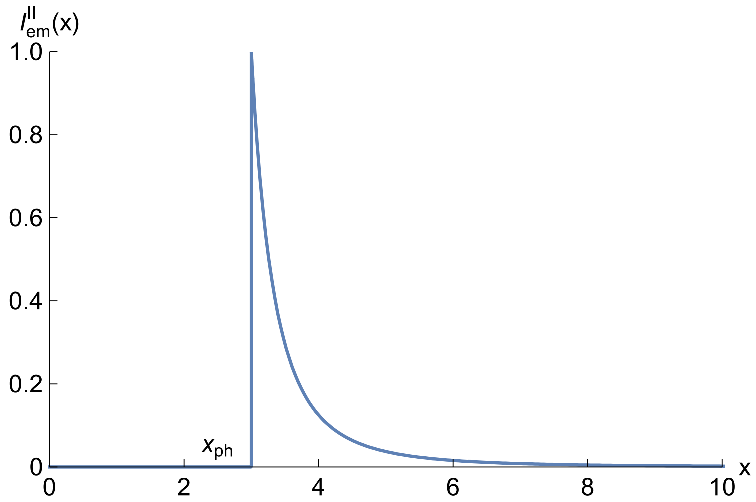
1. S. Gralla *et al. Phys.Rev.D* 100 (2019) 2, 024018

Accretion disk models

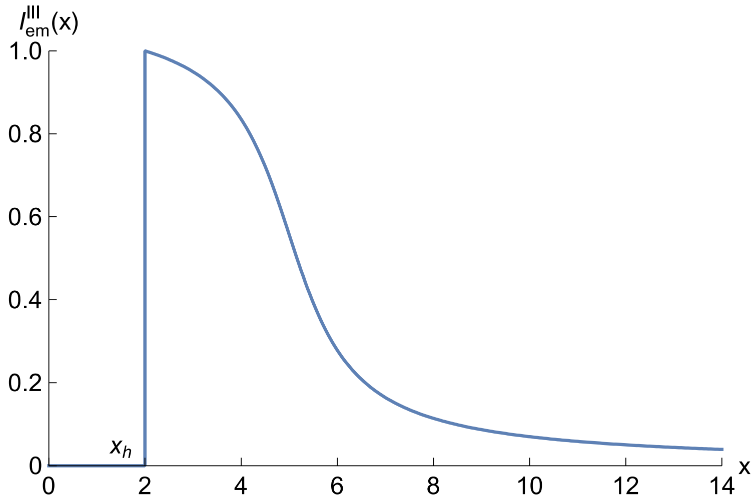
- To simulate several stages of temporal evolution, we employ three canonical toy models with different inner edges, smoothly falling off asymptotically with different tails



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).

Observed intensity

- The observed intensity is the emited corrected by two factors:
  1. The gravitational redshift
  2. The additional luminosity picked on each interaction with the accretion disk
- In particular, it has the following form,

$$I^{ob}(b) = \sum_m A^2(x)\, I^{em}(x)\Big|_{x=x_m(b)}$$

with A being the time metric component and x_m the radius where a given light ray with impact parameter b will have its m-th intersection with the disk.

Results

Black Bounce

- By Black Bounce[1] (BB) we refer to the uniparametric family of solutions given by

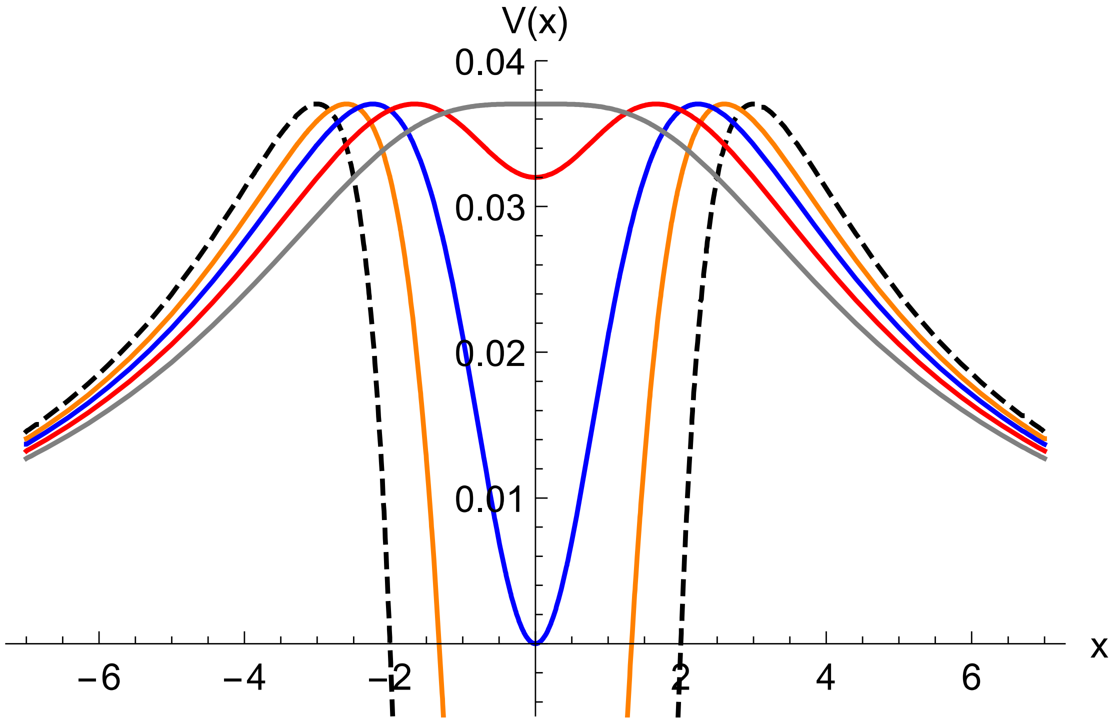
$$A(x) = 1 - \frac{2M}{r^2}$$

$$r^2(x) = x^2 + a^2$$

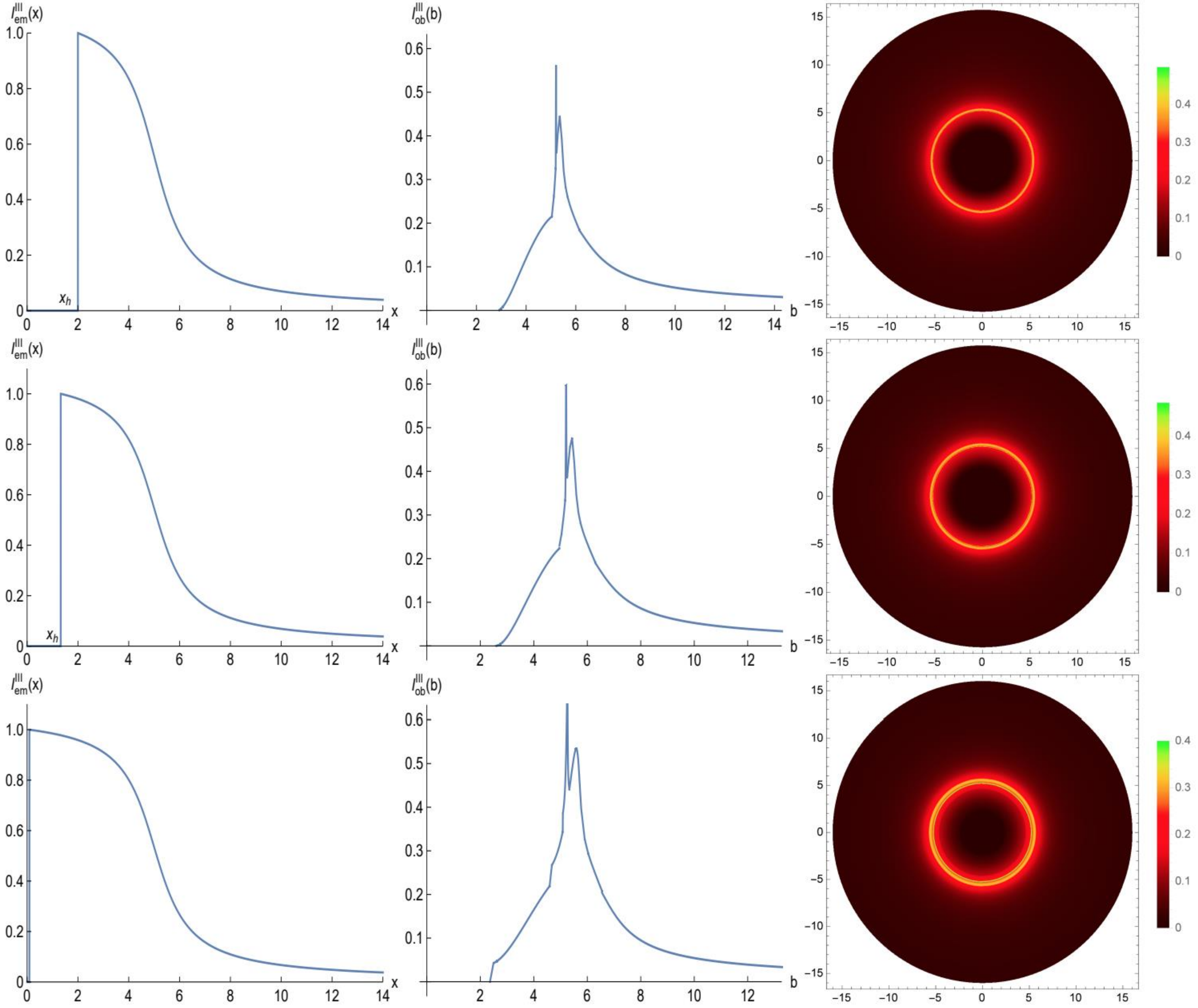
- Depending on the parameter a, the solution corresponds to a BH or a traversable wormhole.

Remember the spherical line element

$$ds^2 = -A(x)dt^2 + \frac{dx^2}{A(x)} + r^2(x)d\Omega^2$$



1. A. Simpson *et al.* *JCAP* 02 (2019) 042



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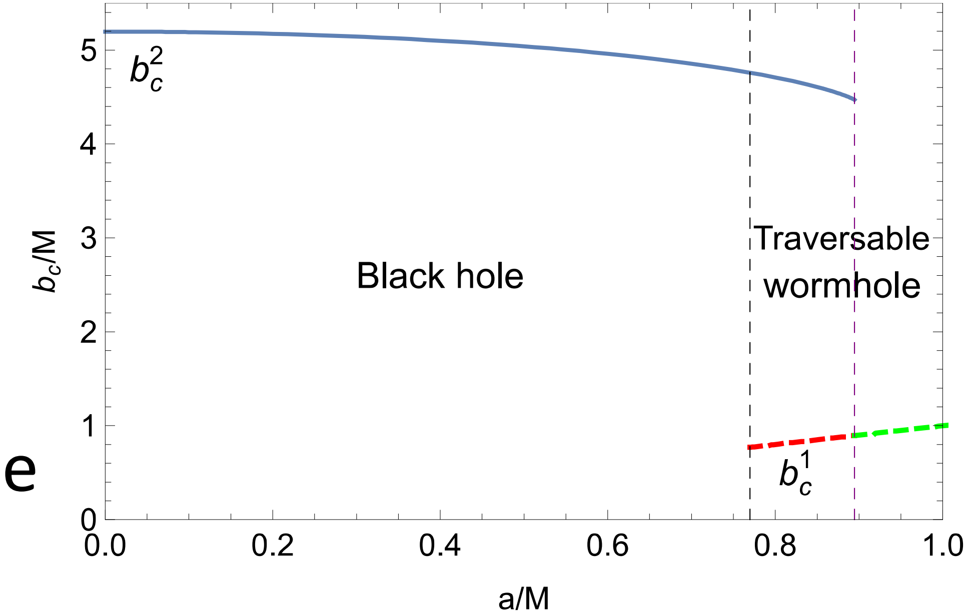
Generalization of the Black Bounce

- A generalized version of black bounce-type geometry[2], where the metric functions are given by

$$A(x) = 1 - \frac{2Mx^2}{(x^2 + a^2)^{3/2}}$$

$$r^2(x) = x^2 + a^2$$

- Depending on the parameter a, the solution corresponds to a BH or a traversable wormhole with one or two critical curves.

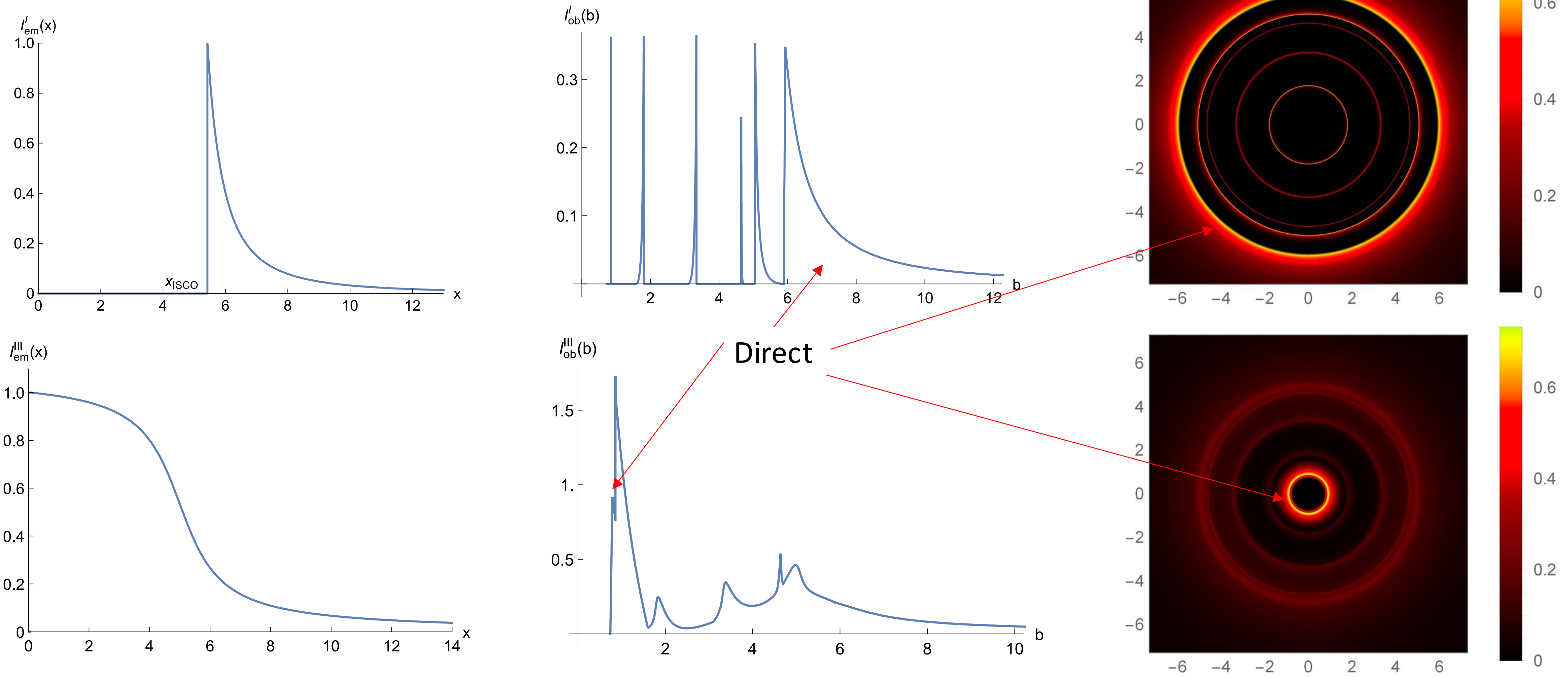


2. F. SN Lobo *et al.* Phys.Rev.D 103 (2021) 8, 084052

Generalization of the Black Bounce

Emitted intensity of the disk

Observed intensity



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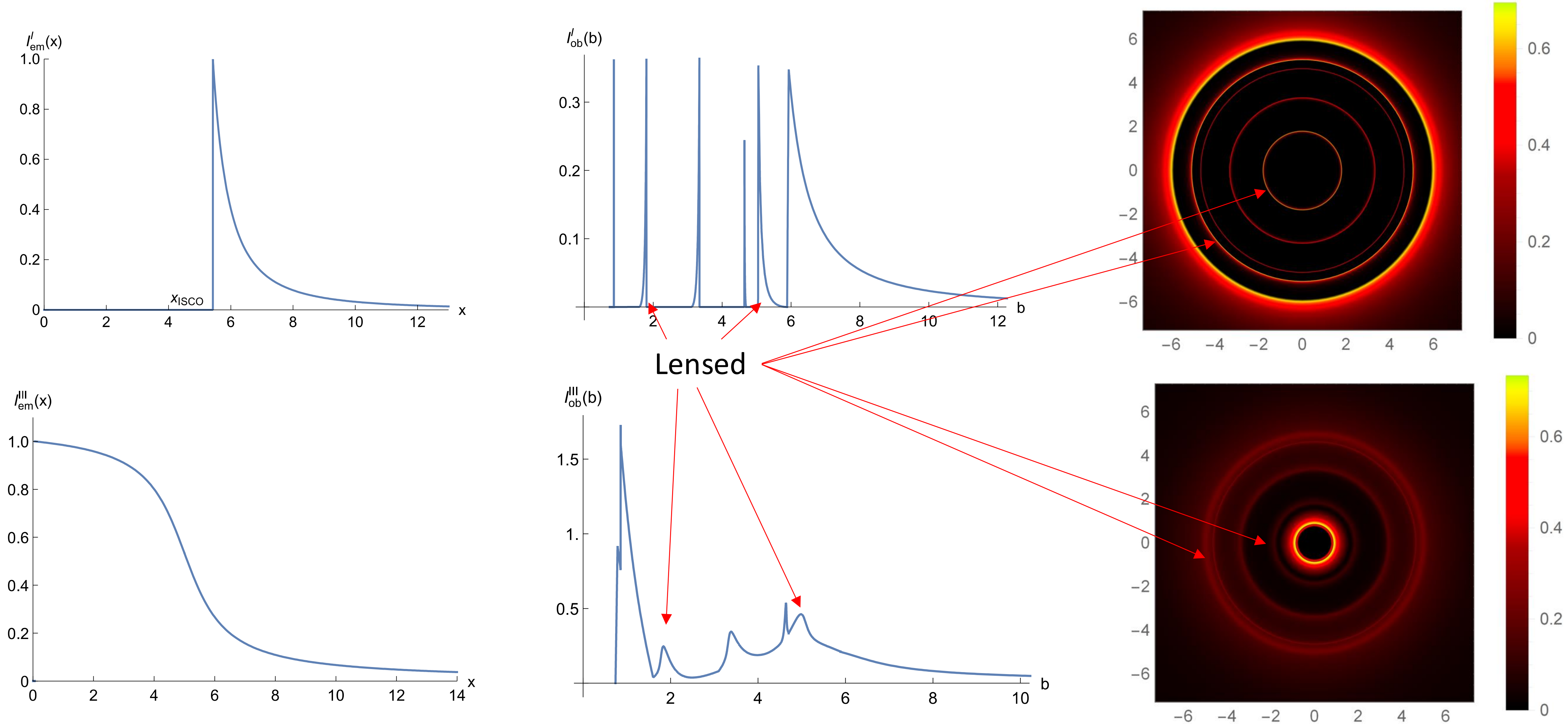
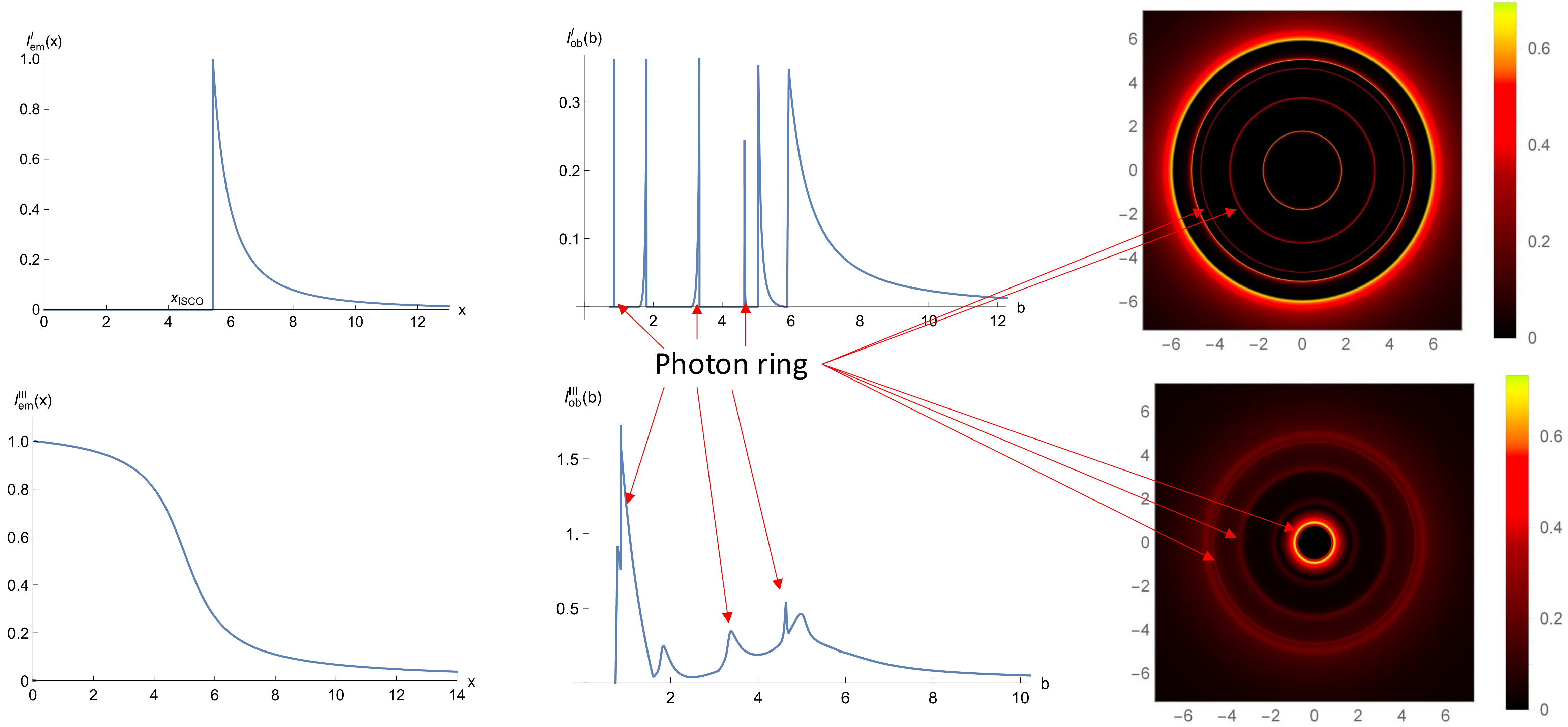


Generalization of the Black Bounces

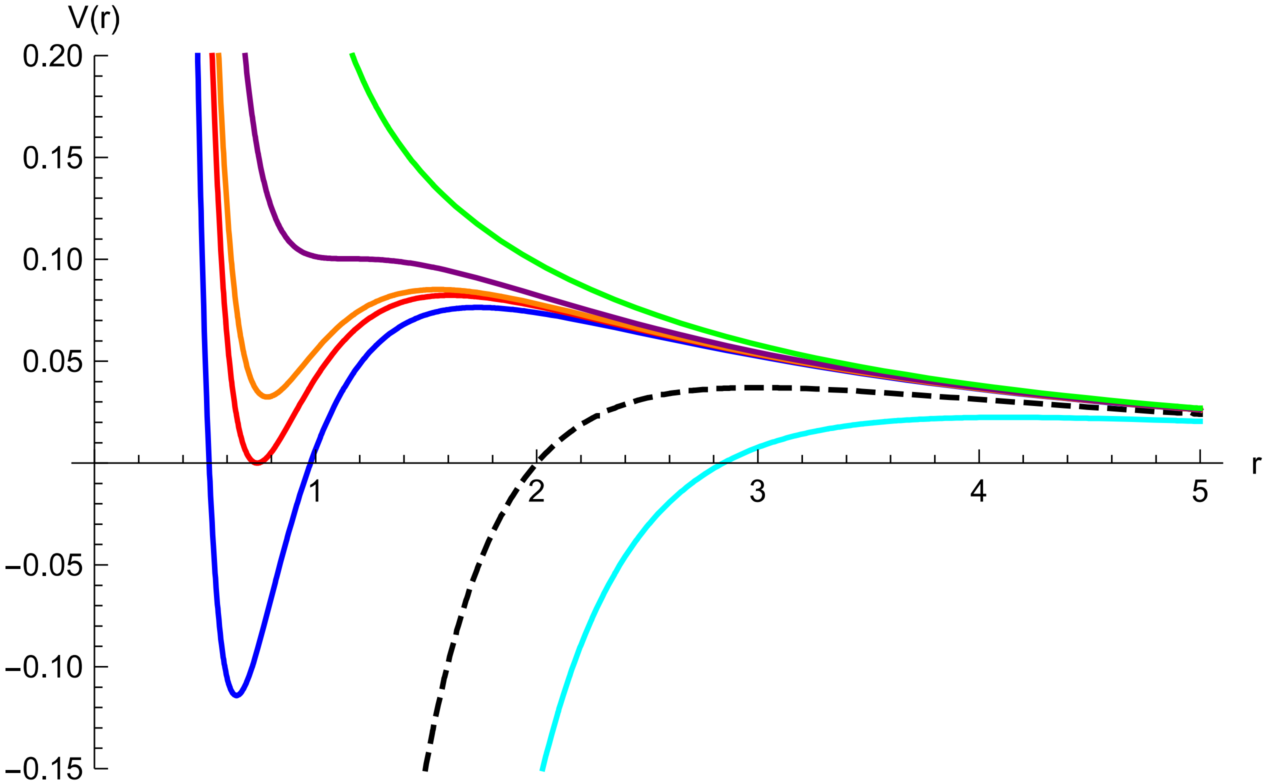


The Eye of the Storm[4]

- The metric function is given by the non-rotating limit of a family of configurations[4] as

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

- 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

Potential

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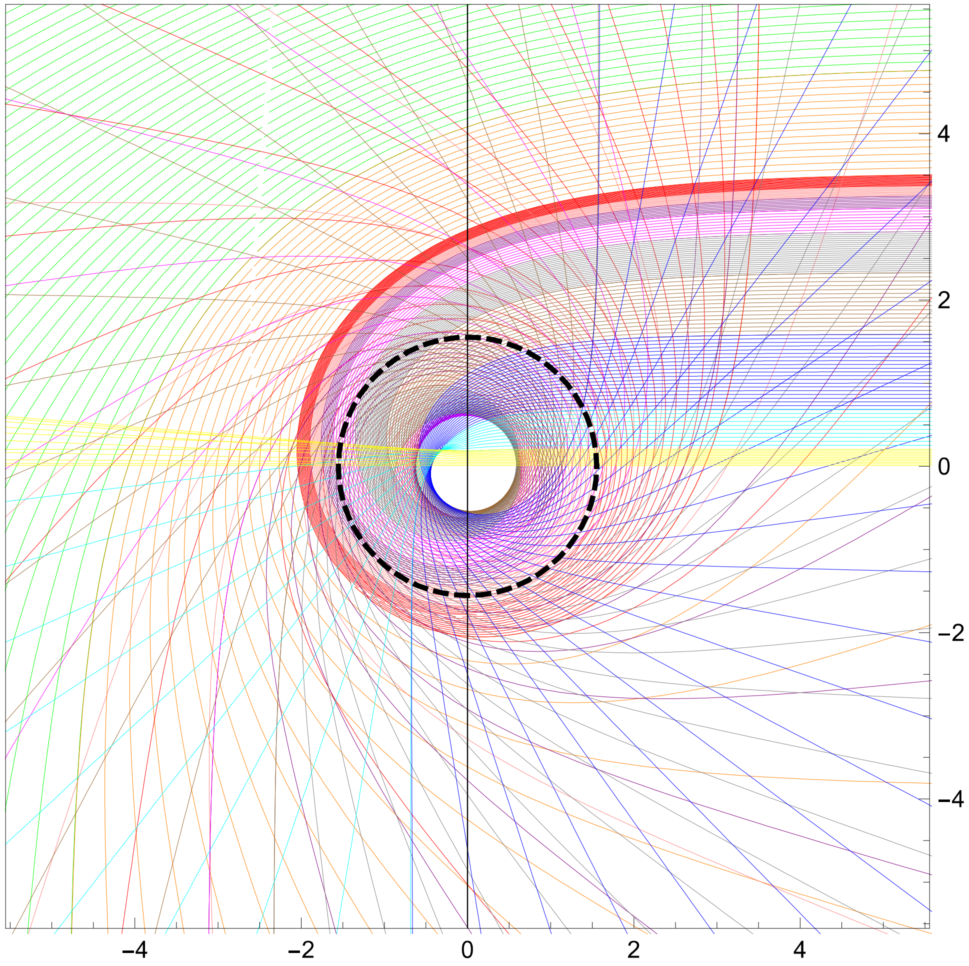
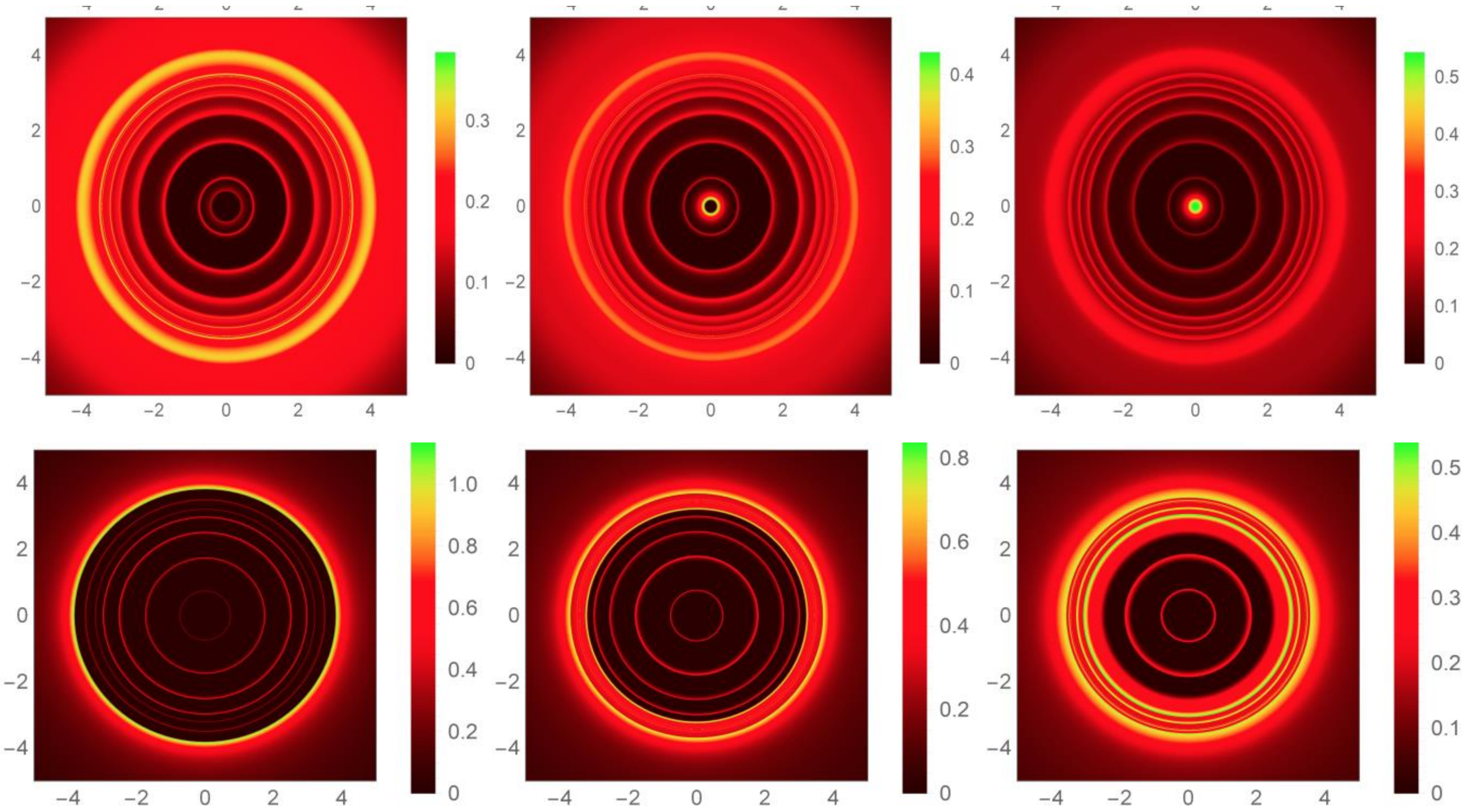


Ray-tracing

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

The Eye of the Storm[5]



5. **M. Guerrero**, G. J. Olmo, D. Rubiera-Garcia, D. Saez-Chillon Gomez, Phys.Rev.D 106 (2022) 4, 044070

Conclusions

- A new playground for testing our favorite compact objects and alternative models to GR is currently at our disposal.
- 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 or the ring pattern) are already available.
- Difficulty in managing the numeric of GRMHD. Resort to analytical approximations and/or toy models to get some glimpse on the new Physics that can be expected.

Thank you for your attention