M87*: black hole or not? What can be inferred from “black hole images”.

Frédéric Vincent


1CNRS/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
Intro

High-order image

Model

Alternatives

EHT image

Model

Obs

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M87*: Kerr or alternative?
Intro
High-order image
Model
Alternatives

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

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

Absorbing sphere

Flat spacetime shadow

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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 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

M87*: Kerr or alternative?
Black hole shadow in real life

Observing the shadow: EHT

Falcke+00
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 photon orbits

- Winding of photons $\rightarrow$ **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
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: $r_{\text{in}}, \theta_{\text{op}}$
- 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
Intro High-order image Model Alternatives

$r_{in} = r_{ISCO} = 2.91M$
$r_{in} = r_{H} = 1.6M, v = 1$
$r_{in} = r_{H} = 1.6M, v = 0$

Brightness temperature (10^9 K)

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Intro

High-order image

Model

Alternatives

Non-axisymmetric blob

- Temperature profile \( T(\rho, \varphi) = T_{\text{axisym}}(\rho) + T_0 \, G(\rho, \varphi) \)

  where \( G \) is a 2D Gaussian

- Factor \( \approx 10 \) 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?
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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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)