揚州大學
YANGZHOU UNIVERSITY

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Optical appearances of Horndeski hairy black hole

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Outline

1. Introduction

2. Optical appearances of Horndeski hairy black hole

3. Summary

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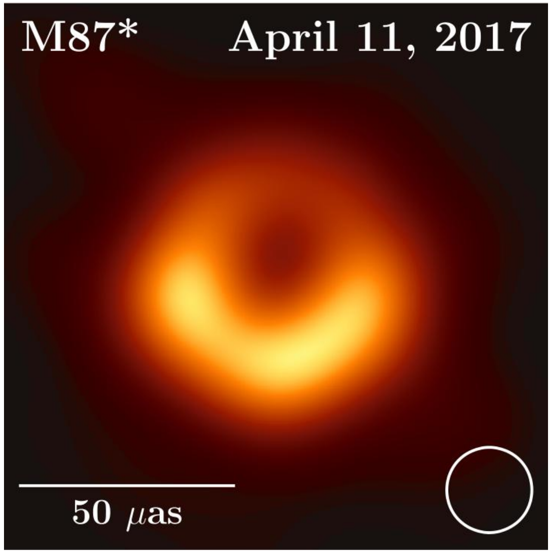
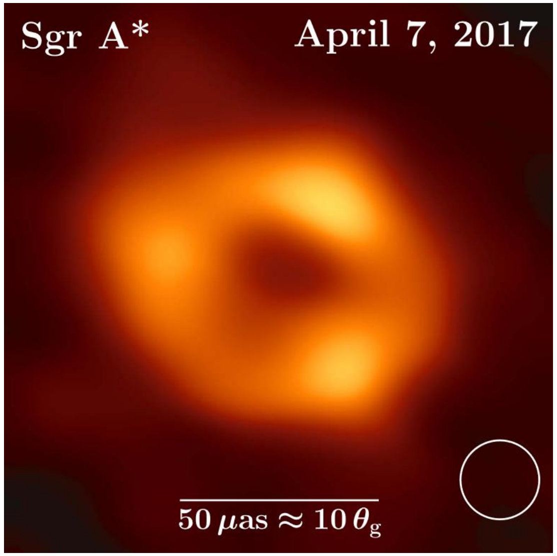
1. Introduction

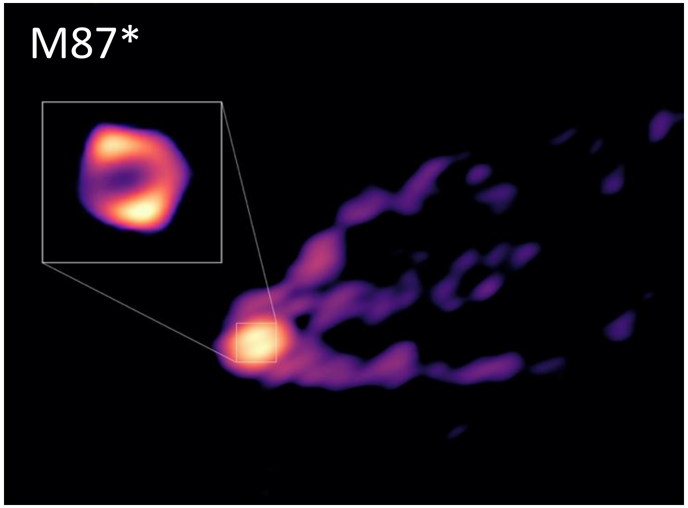
The three current black hole images



Astrophys.J.Lett.
875 (2019) L1



Astrophys.J.Lett.
930 (2022) 2, L12



Nature 616 (2023)
7958, 686-690

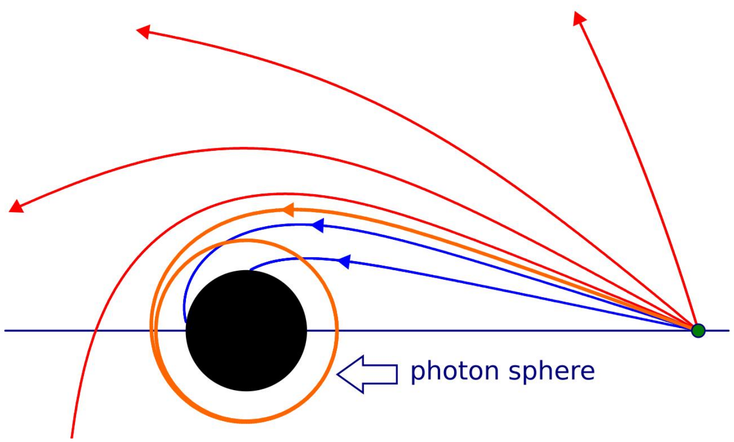
1. Introduction

[V. Perlick et.al, Phys.Rept. 947 (2022) 1-39]

null geodesic:

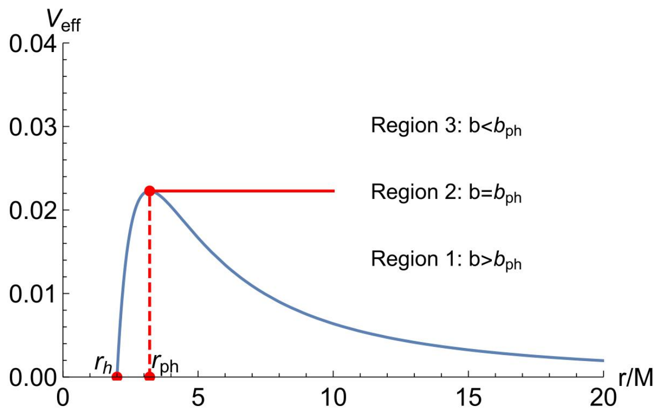
$$\left(\frac{dr}{d\phi}\right)^2 = r^4\left(\frac{1}{b^2} - V_{\rm eff}(r)\right)$$

with $V_{\rm eff}(r) = \frac{f(r)}{r^2}$



photon sphere:

$$V_{\rm eff}(r_{ph}) = \frac{1}{b_{ph}^2}, \quad V_{\rm eff}'(r_{ph}) = 0.$$



1. Introduction

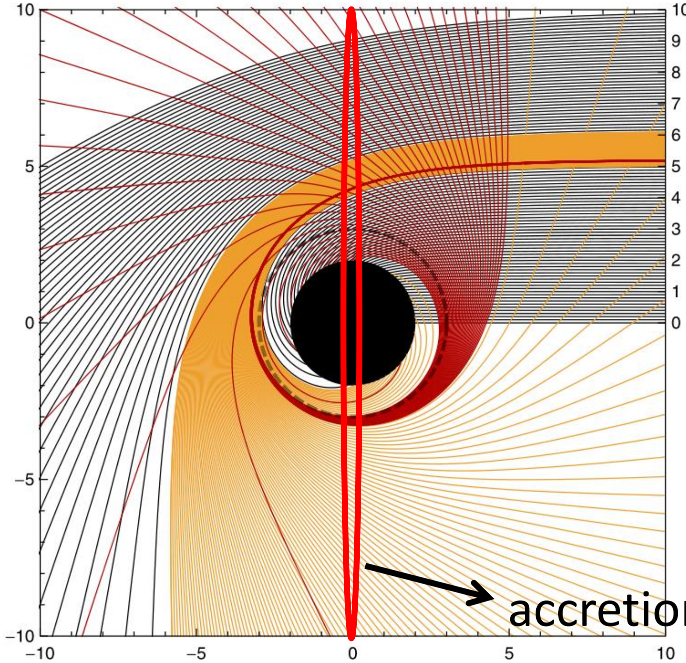
Assume the emission originates near the black hole from an optically thin and geometrically thin accretion disk.

***Three types of light rays*:**

- direct emission : at most once, $0<n<3/4$
- lensed ring emission : at least twice, $3/4<n<5/4$
- photon ring emission : at least three times, $n>5/4$

where

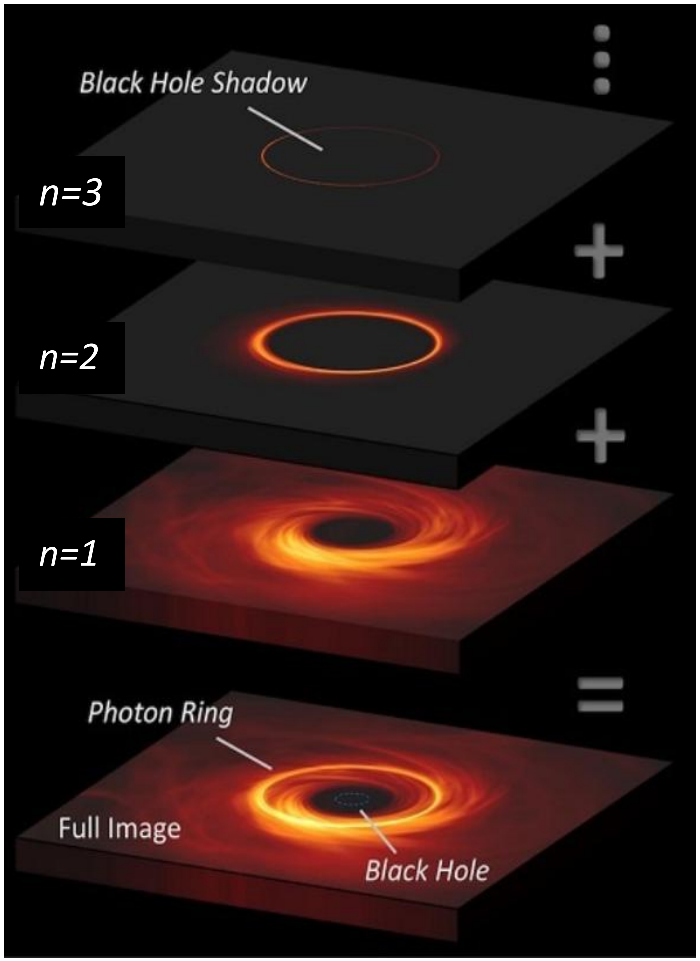
orbit numbers $n = \phi/(2\pi)$



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

1. Introduction

[*M.D. Johnson et.al, Sci.Adv. 6 (2020) 12, eaaz1310*]

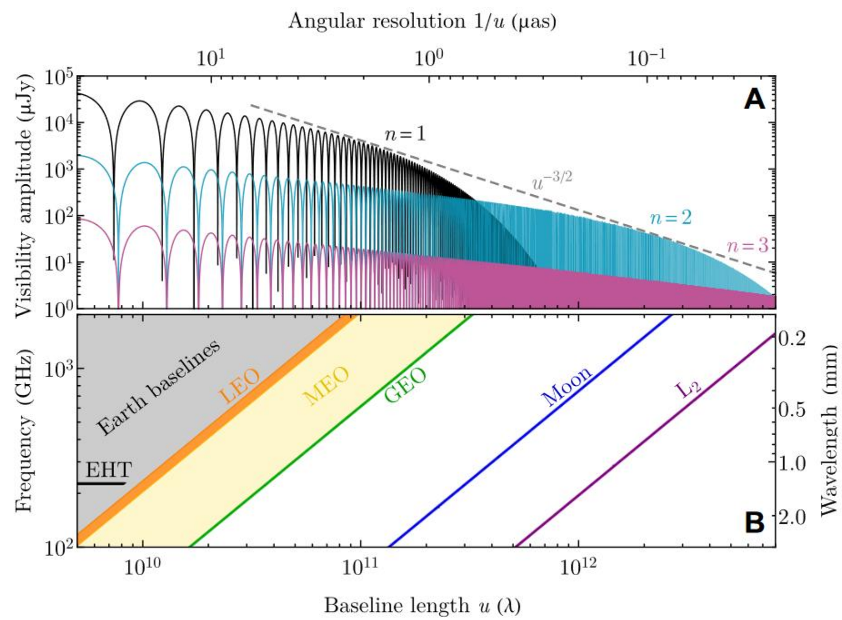


SCIENCE ADVANCES | RESEARCH ARTICLE

ASTRONOMY

Universal interferometric signatures of a black hole's photon ring

Detection of the photon ring's universal interferometric signatures requires measurements on longer baselines, with finer angular resolution than those currently available to the EHT.



The EHT observation of subrings becomes possible! To test gravity!

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2. Optical appearances of Horndeski hairy black hole

Does black hole hair have print on the optical appearance?
Test GR or Scalar-Tensor gravity?
Test no-hair theorem?

Rings and images of Horndeski hairy black hole illuminated by various thin accretions

Xi-Jing Wang, Xiao-Mei Kuang, Yuan Meng, Bin Wang, Jian-Pin Wu

[*Phys.Rev.D 107 (2023) 12, 124052, arXiv: 2304.10015*]

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

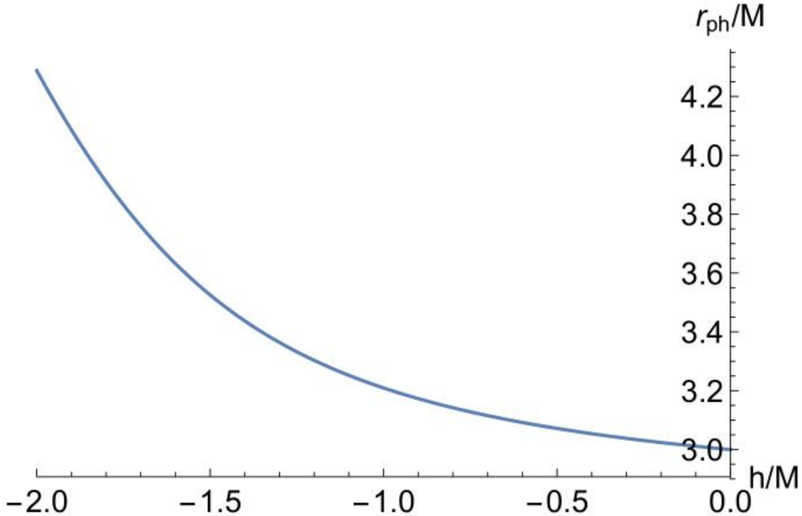
$$\text{with} \quad f(r) = 1 - \frac{2M}{r} + \frac{h}{r}\ln\left(\frac{r}{2M}\right).$$

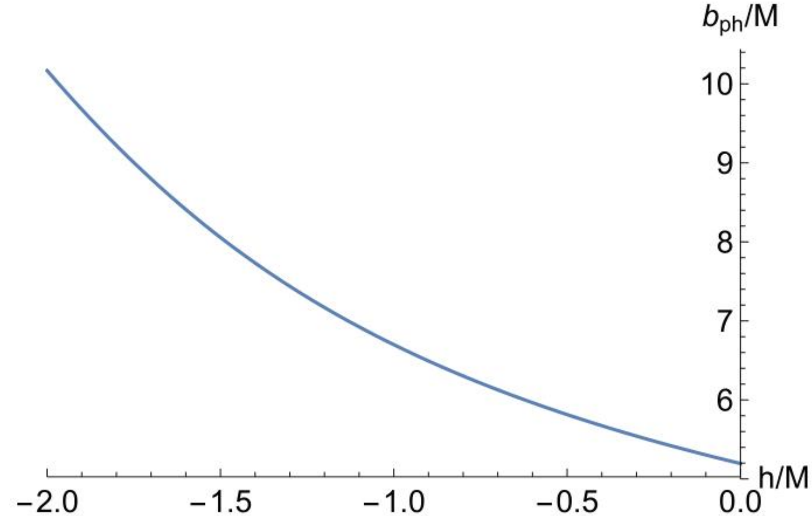
h: scalar hairy parameter

[*S.E.P. Bergliaffa et.al, arXiv: 2107.07839*]

2. Optical appearances of Horndeski hairy black hole

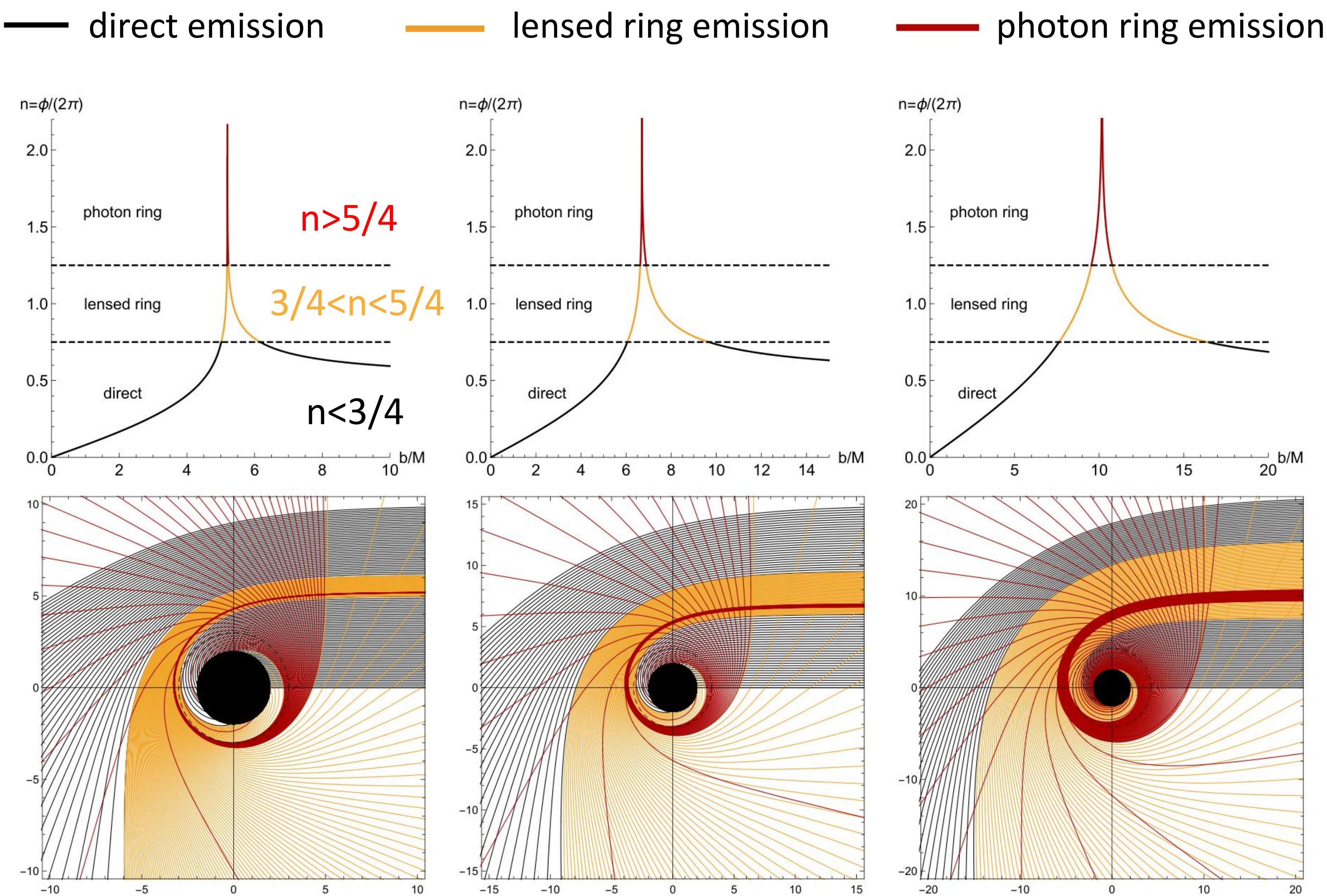
The radius of photon sphere r_{ph} and critical impact parameter b_{ph}





The radius of event horizon is always r_h = 2M.

2. Optical appearances of Horndeski hairy black hole



(a) $h = 0$ (b) $h = -1$ (c) $h = -2$

2. Optical appearances of Horndeski hairy black hole

Specific intensity received by the observer

$$I_o(r,\nu_o) = g^3 I_e(r,\nu_e)$$

The total observed intensity

$$I_{obs}(r) = \int I_o(r,\nu_o) d\nu_o = \int g^4 I_e(r,\nu_e) d\nu_e = f(r)^2 I_{em}(r)$$

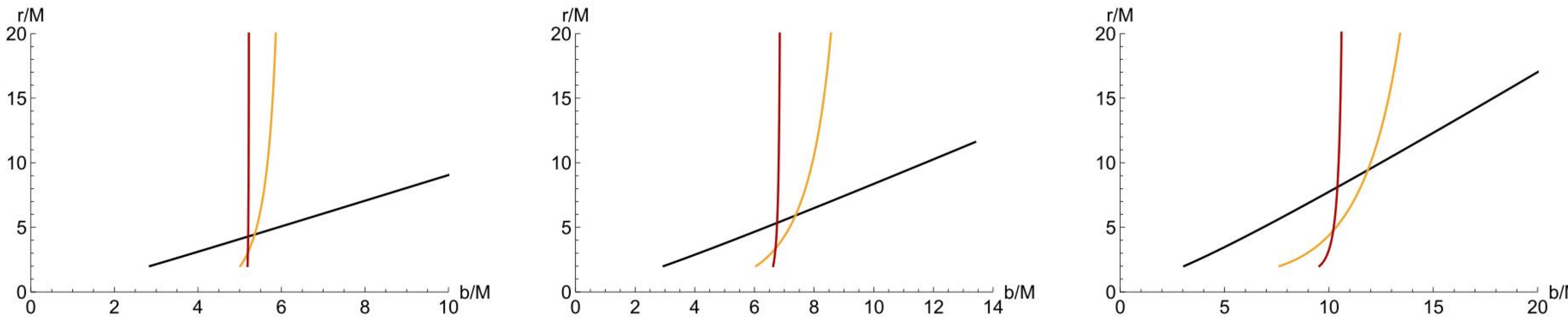
If the trajectory of photon followed backward from the observer intersects the disk, the different types of the photon depended on the light ray's impact parameter *b* will extract energy from the thin accretion disk and contribute the different brightness to the observer, so

$$I_{obs} = \sum_m f(r)^2 I_{em}(r)|_{r=r_m(b)}, \;\; r_m(b) \; : \text{ transfer function}$$

A transfer function directly shows where on the disk a light ray of impact parameter will hit.

2. Optical appearances of Horndeski hairy black hole

transfer function: m=1
m=2
m=3

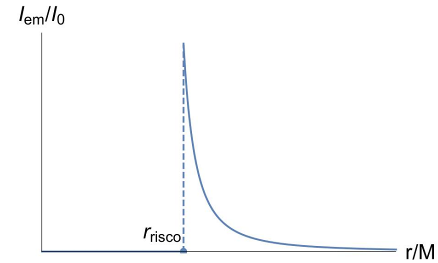


(a) $h = 0$ (b) $h = -1$ (c) $h = -2$

2. Optical appearances of Horndeski hairy black hole

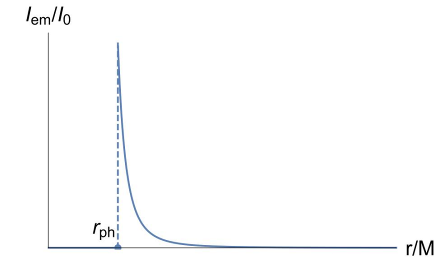
accretion disk emission profile: three toy-model

$$\text{profile 1:}\quad I_{em}(r) := \begin{cases} I_0\left[\frac{1}{r-(r_{isco}-1)}\right]^2, & r > r_{isco} \\ 0, & r \leqslant r_{isco} \end{cases}$$



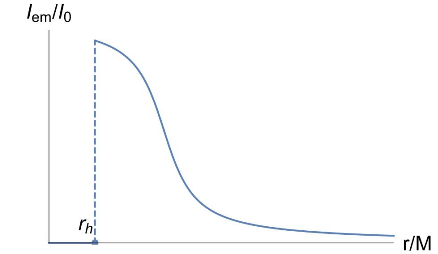
profile 1

$$\text{profile 2:}\quad I_{em}(r) := \begin{cases} I_0\left[\frac{1}{r-(r_{ph}-1)}\right]^3, & r > r_{ph} \\ 0, & r \leqslant r_{\rm ph} \end{cases}$$



profile 2

$$\text{profile 3:}\quad I_{em}(r) := \begin{cases} I_0\frac{\frac{\pi}{2}-\arctan[r-(r_{isco}-1)]}{\frac{\pi}{2}-\arctan[r_h-(r_{isco}-1)]}, & r > r_h \\ 0, & r \leqslant r_h \end{cases}$$

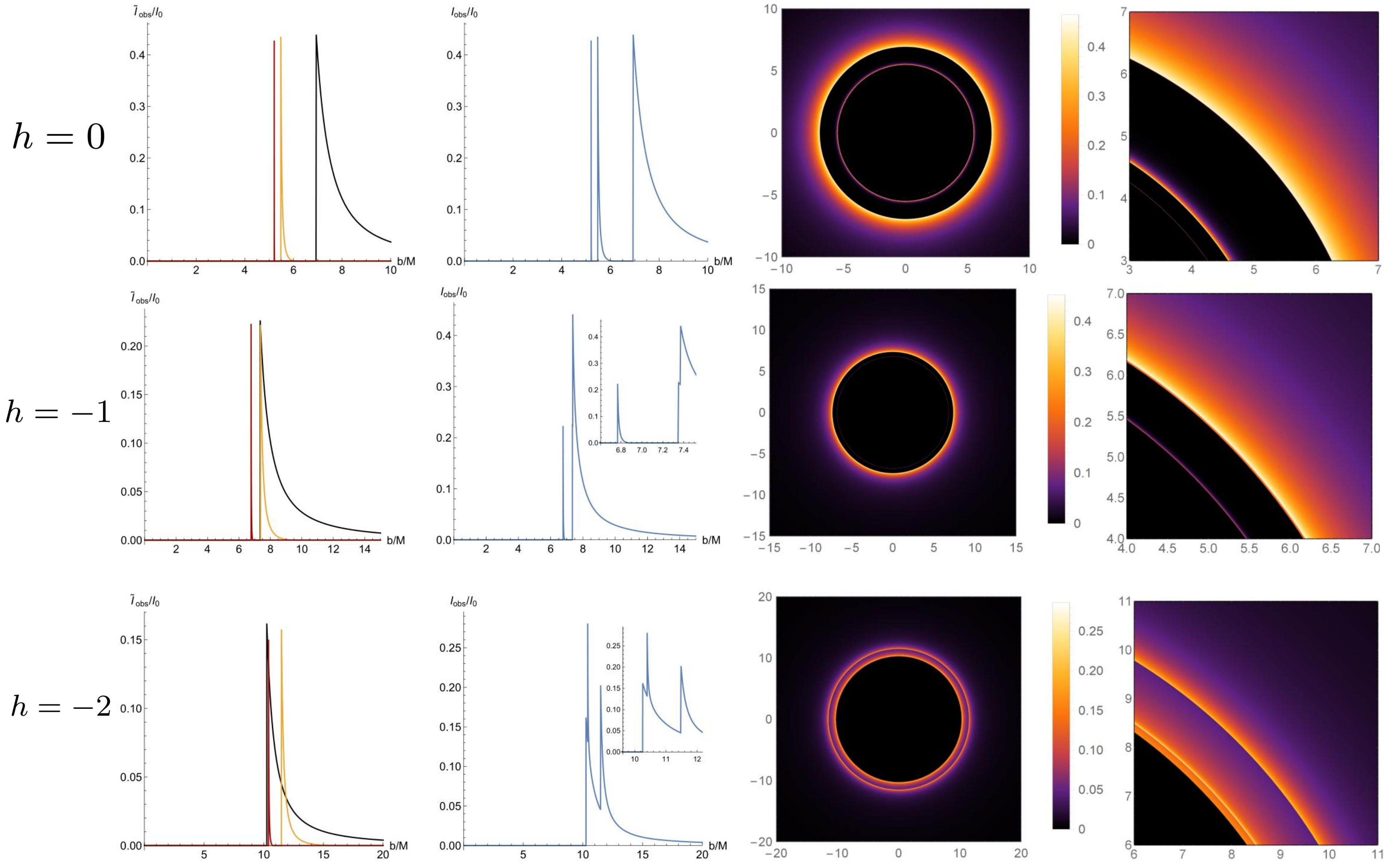


(c) profile 3

I_0 is the maximum intensity

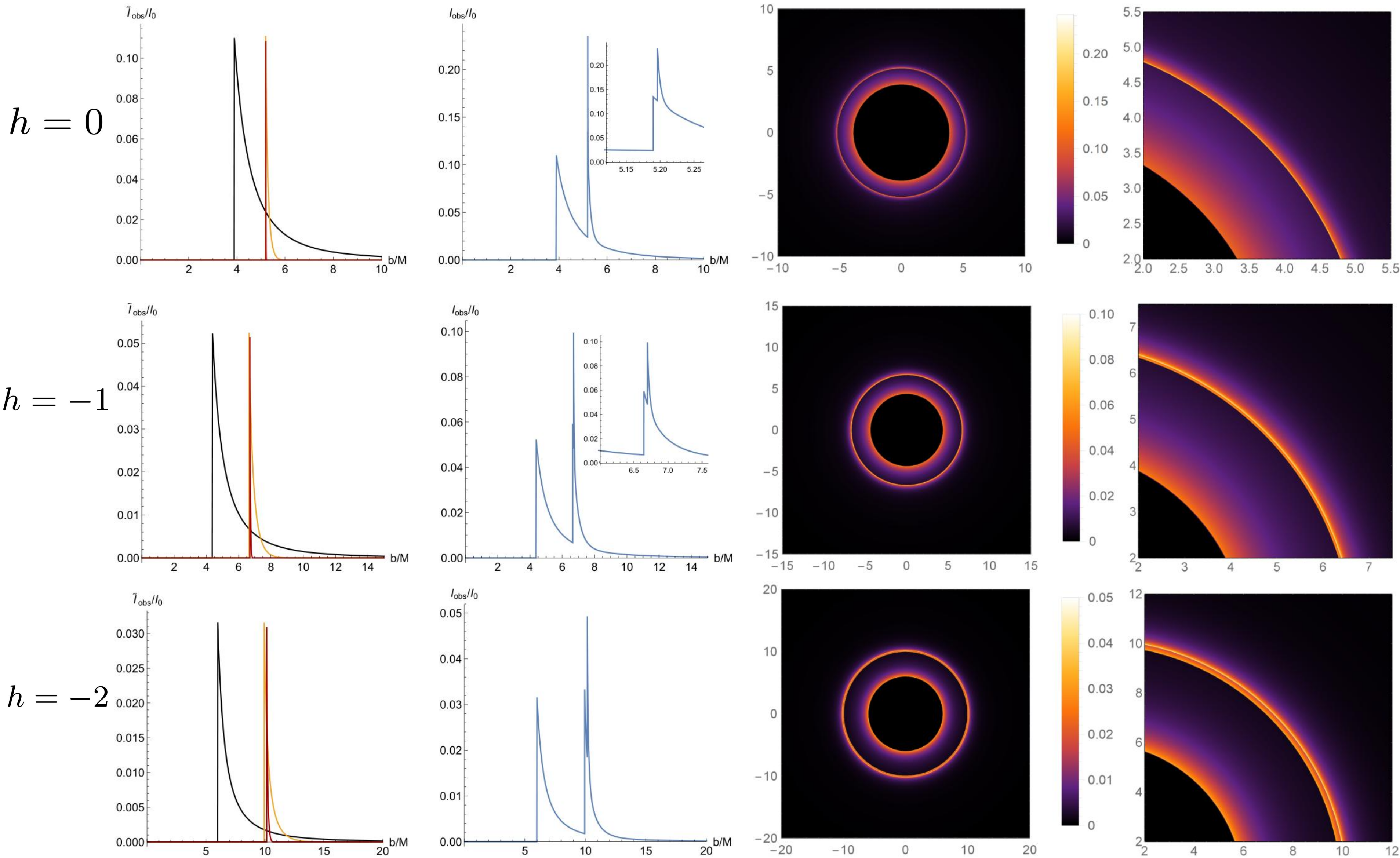
2. Optical appearances of Horndeski hairy black hole

profile 1 — : m=1 : m=2 : m=3



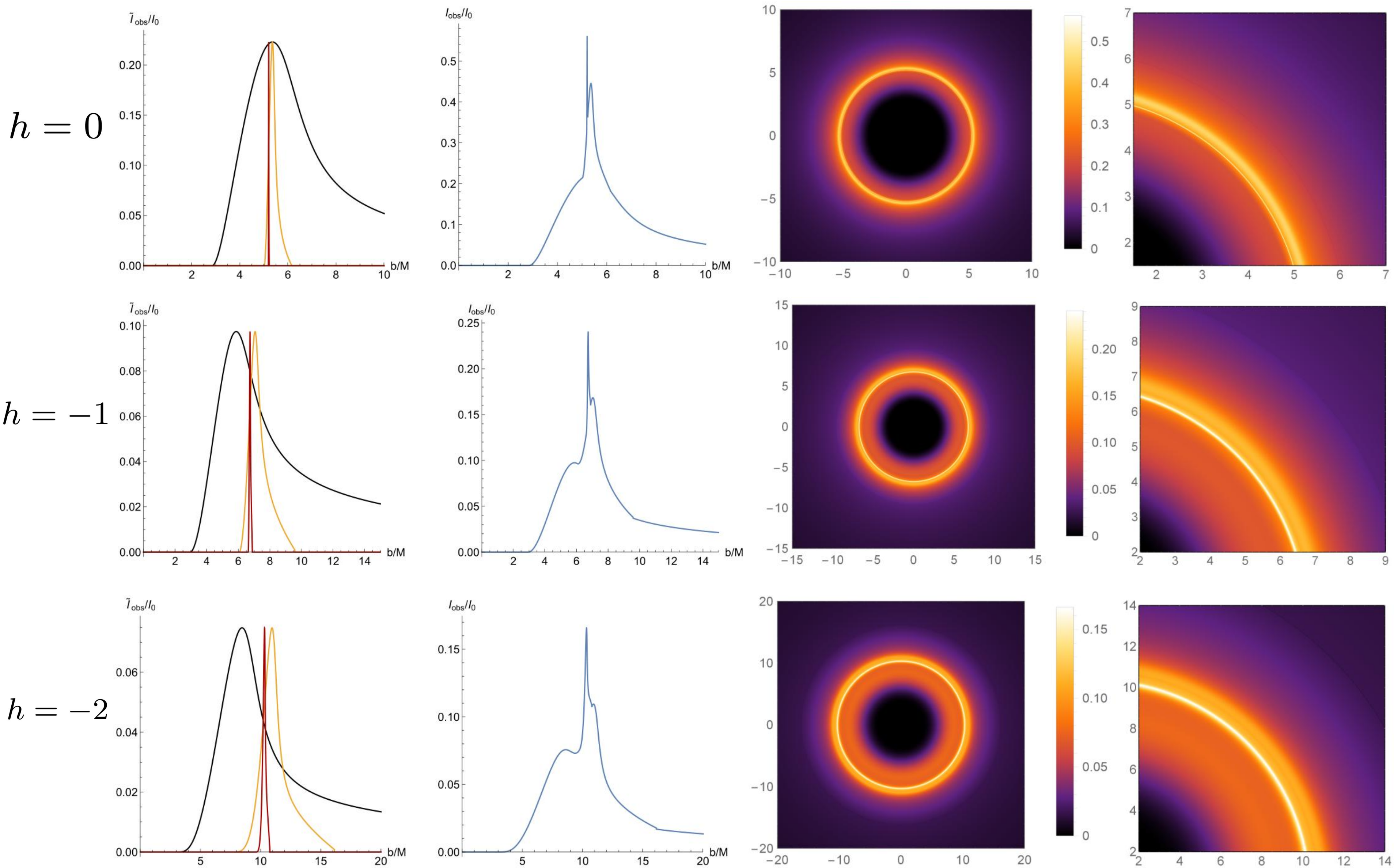
2. Optical appearances of Horndeski hairy black hole

profile 2 : m=1 : m=2 : m=3



2. Optical appearances of Horndeski hairy black hole

profile 3 — : m=1 : m=2 : m=3



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4. Summary and outlook

- We investigate the optical appearances of the Horndeski hairy black hole surrounded by the thin accretion disk.

- The black hole hair could significantly affect the brightness distribution which can be arbitrary combinations among intensity of different orders of emissions.

- This study provides potential way to distinguish Horndeski hairy black hole from static black hole in GR. We expect that these preliminary results could shed light on the future test of no-hair theorem using black hole images.

Thanks!

Speaker: Xi-Jing Wang (王熹景)

Reference: *arXiv: 2304.10015*

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