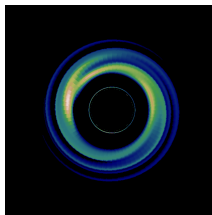


Using light to probe the vicinity of supermassive black holes

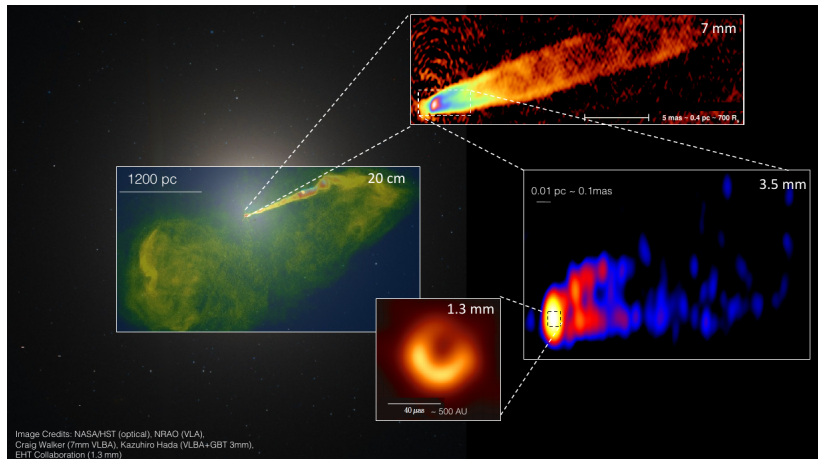
Frédéric Vincent¹

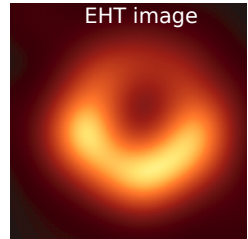
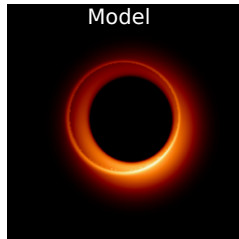
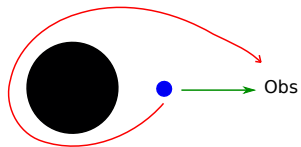
¹CNRS/Observatoire de Paris/LESIA

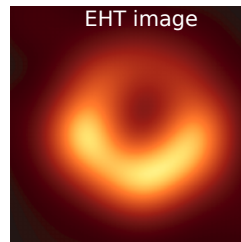
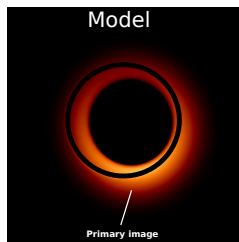
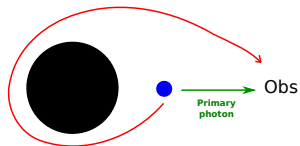


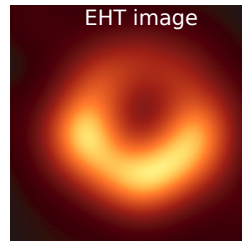
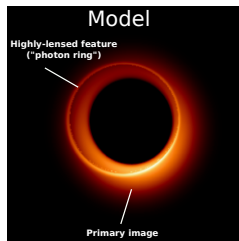
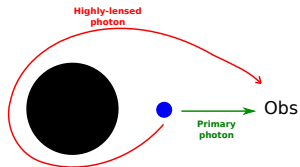
- 1 The goal of this talk
- 2 Strongly-lensed image features
- 3 Observing the secondary ring
- 4 Imaging BHs and alternatives

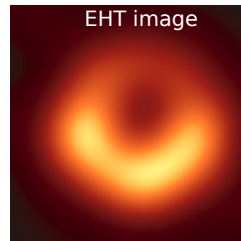
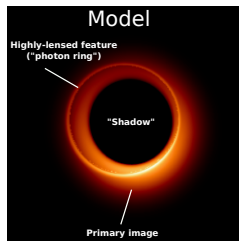
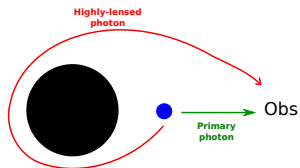
M87: low-luminosity galactic nucleus with kpc jet











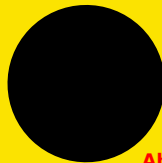
Testing BH paradigm from EHT-like image

- Definitions of “photon ring” and “shadow”
- Can we use these notions to test BH paradigm?

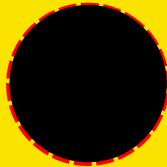
- 1 The goal of this talk
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Shadow/photon ring: simple introduction

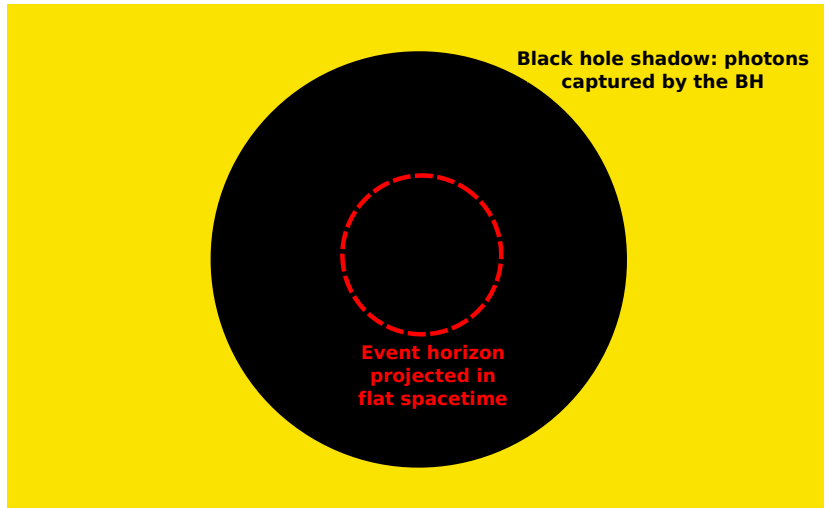




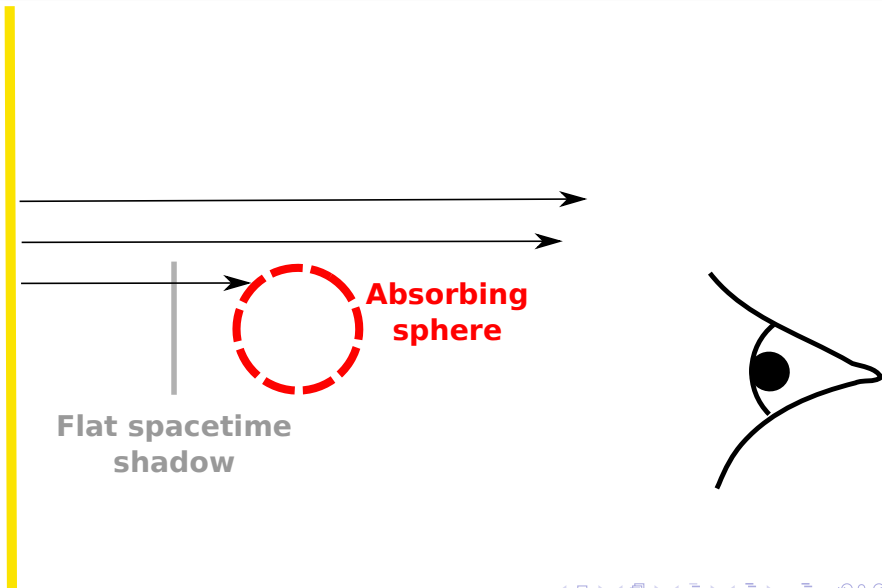
Absorbing sphere



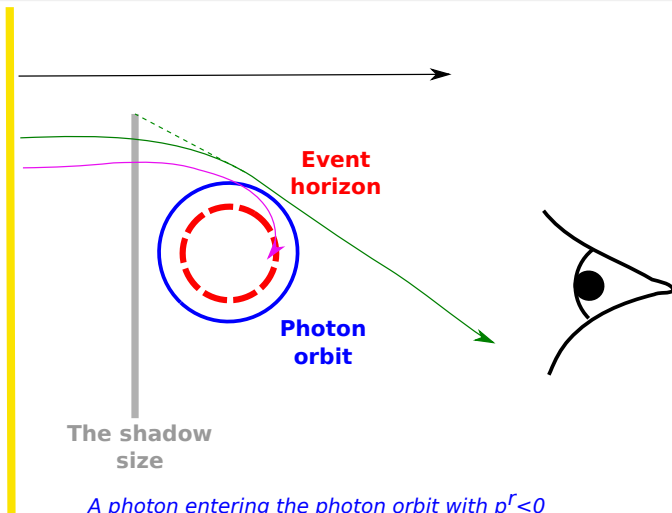
**Event horizon
projected in
flat spacetime**



Flat spacetime shadow

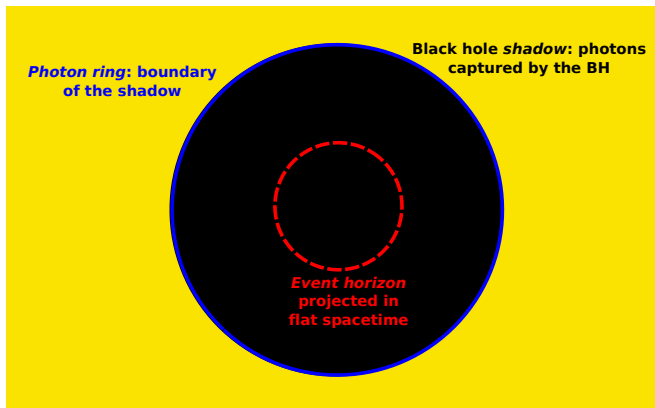


Black hole shadow



*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**.*

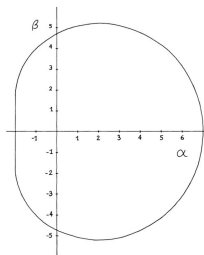
Shadow/photon ring: theory definition



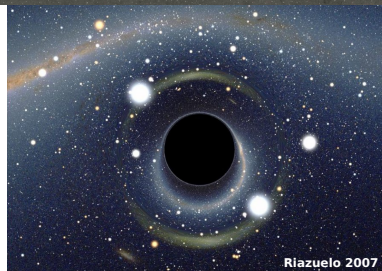
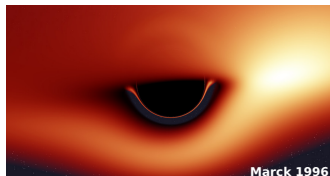
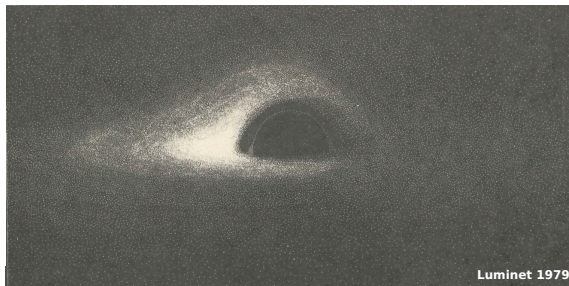
Shadow and photon ring

- Pure-gravitation, no-dirty-astrophysics definitions
- Great probes of gravity!... Really? To what extent?

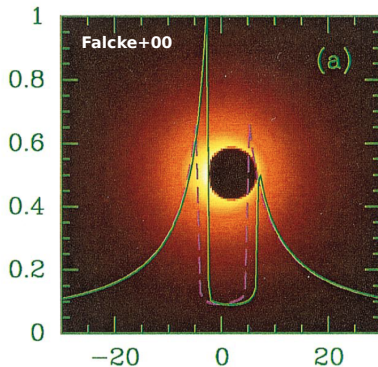
Black hole shadow in real life



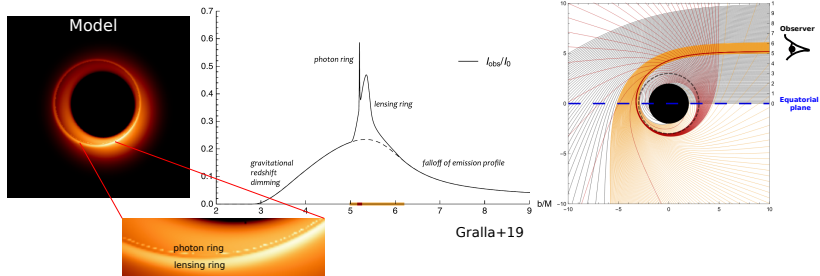
Bardeen 1972



Black hole shadow in real life



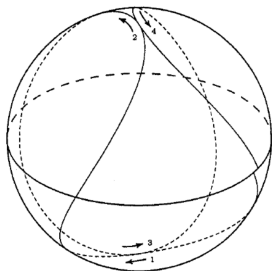
Observing the shadow: EHT



A more precise definition

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

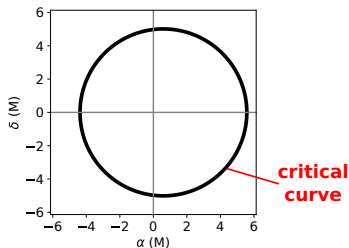
Spherical orbit (Teo 2003)



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 $n_{\text{cross}} = \infty$ photons
- Recap: $n_{\text{cross}} = 1$ primary image; $n_{\text{cross}} = 2$ lensing ring;
 $n_{\text{cross}} = 3+$ photon ring; $n_{\text{cross}} = \infty$ critical curve...
what else?

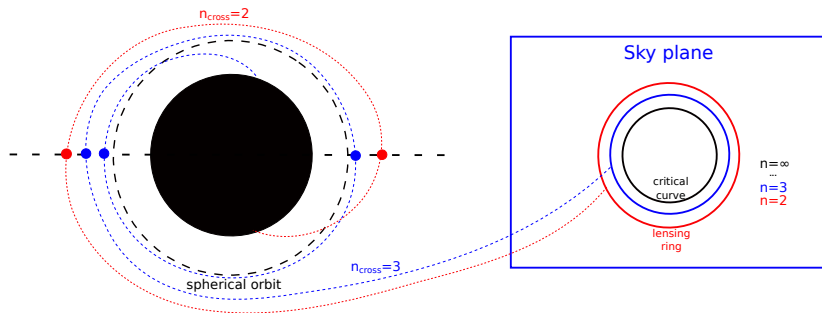
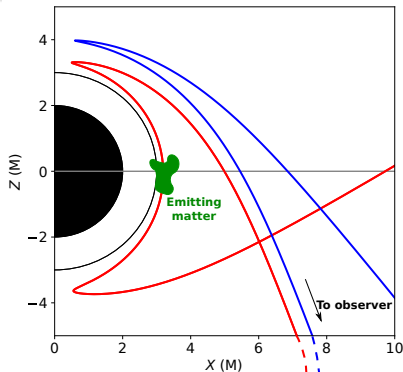


Image spectroscopy

- 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



Observer sky plane

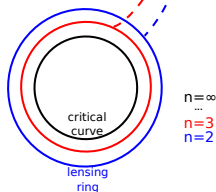
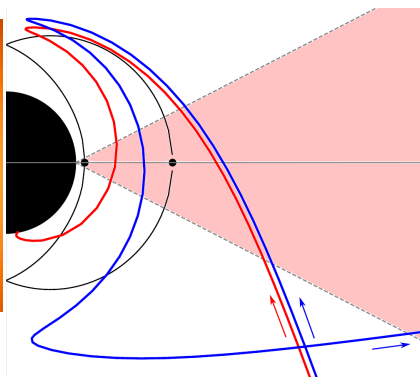
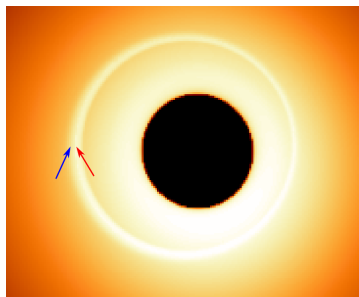


Image spectroscopy

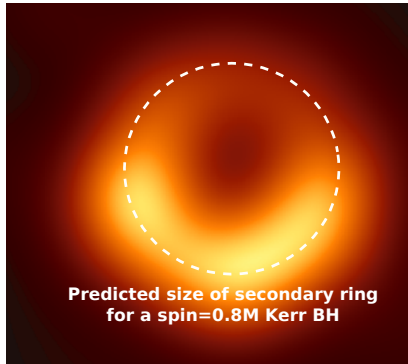
- Observable = subset **where there is emission**
- **Secondary ring**: the part of these subrings where there is detectable flux (model-dependent)
- Well-posed question: what is the secondary ring of *that* BH surrounded by *that* particular accretion model?



Model-dependent definition

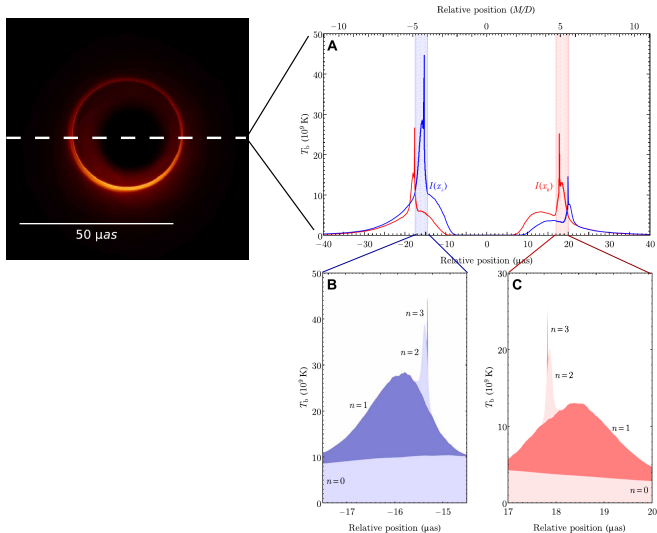
- Shadow = geodesics asymptotically approaching horizon **and** not visiting the flow

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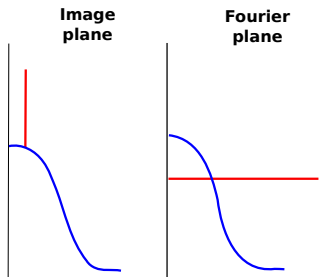


Today's observations

- EHT image *consistent* with Kerr secondary ring
- But also consistent with a lot of other things...

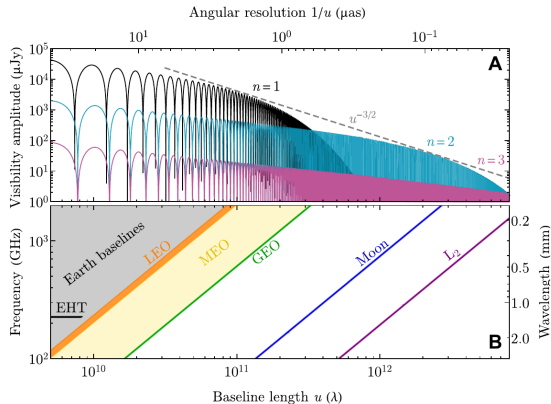


Johnson+20, Sci. Adv., 6, 12



Detecting sharp features

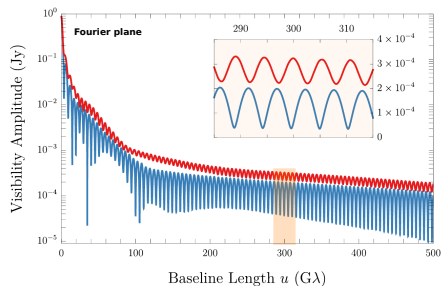
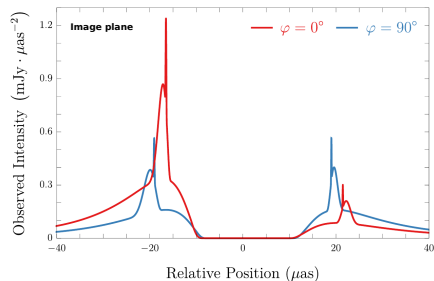
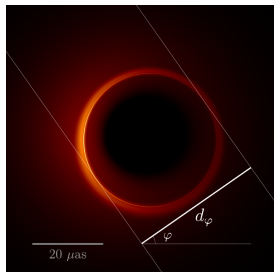
- Image = Gaussian primari + sharp feature
- FT = Gaussian + flat
- So sharp feature should dominate at high freq



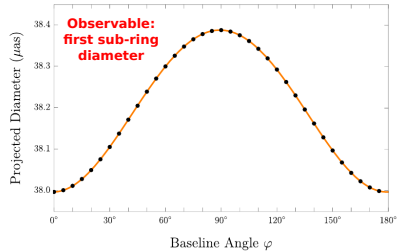
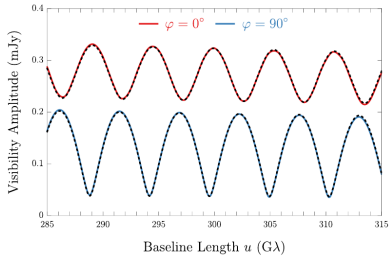
Johnson+20, Sci. Adv., 6, 12

Tomorrow's observations

- Different rings dominate at different baselines
- Observable question: Are there thin rings?
- This is still not a test of GR



Gralla+20, arXiv:2008.03879



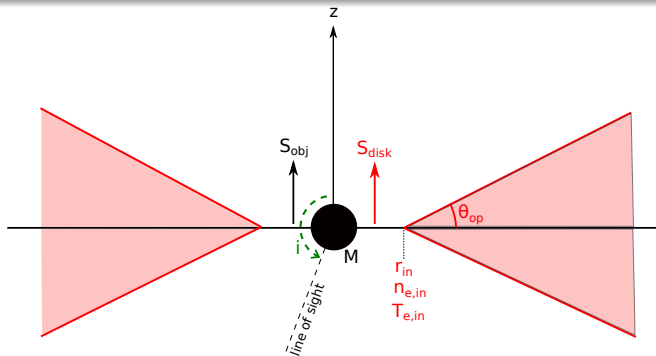
$$|V| = \frac{1}{\sqrt{u}} \sqrt{\underbrace{(\alpha_\varphi^L)^2 + (\alpha_\varphi^R)^2}_{\text{parameters linked to intensity profile}} + 2\alpha_\varphi^L \alpha_\varphi^R \sin(2\pi d_\varphi u)}.$$

Gralla+20, arXiv:2008.03879

Fitting sub-ring diameters

- Still a *consistency* check
- Is it a test of GR?
- Very likely that other theories would lead to similar profiles

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Accretion flow model

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

Does M87* have an event horizon?

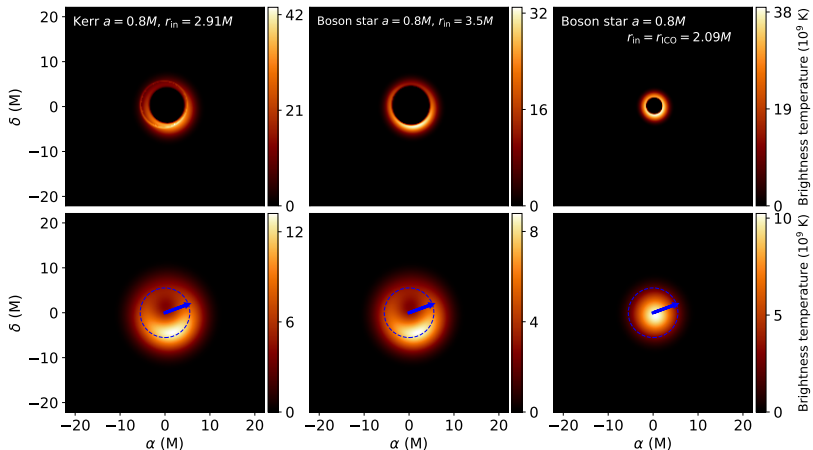
- Rotating **boson star**

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

Behaves as a single quantum body

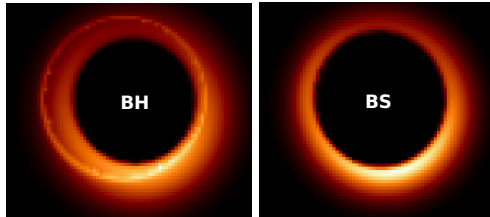
Does not collapse because of Heisenberg principle

- No hard surface, **no event horizon**, no singularity
- **No photon spherical orbits** to avoid stability issues



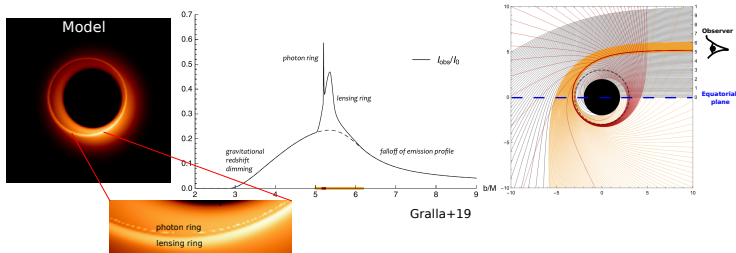
Does M87* have an event horizon?

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



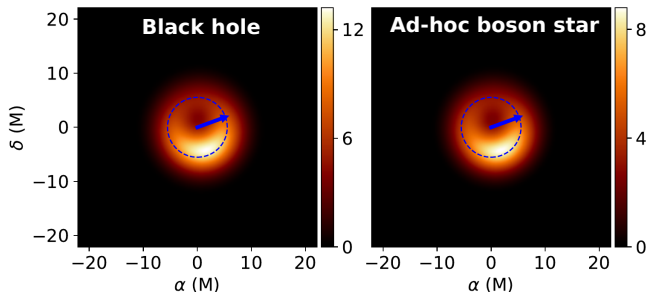
Detecting sharp features (inspired by Johnson+20)

- Investigate the high-freq difference
- ... in progress



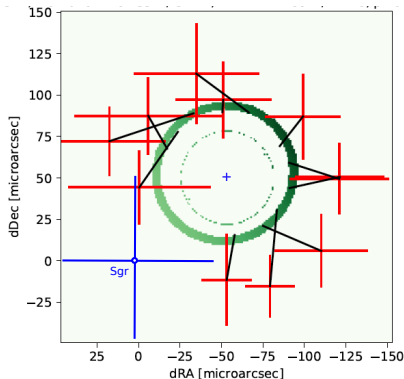
Conclusion: highly-lensed features

- Published terminology for highly-lensed features:
lensing ring ($n_{\text{cross}} = 2$), photon ring $n_{\text{cross}} > 2$, photon subrings, critical curve $n_{\text{cross}} = \infty$. 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)



GRAVITY Collaboration, A&A 618, L10 (2018)

Conclusion: GRAVITY

- Orbital motion near horizon of Sgr A*
- Another fascinating probe of near-horizon physics