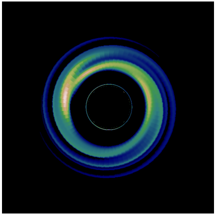
M87*: black hole or not?

What can be inferred from “black hole images”.

Frédéric Vincent[1]

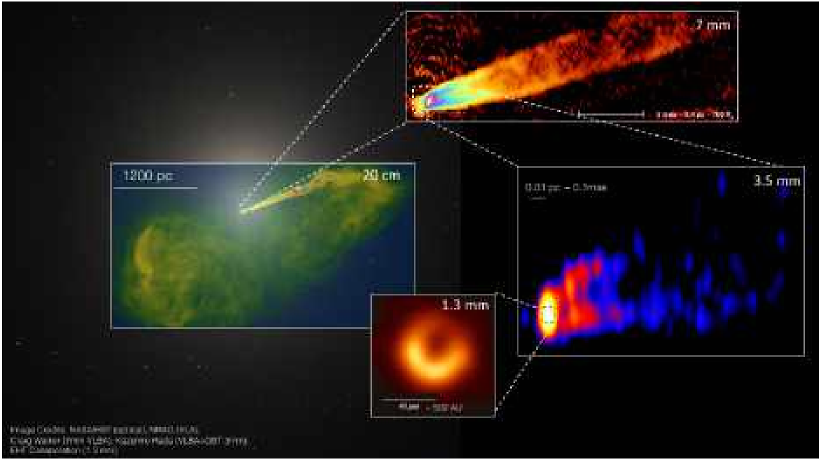
M. Wielgus, M. Abramowicz, E. Gourgoulhon,
J.-P. Lasota, T. Paumard, G. Perrin

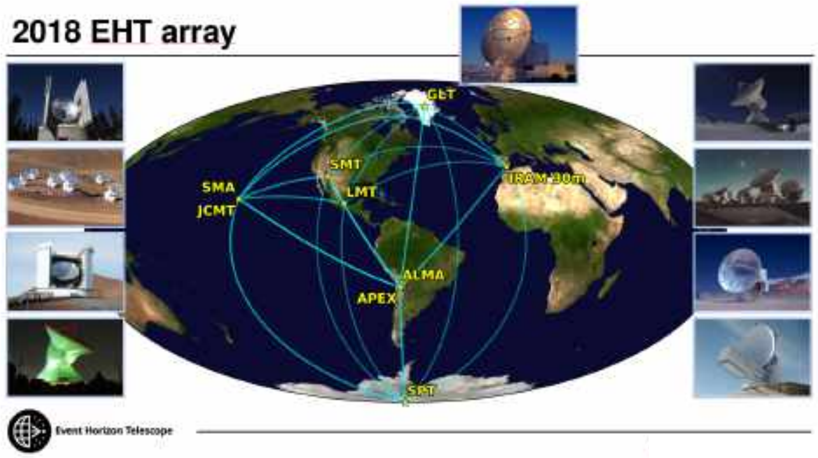
[1]CNRS/Observatoire de Paris/LESIA



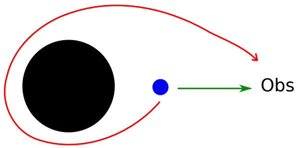
1. The goal of this talk
2. Strongly-lensed image features
3. Geometric modeling of M87*
4. Alternatives to Kerr

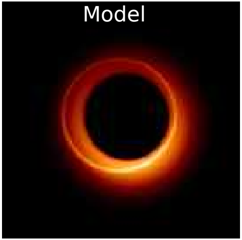
M87: low-luminosity galactic nucleus with kpc jet



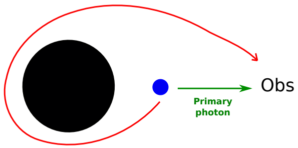


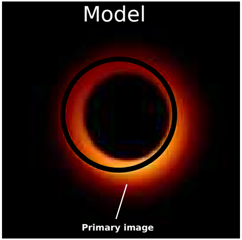
EHT: an array of millimeter antennas


Obs

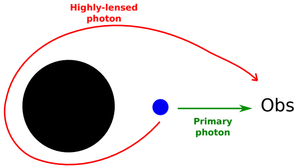

Model

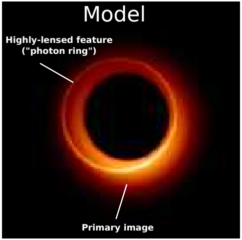

EHT image


Obs
Primary
photon

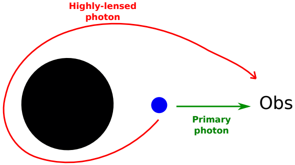

Model
Primary image

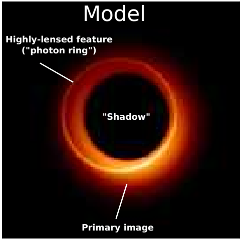

EHT image


Highly-lensed
photon
Primary
photon
Obs


Model
Highly-lensed feature
("photon ring")
Primary image


EHT image





Testing BH paradigm from EHT image

- EHT goal: detect “shadow”, “photon ring”
- My goal 1: provide precise (new?) definitions of these
- My goal 2: can we use them to tell a black hole?

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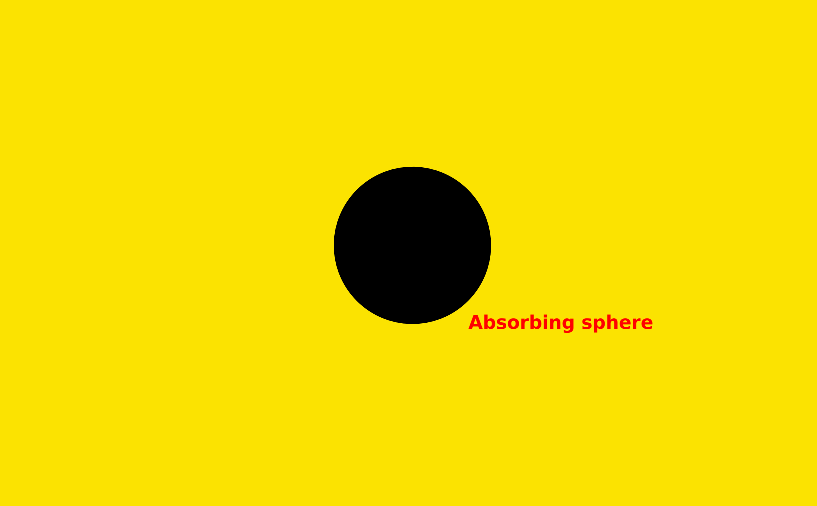
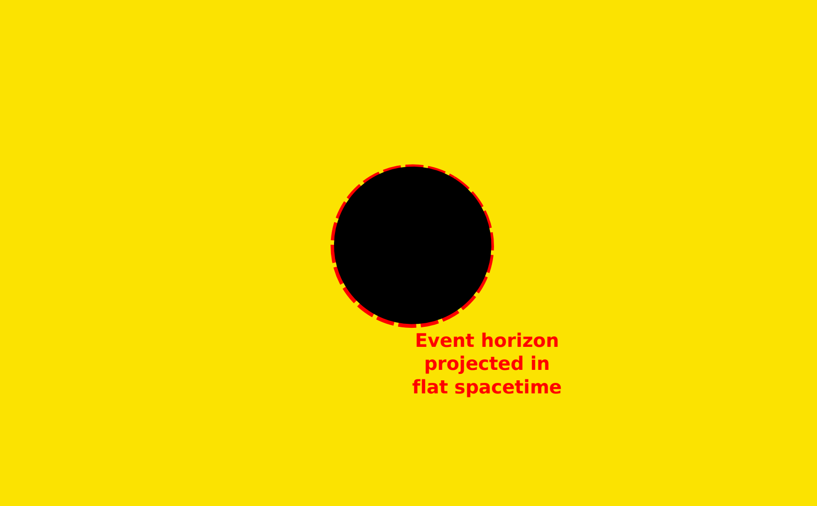
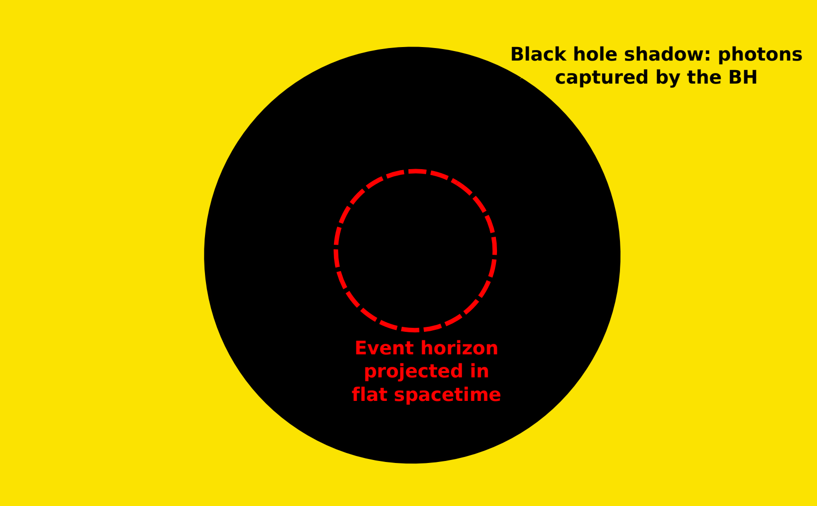
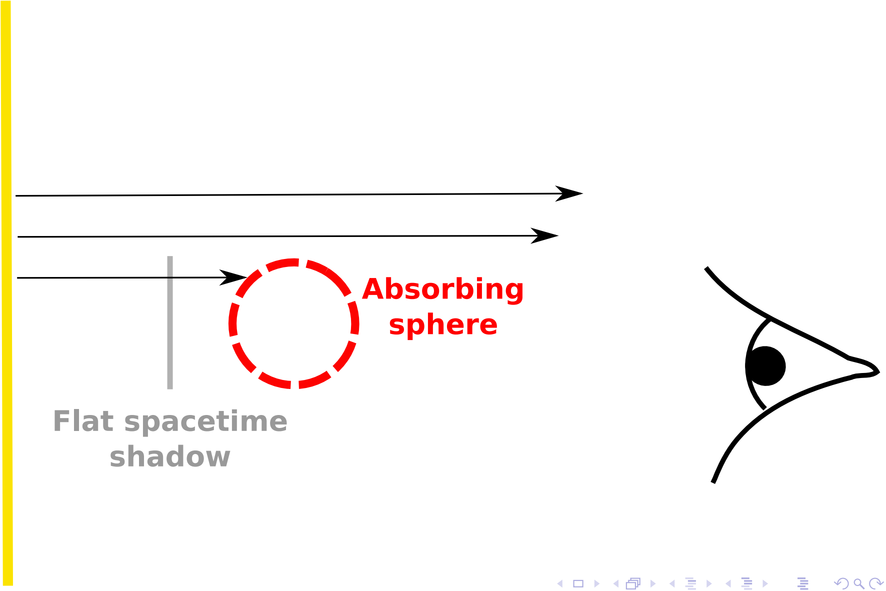
Shadow/photon ring: simple introduction


Absorbing sphere

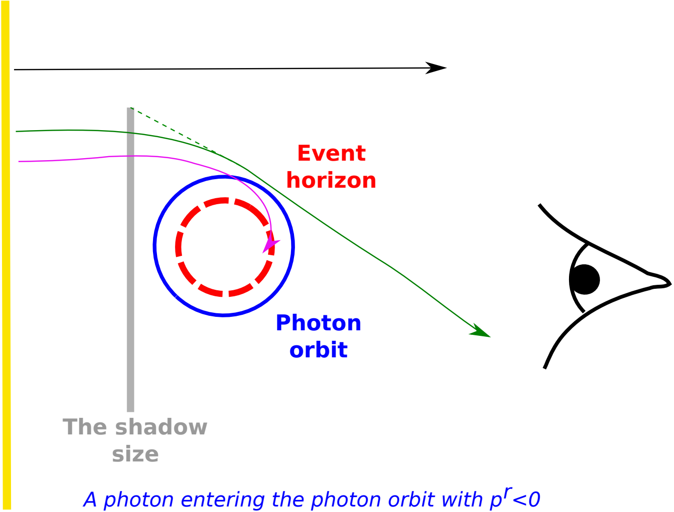

Event horizon
projected in
flat spacetime


Black hole shadow: photons
captured by the BH
Event horizon
projected in
flat spacetime

Flat spacetime shadow



Black hole shadow



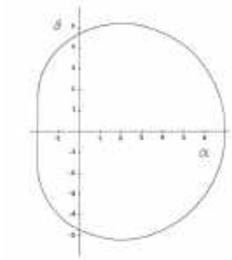
A photon entering the photon orbit with $p^r<0$ will fall into the event horizon.
So the boundary of the shadow coincides with the image of the photon orbit, called the ***photon ring****.*

Shadow/photon ring: theory definition

Shadow and photon ring

- Pure-gravitation, no-dirty-astrophysics definitions
- Great probes of gravity!

Black hole shadow in real life



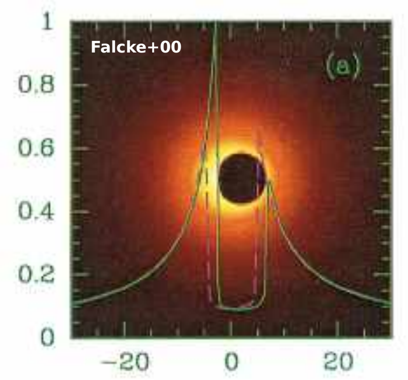
Bardeen 1972

Luminet 1979

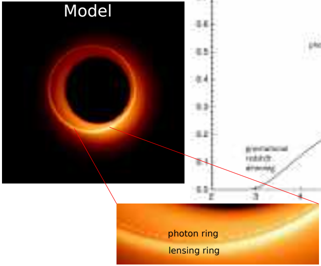
Marck 1996

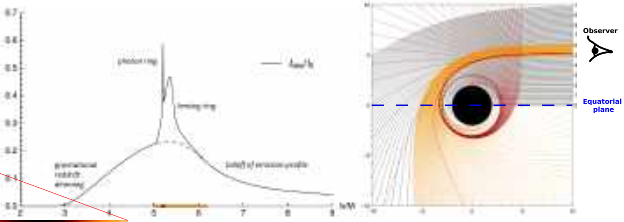
Riazuelo 2007

Black hole shadow in real life



Observing the shadow: EHT



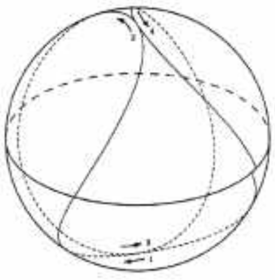


Gralla+19

A more precise definition

- What is the highly-lensed ring in the theory image?
- Gralla+19: lensing ring ($n_{\rm cross} = 2$), photon ring ($n_{\rm cross} > 2$)
- This is still pure-gravitation definition

Spherical orbit (Teo 2003)

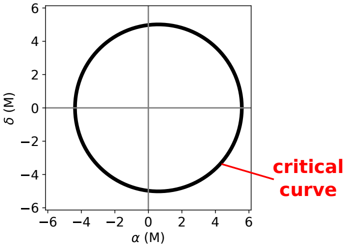


project

→

on sky

Sky projection (Johnson+20)



Spherical photon orbits

- Winding of photons → **spherical photon orbits**
- Critical curve = image on sky of spherical photon orbits i.e. of $n_{\rm cross} = \infty$ photons
- Recap: $n_{\rm cross} = 1$ primary image; $n_{\rm cross} = 2$ lensing ring; $n_{\rm cross} = 3+$ photon ring; $n_{\rm cross} = \infty$ critical curve... what else?

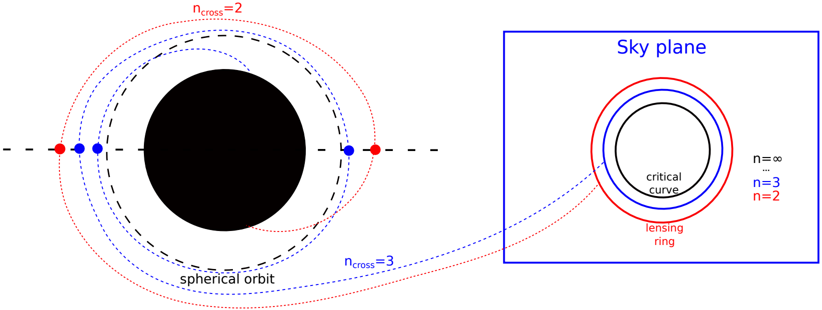


Image spectroscopy

- Highly-lensed feature of BH image = infinite set of pure-gravity-dictated subrings on sky
- *Theoretical locus* on sky, not directly observable
- The *flux distribution* within this locus is not pure gravity

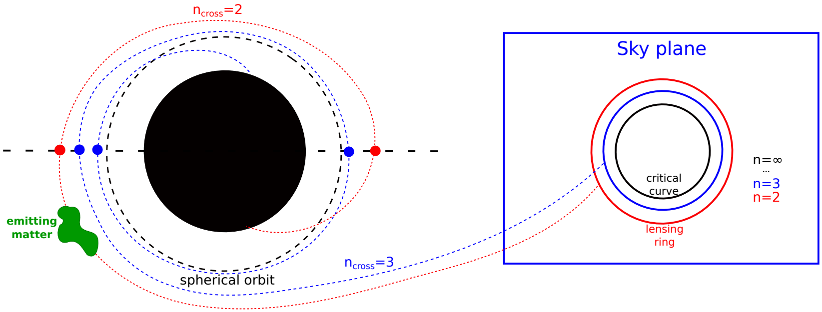
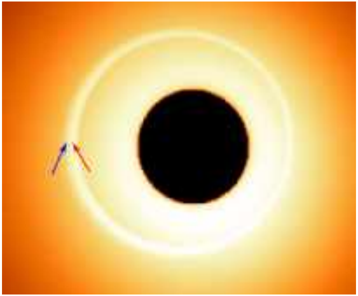
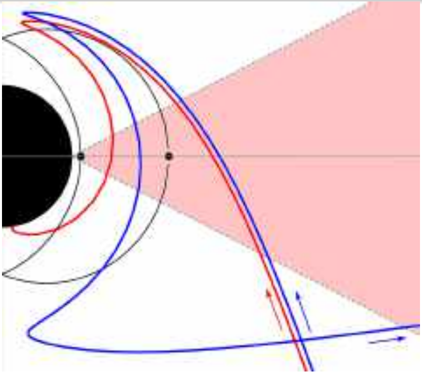


Image spectroscopy

- Observable = subset **where there is emission**
- **Secondary ring**: the part of these subrings where there is detectable flux (model-dependent)
- Well-posed question: what is the secondary ring of *that* BH surrounded by *that* particular accretion model?





Model-dependent definition

- Observable feature = geodesics approach spherical orbits **and** visit the innermost regions of the flow
- We call such a feature the *secondary ring*
- Shadow = geodesics asymptotically approaching horizon **and** not visiting the flow

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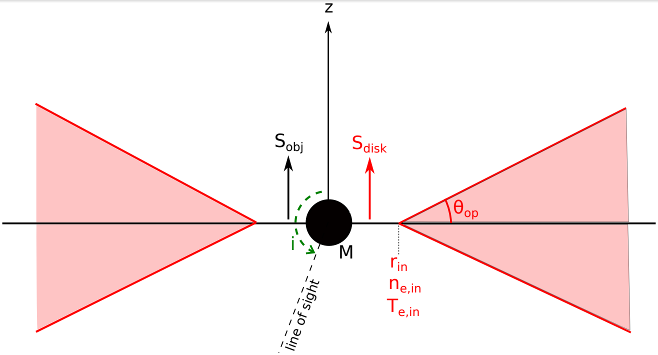
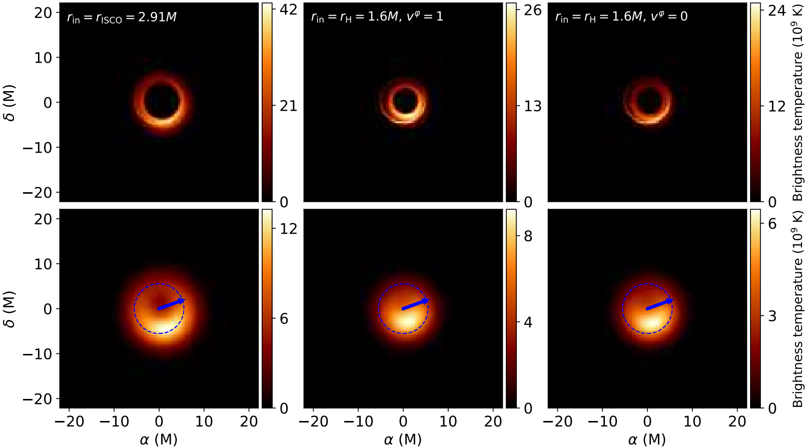


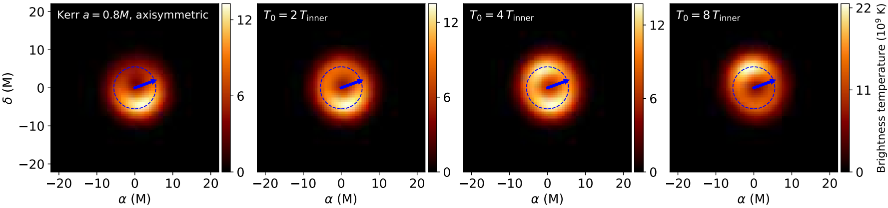
Accretion flow model

- Geometry: $r_{\rm in}$, $\theta_{\rm op}$
- Physics: $n_{e,\rm in}$, $T_{e,\rm in}$, $\sigma \propto B^2/n_e$
- Emission: synchrotron radiation
- Velocity: Keplerian above ISCO

  Below: radial or azimuthal flow



$r_{in} = r_{ISCO} = 2.91M$
$r_{in} = r_H = 1.6M,\ v^\varphi = 1$
$r_{in} = r_H = 1.6M,\ v^\varphi = 0$
δ (M)
α (M)
Brightness temperature (10^9 K)



Non-axisymmetric blob

- Temperature profile $T(\rho, \varphi) = T_{\rm axisym}(\rho) + T_0\, G(\rho, \varphi)$ where G is a 2D Gaussian
- Factor ≈ 10 needed on T

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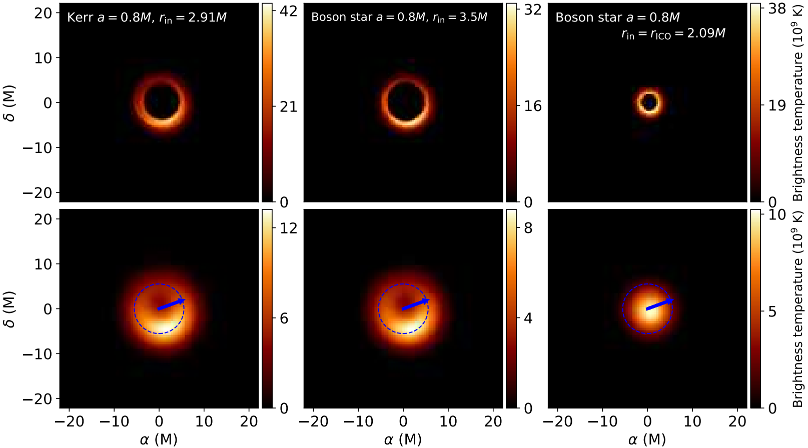
Does M87* have an event horizon?

- Rotating **boson star**

  Assembly of spin-0 boson (e.g. Higgs)

  Behaves as a single quantum body

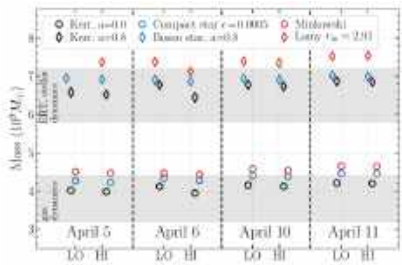
  Does not collapse because of Heisenberg principle
- No hard surface, **no event horizon**, no singularity
- **No photon spherical orbits** to avoid stability issues



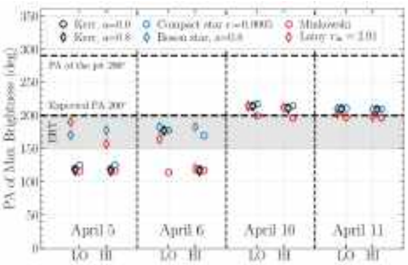
Does M87* have an event horizon?

- Difference only due to MHD on current images
- Future: tell the secondary ring?

Bestfit mass

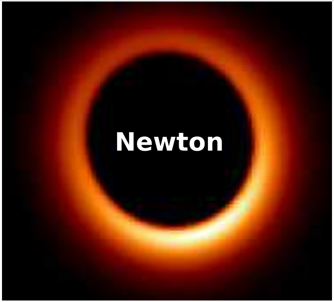


Bestfit position angle



EHT fitting

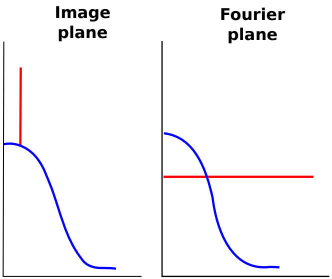
- Results reasonably consistent with EHT
- Fit quality similar to GRMHD snapshots
- Analytical model $\approx$ averaged GRMHD



Detecting sharp features (inspired by Johnson+20)

- Image = Gaussian primari + sharp feature
- FT = Gaussian + flat
- So sharp feature should dominate at high freq
- Seen in Schwarzschild vs. “Newtonian BH”
- Not in Kerr vs. boson star

  probably because Sch ring more distinct



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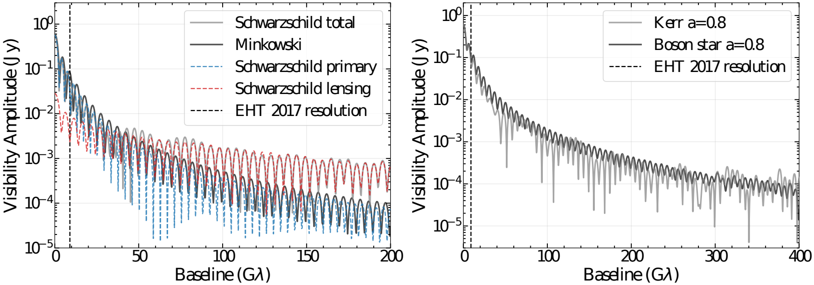

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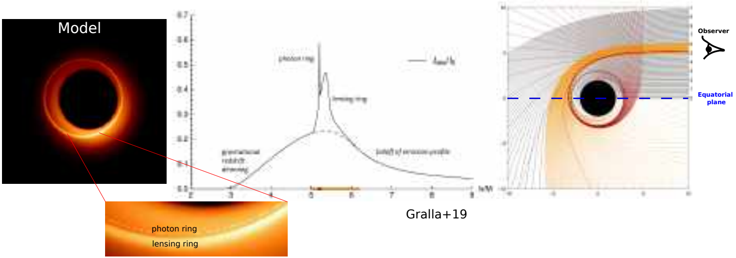


Gralla+19

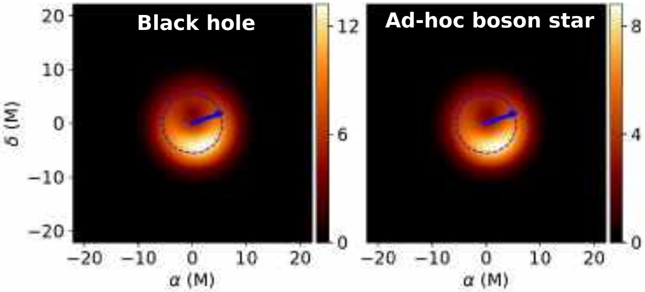
Conclusion: highly-lensed features

- Published terminology for highly-lensed features:

  lensing ring ($n_{\rm cross} = 2$), photon ring $n_{\rm cross} > 2$, photon subrings, critical curve $n_{\rm cross} = \infty$. Pure gravitation.
- We introduce:

  secondary ring = all subrings

  AND depends on emission model (**not pure gravitation**)
- Theoretical locus on sky $\neq$ observable



Conclusion: compact object nature

- There is no “clean”, “pure-gravitation” probe
- You must trust plasma physics to test the nature of a compact object
- Fascinating (but not fully clear yet) perspective: distinguish sharp features (space VLBI)