EfFOORTlessly simulating observable signatures of microstructure in black hole imaging
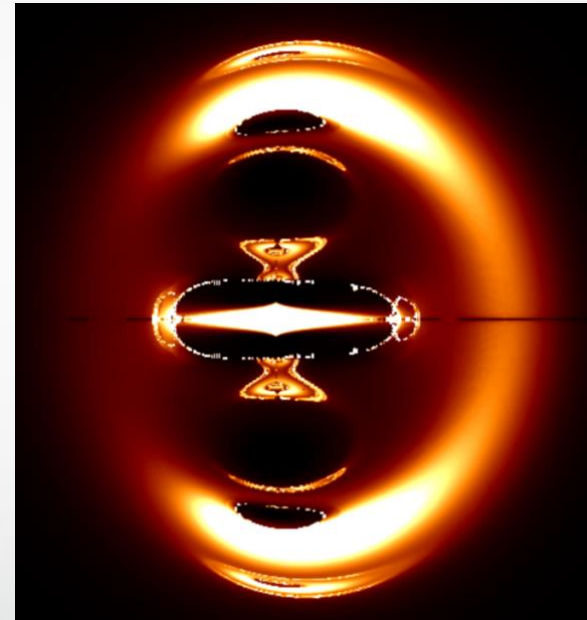
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"New horizons for (no-)horizon physics:
From gauge to gravity and back II"
GGI, Florence - April 19th, 2023

- *[2303.02111]* *with Seppe Staelens, Fabio Bacchini,*
  Bart Ripperda, Lorenzo Kuchler
- *[2305.xxxxx]* *with Fabio Bacchini*

- *[2103.12075]* *with Fabio Bacchini, Bart Ripperda,*
  Jordy Davelaar, Hector Olivares, Thomas Hertog,
  Bert Vercnocke

Introduction: Imaging with microstructure?

- Event Horizon Telescope:
  « picture » of black hole horizon

- (How) Does this picture change if:

  - No horizon?
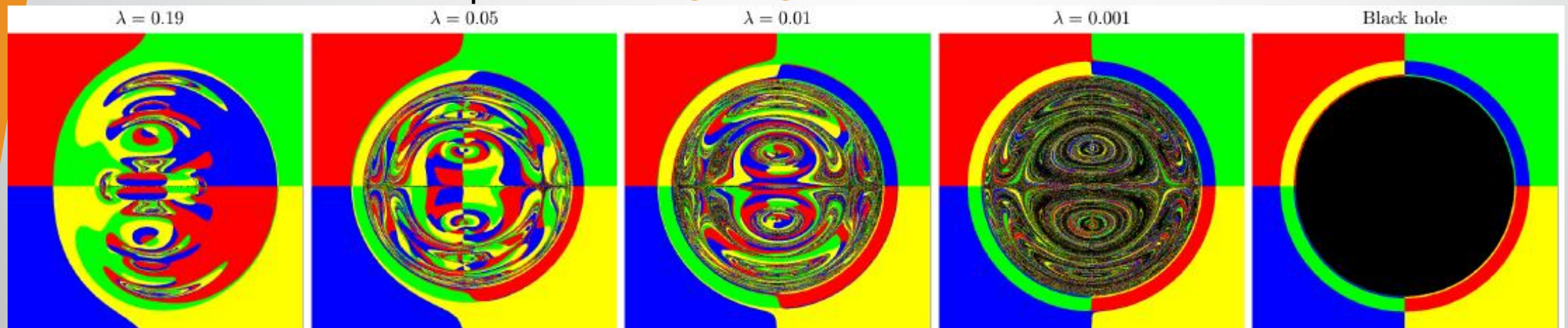
  - Different horizon/BH than Kerr?

First attempt: four-color screen
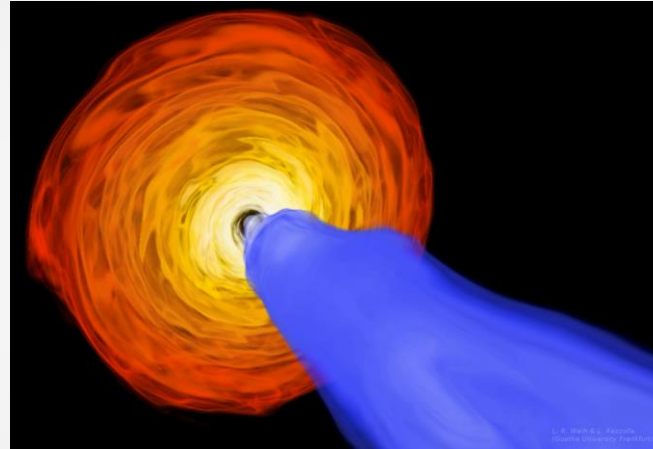
- First « naive » picture: four-color screen

- No horizon – transparent?! [2103.12075] Bacchini, DRM, et al.

$\lambda = 0.19$ $\lambda = 0.05$ $\lambda = 0.01$ $\lambda = 0.001$ Black hole
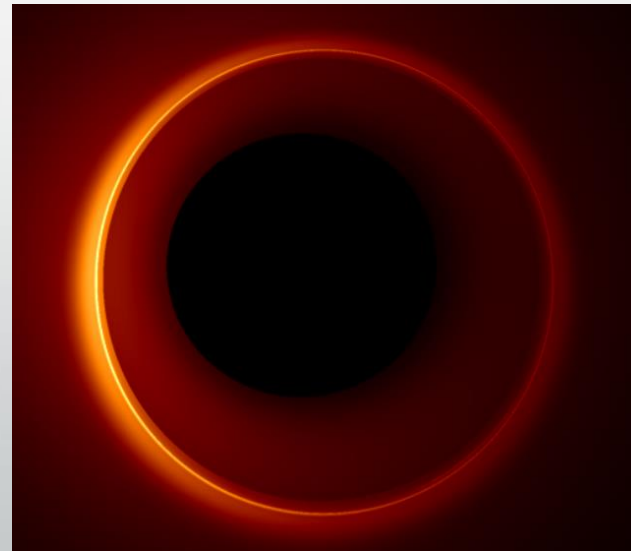
- Redshift, tidal effects, long escape time -> « effective blackness »

- Key property: *compactness*!

- *What are observable signatures and how to model them?*

Ingredient 1: More realistic emission

- True photon emission?
- Series of approximations
- GRMHD (fluid)

Weih & Rezolla, EHT collab

- « Effective » models
  (mimic time-average GRMHD)
  [1907.04329] Johnson et al.
  [2008.03879] Gralla, Lupsasca, Marrone

  - Equatorial disc
  - Radial profile emission intensity
  - Accretion « fluid » velocity
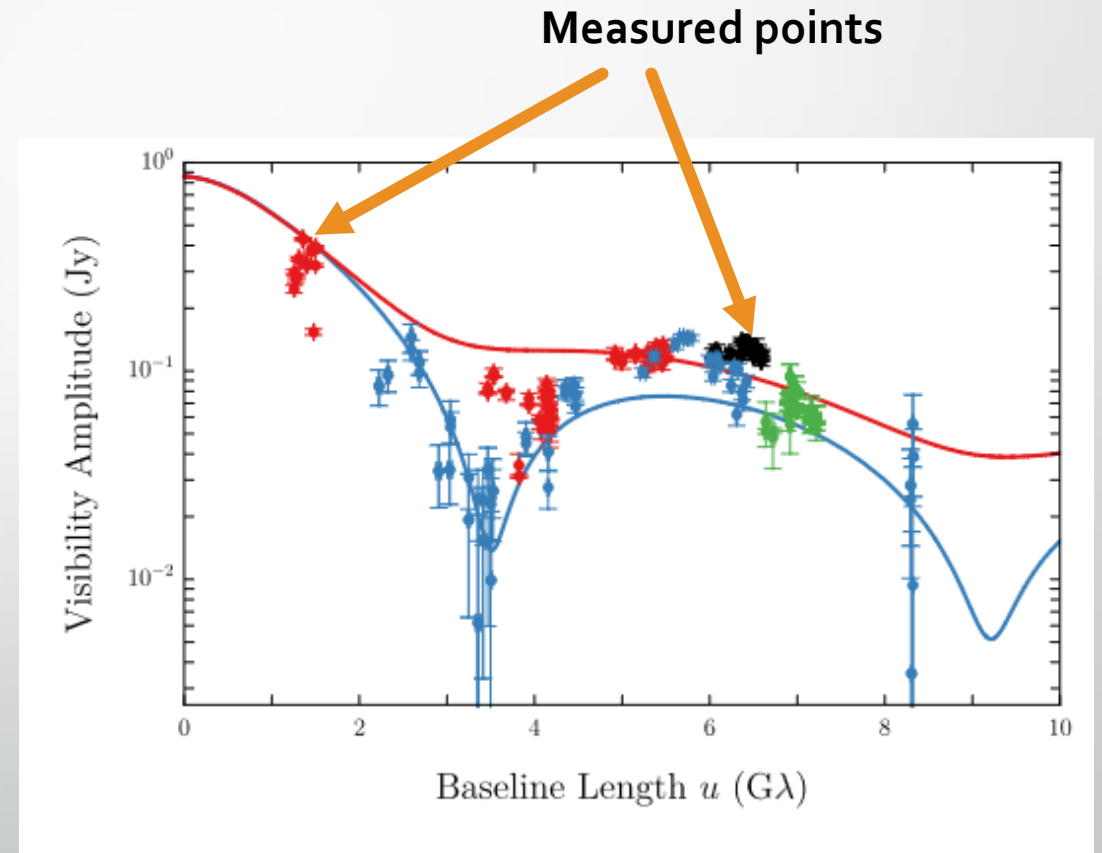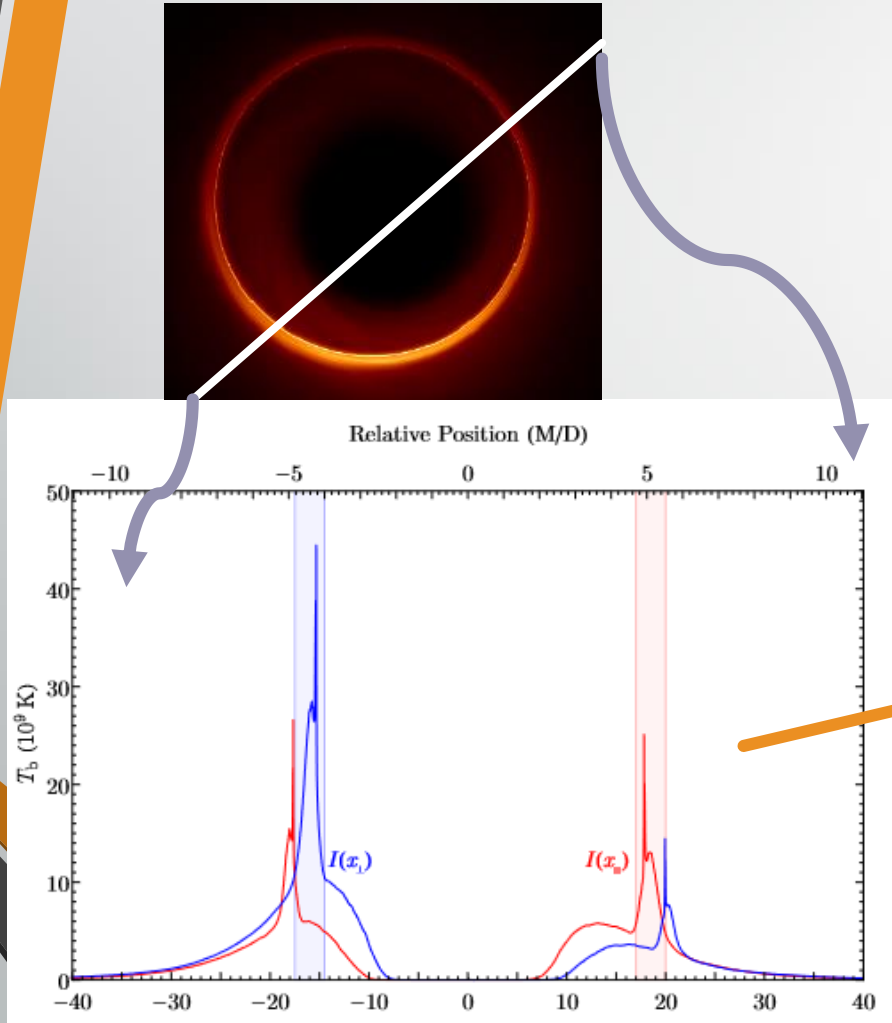
Ingredient 2: Visibility amplitude (1)

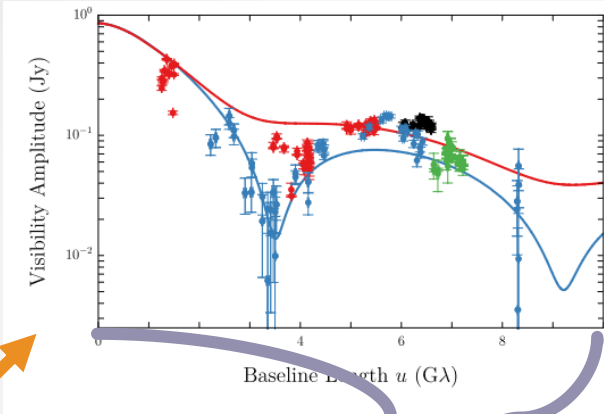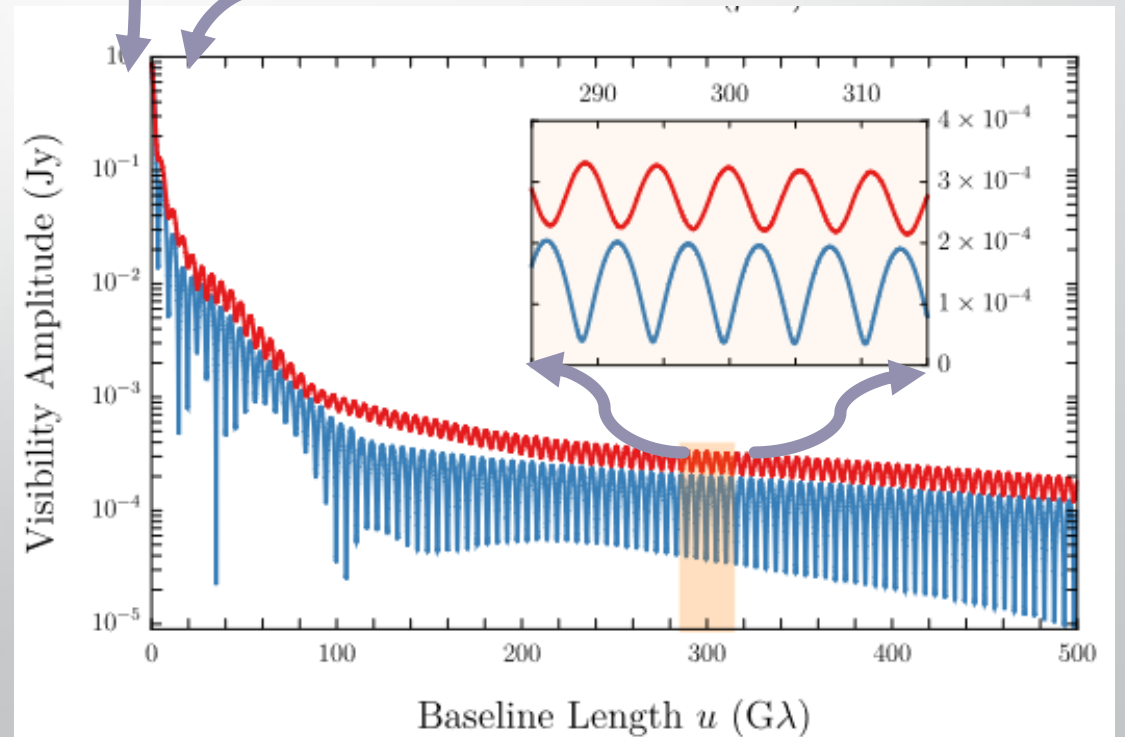- EHT is interferometer – **visamp** is measured!
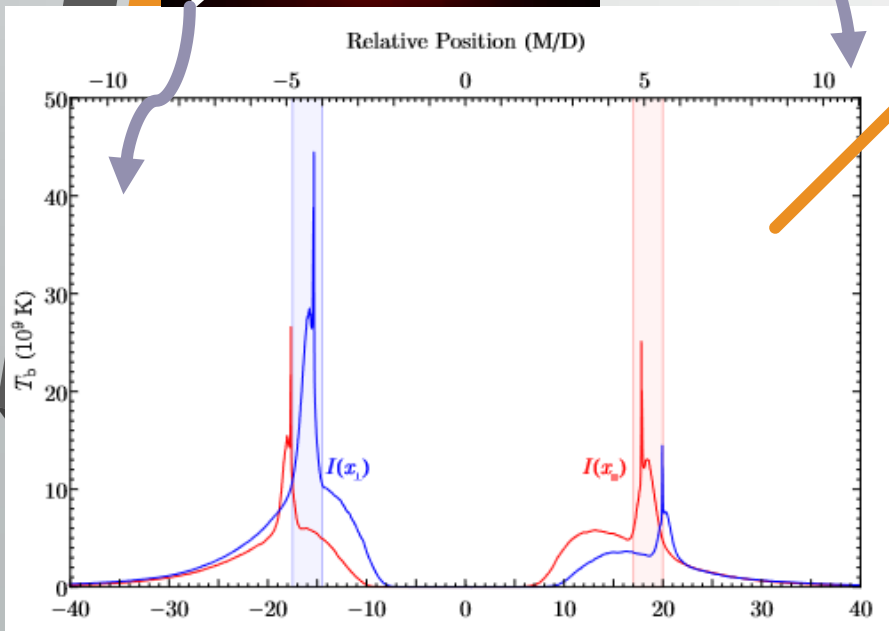

Measured points

Fourier transform
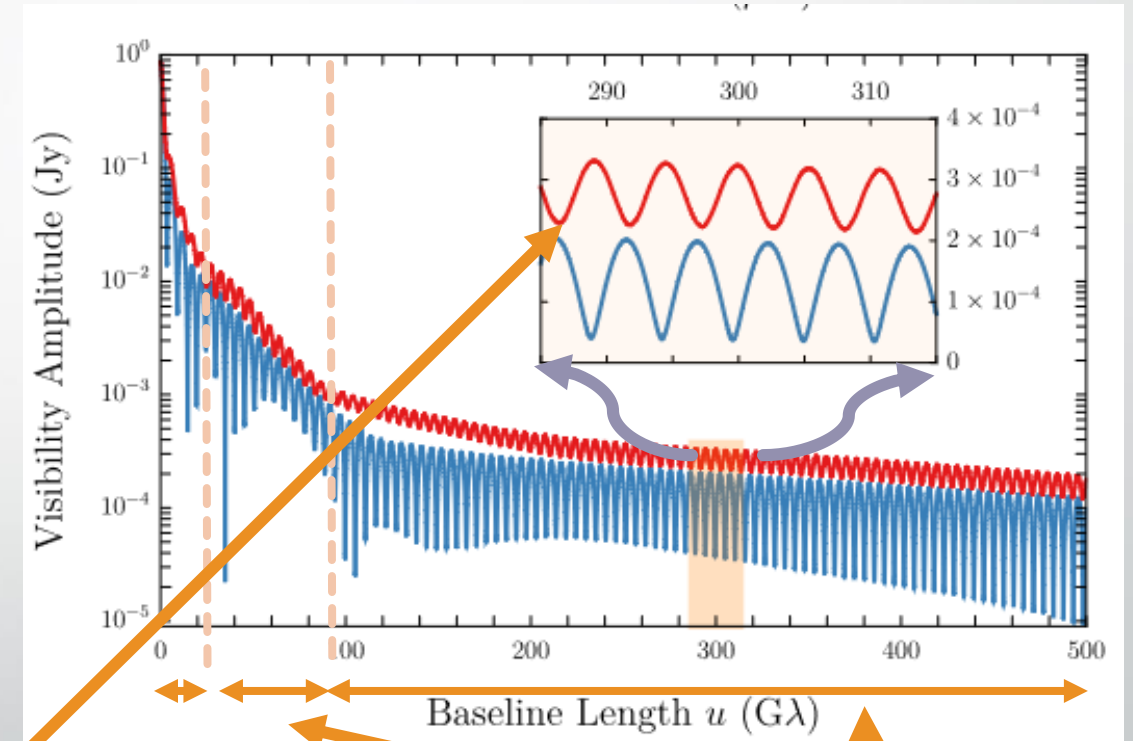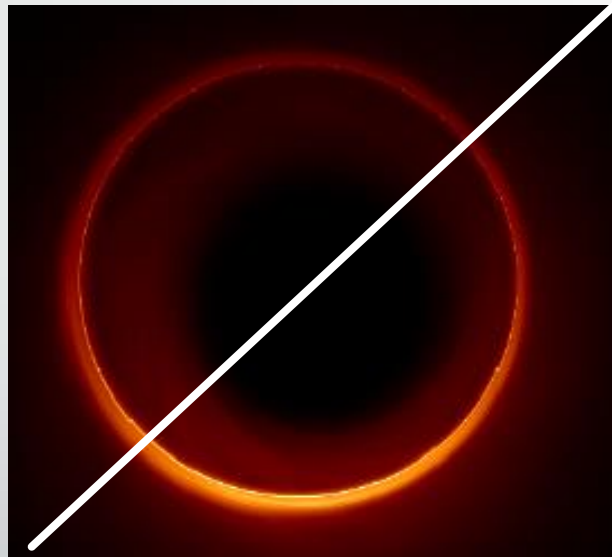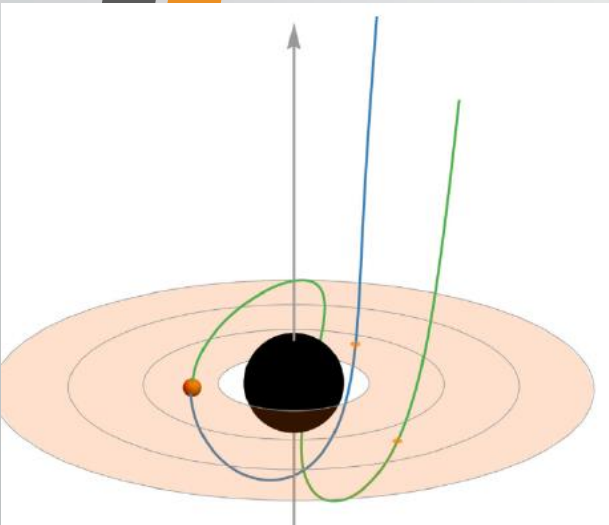
Ingredient 2: Visibility amplitude (2)

EHT

Fourier transform

Together: Emission & Visamp

- Details that depend on emission details/parameters: not robust!

- **Features independent of emission?**

- Photon rings!

Shape: Periodicity ~ diameter
[2008.03879] Gralla, Lupsasca, Marrone

Relative widths (« Lyapunov »)
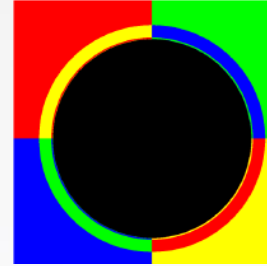[1907.04329] Johnson et al.

Photon Rings: Shape & Lyapunov

- *How well do PR shape & Lyapunov (relative widths) distinguish <u>not-Kerr</u>?*

- Three BHs with continuous Kerr limit
  [2303.02111] S. Staelens, DRM, F. Bacchini, B. Ripperda, L. Kuchler

  - Johanssen (deviation with geodesic integrability)

  - Rasheed-Larsen (electric and magnetic charge)

  - Manko-Novikov (« multipole bump »)

- Shape is « universal »: hard to find deviations

- Lyapunov exponent is very sensitive to deviations!
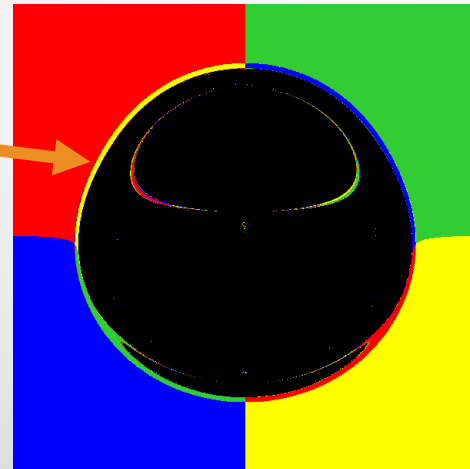
  - Not yet feasible to measure!

Photon Rings: Measurable signatures?

- *What signatures might there still be?*

- « Chaos »: breaking of integrability leads to chaotic behaviour

  - « Shadow » is not connected

  - Photon rings « approach » shadow boundary
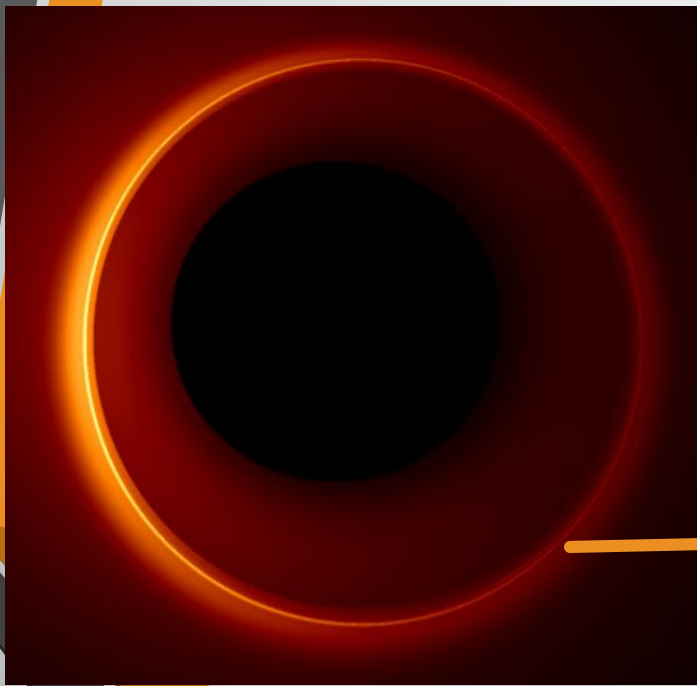
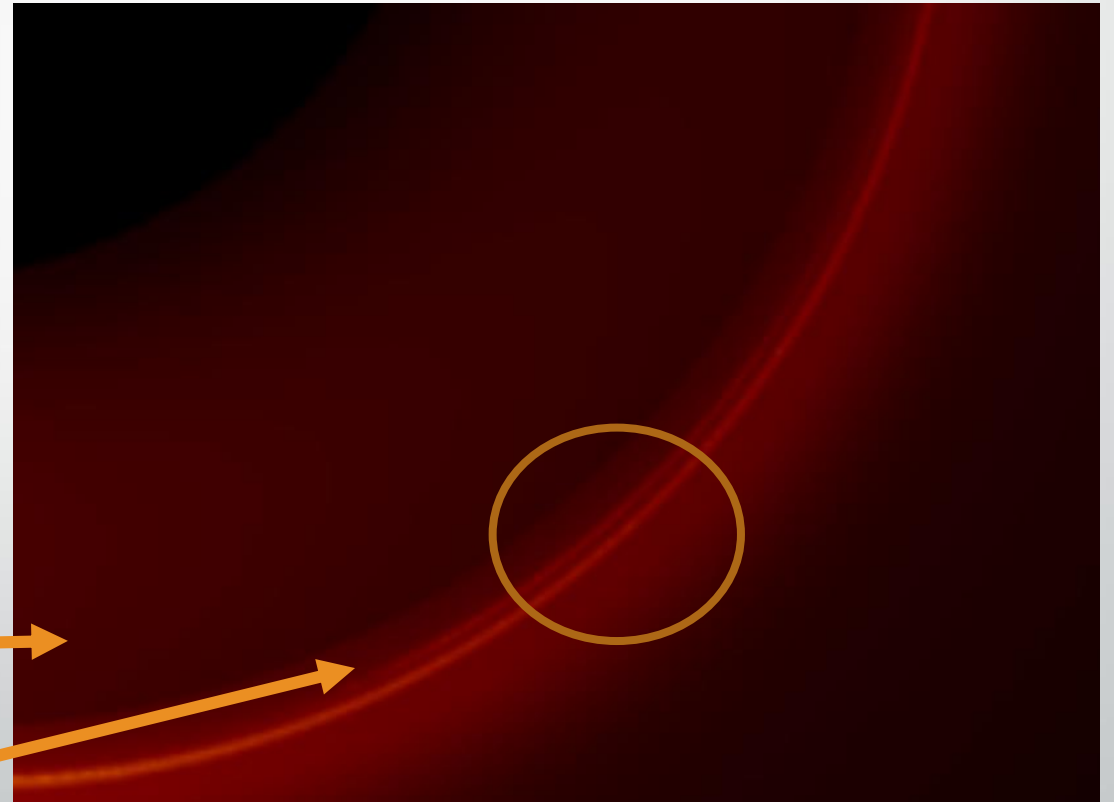 - So: Photon rings not connected?

Manko-Novikov (BH)

Fuzzball (horizonless)

Photon Rings: Measurable signatures?

- *What signatures might there still be?*
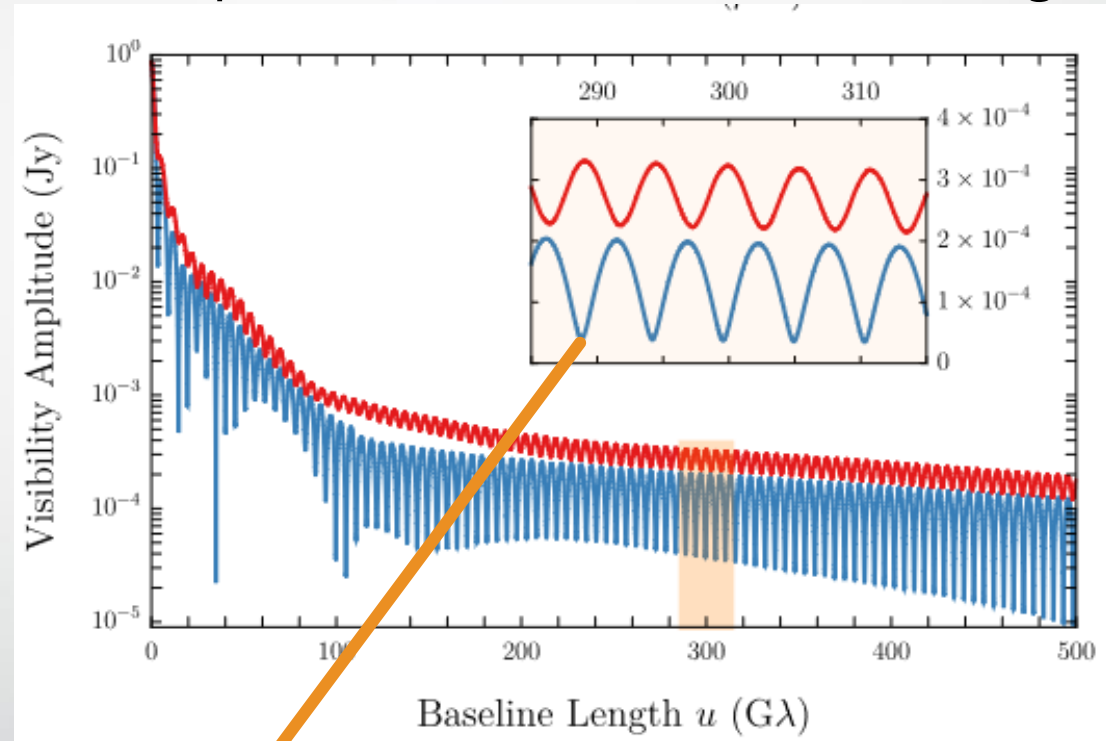
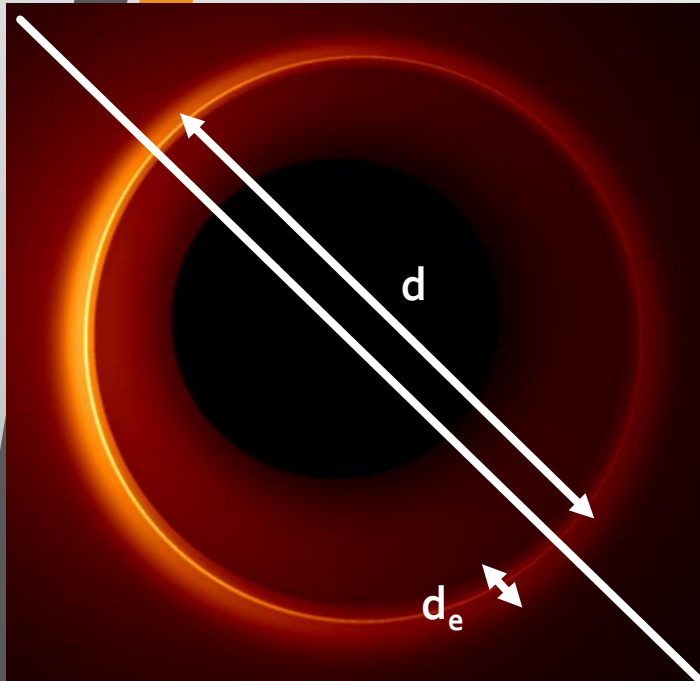- « Disconnected photon rings »?!

« Ring echo »

Photon Rings: Measurable signatures?

- « Disconnected photon rings » - three peaks – « beats » in diameter signal

$$|I(u)| \sim \frac{1}{\sqrt{u}}\sqrt{A + B\sin(2\pi du)}$$

[2008.03879] Gralla, Lupsasca, Marrone

$$|I(u)| \sim \frac{1}{\sqrt{u}}\sqrt{A + B\sin(2\pi du) + C\sin(2\pi(d - d_e)u) + D\cos(2\pi d_e u)}$$

Tangent: Necessity of tools

- These questions require simulations of images

  - Different metrics easy to implement

  - Realistic emission models

  - Visamp signatures

- **FOORT**: Flexible Object-Oriented Ray Tracing
  [2305.xxxxx] DRM, Bacchini and https://github.com/drmayerson/FOORT

  - Open invitation for more metrics / tools!

- Need for such tools in GW phenomenology!

Summary & Conclusions

- Black hole imaging phenomenology beyond GR/Kerr
- Four-color screens give some insight
- Realistic observation ingredients:
  - Emission models
  - Visamp
- Focus on emission-independent features in visamp!
- Photon rings
  - Shape: « universal »
  - Lyapunov (successive ring widths): sensitive, but not measurable
  - « Ring echoes » from chaos? (beats in visamp signal)
- FOORT as tool for realistic beyond-GR pheno in BH imaging
  - https://github.com/drmayerson/FOORT