Black hole imaging as GR tests

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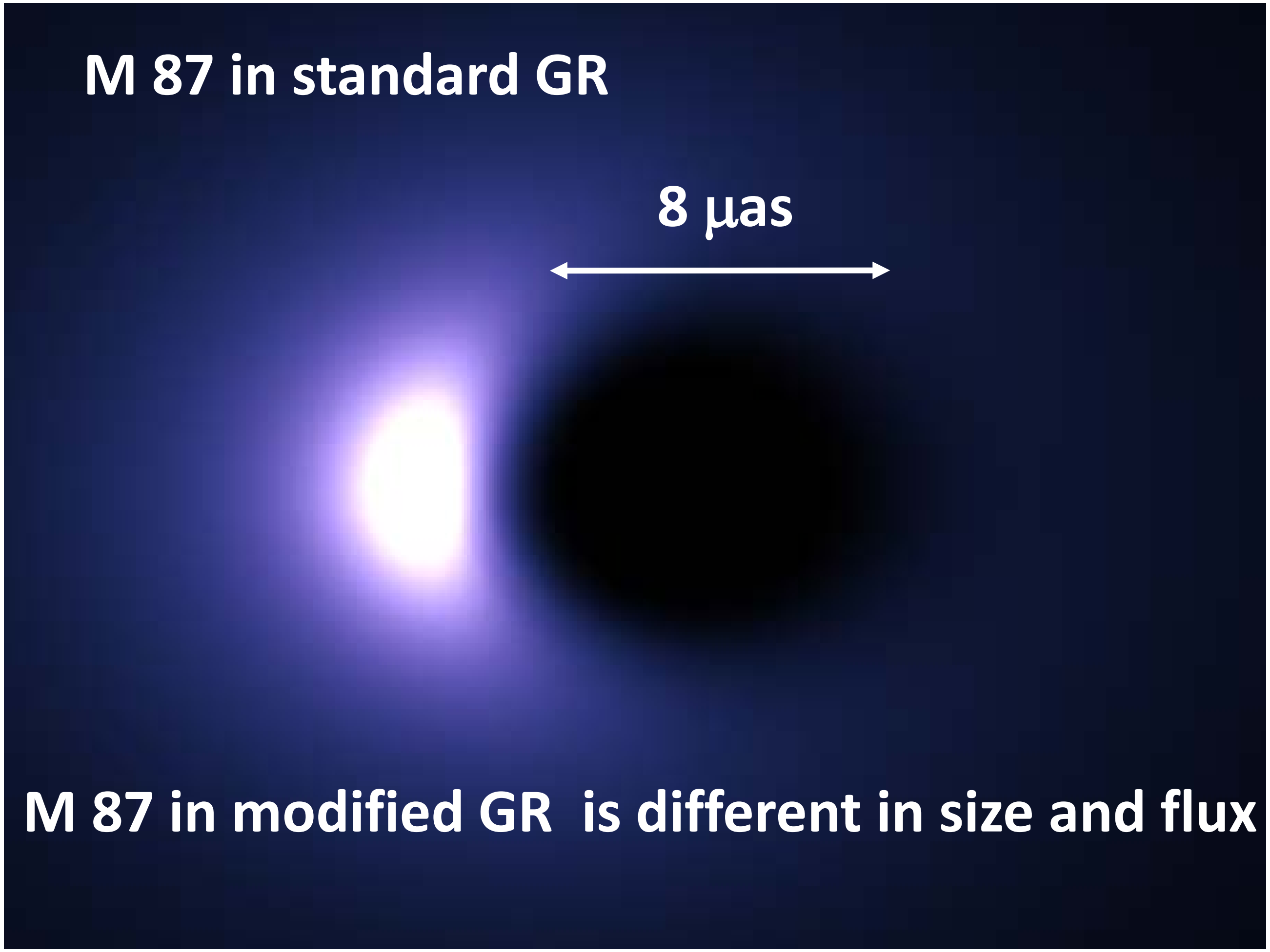
Black Hole imaging of M87 and the GC (VLBI + ALMA)



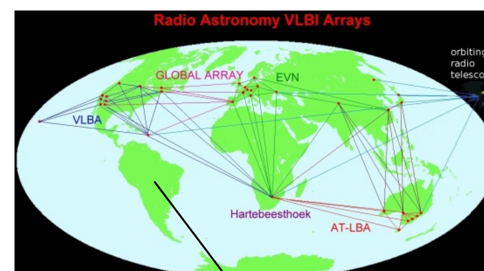
$M = 6.6 \times 10^9 M_{sun}$

$R_S = 1.8 \times 10^{15}$ cm

$\Delta x = 8\ \mu as = 1 R_S$

observing:
- sub mm shadowing
- disk tomography

VLBI + ALMA

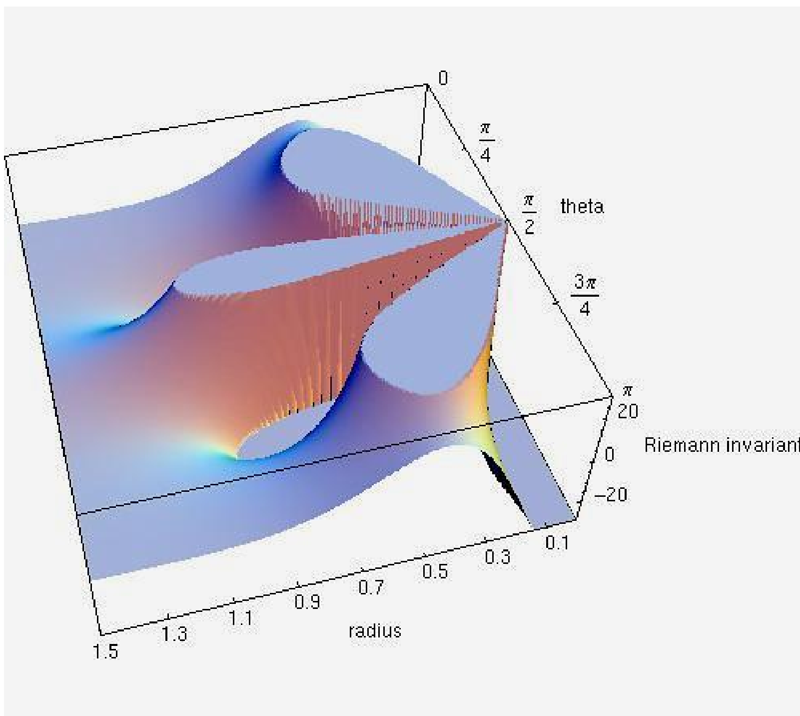


ray-tracing images differ due to different z_G and emmisivity profiles

Motivation going beyond standard GR

GR theory has up to now withstood all experimental tests

nevertheless, there are extreme situations in GR, like the formation of
curvature singularities and coordinate singularities at the event horizon



Kretschmann-scalar = curvature singularity

shows how the curvature in the vicinity of the BH behaves

far away from the BH: space time is flat

close to the BH: space time curves strongly

at r=0: curvature diverges

these are reasons to search for possible extensions to GR, i.e. pc-GR

The Pseudo-Complex Theory

Hess, Greiner et al. >2009

1. the Ansatz

2. the effective potential

3. last stable orbits

Acceptance of pc-GR in astronomical community

1. pc-GR is part of the Athena science goals for ESA´s Large Mission Programme 2015-2030

2. pc-GR is part of the ALMA science programme for direct imaging of black holes

there is growing interest from galactic and extragalactic experts to perform tests going beyond standard GR

The Pseudo-Complex Theory – the Ansatz **(Hess, Greiner 09)**

$$X = X_R + I\ X_I \quad \text{with} \quad I^2 = +1$$

X: pseudo-complex number

$$R^{\mu\nu} - \frac{1}{2} g^{\mu\nu} R = -\frac{8\pi\kappa}{c^2} T^{\mu\nu} \sigma_-$$

- new Einstein equation
- energy momentum tensor
  allows for repulsion at small r[m]

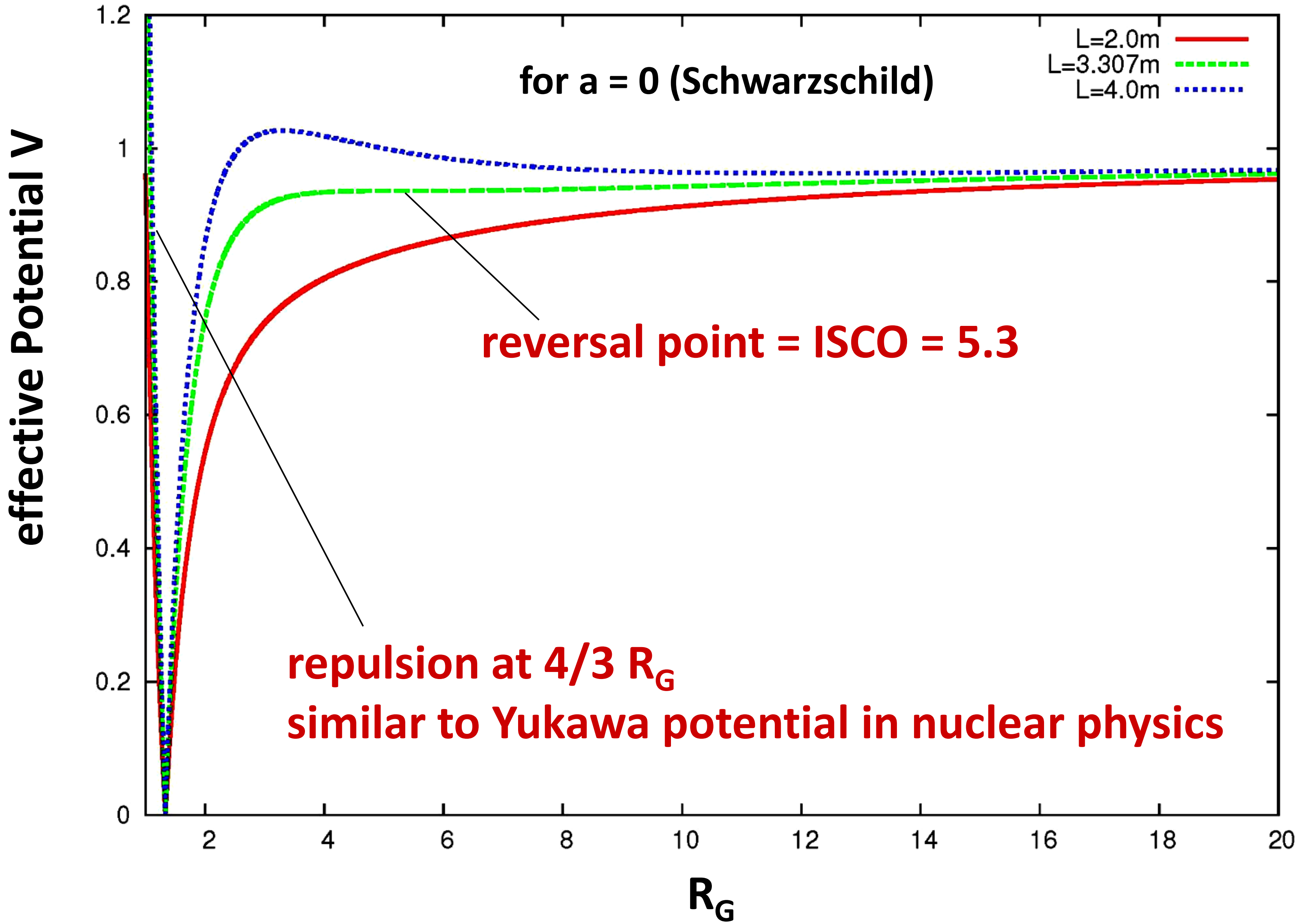
$$\sigma_- = \frac{1}{2}(1 - I) \qquad \sigma_- \sigma_+ = 0 \qquad \sigma_-^2 = \sigma_-$$

$$g_{00} = \frac{r^2 - 2mr + a^2 \cos^2\theta + \dfrac{B}{2r}}{r^2 + a^2 \cos^2\theta}$$

g_{00}: metric tensor
B: new pseudo-complex variable
a: spin parameter

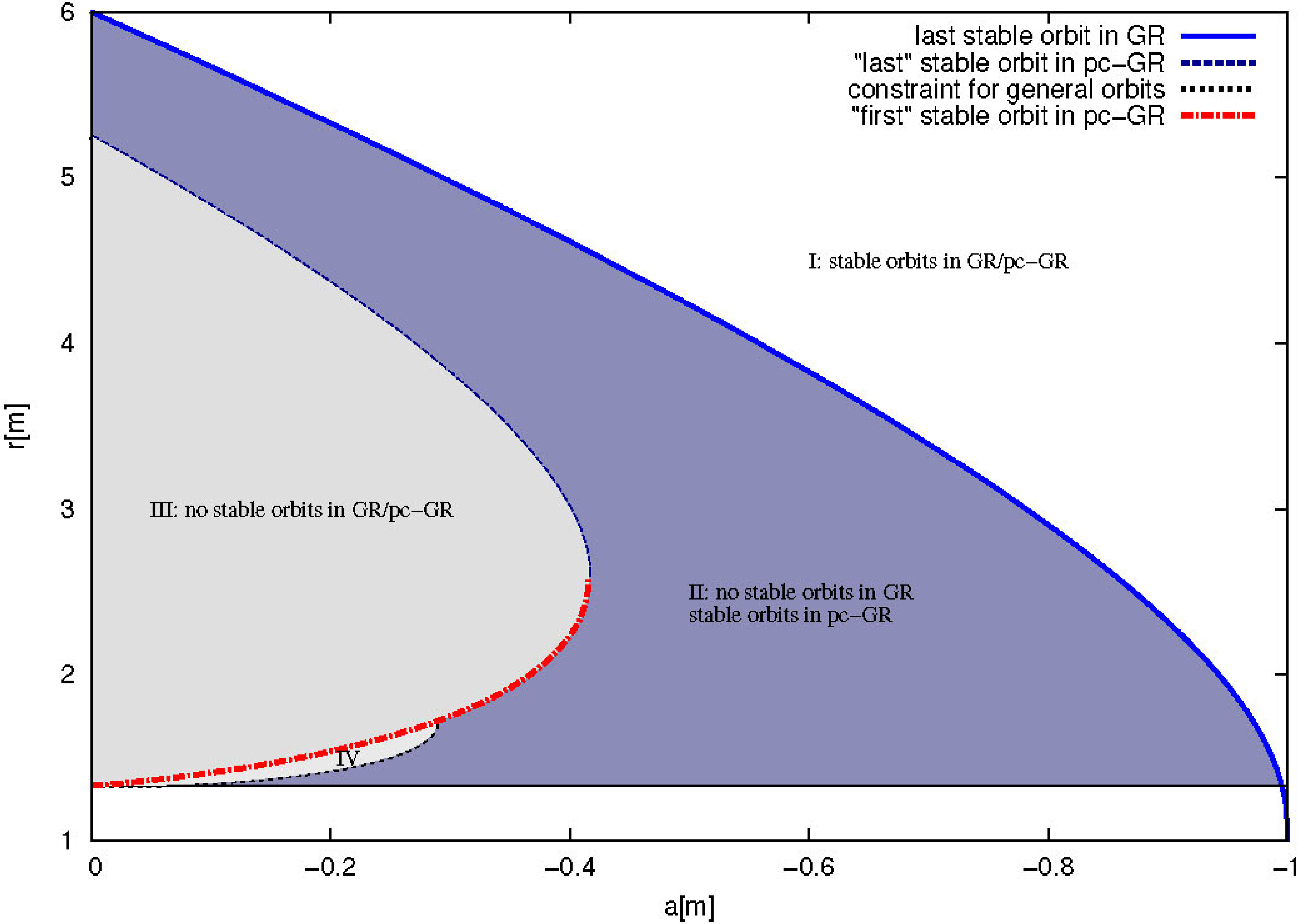
no coordinate singularity
at r = 2m for a = 0

Effective potential of test particle in pc-GR

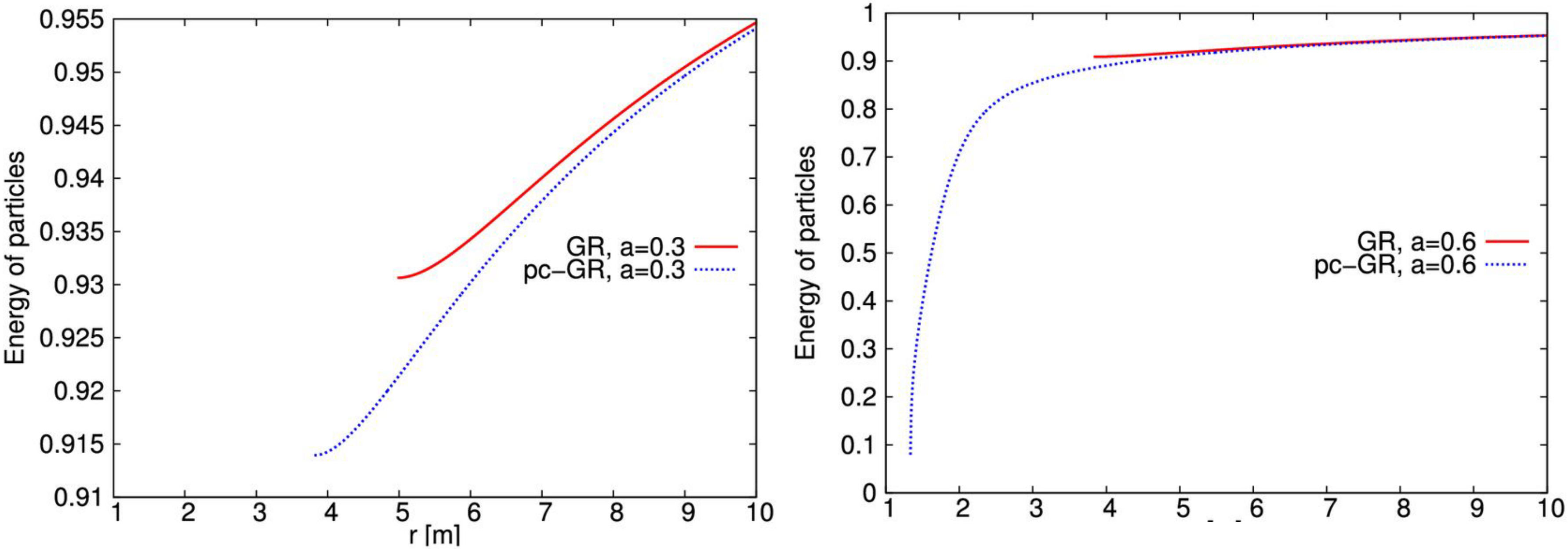


Last stable orbits

Schönenbach_etal[2014]

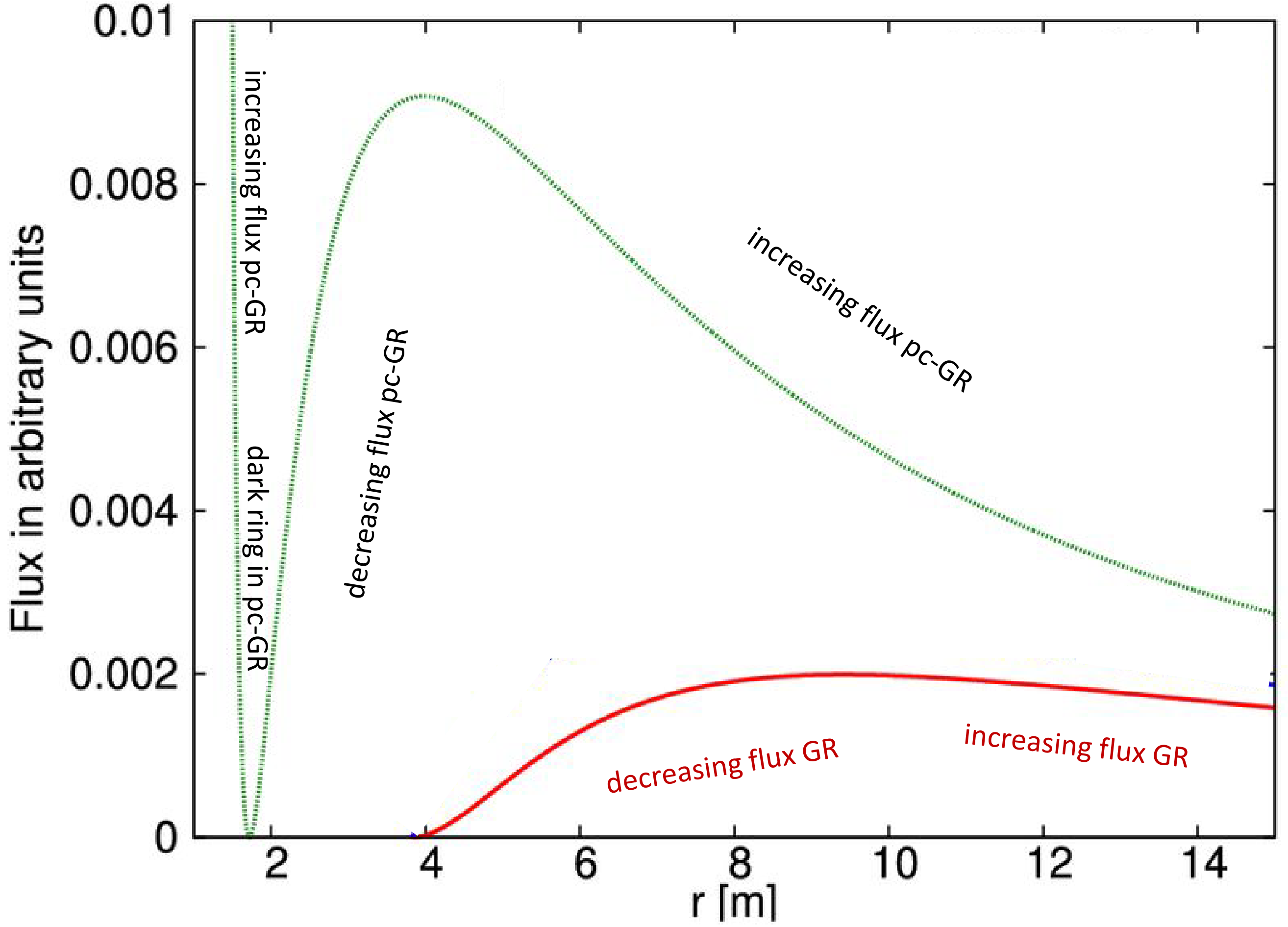


Normalized energy of particles on stable prograde circular orbits



in the pc-GR case, more energy is released as particles move to smaller radii

flux function for GR and pc-GR

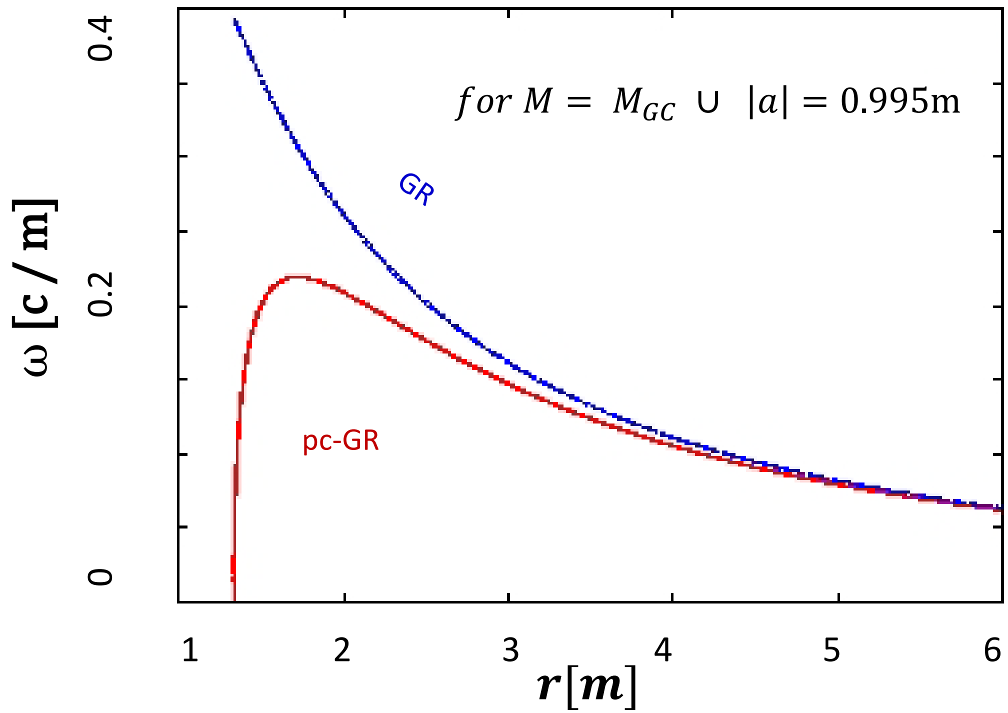


- pc-GR black holes is brighter
- appearance of zero flux in pc-GR

Radial dependence of the angular frequency $\omega(r)$

angular frequency $$\omega\pm = \frac{c}{-a\pm\sqrt{\frac{2r}{h(a,m)}}}$$

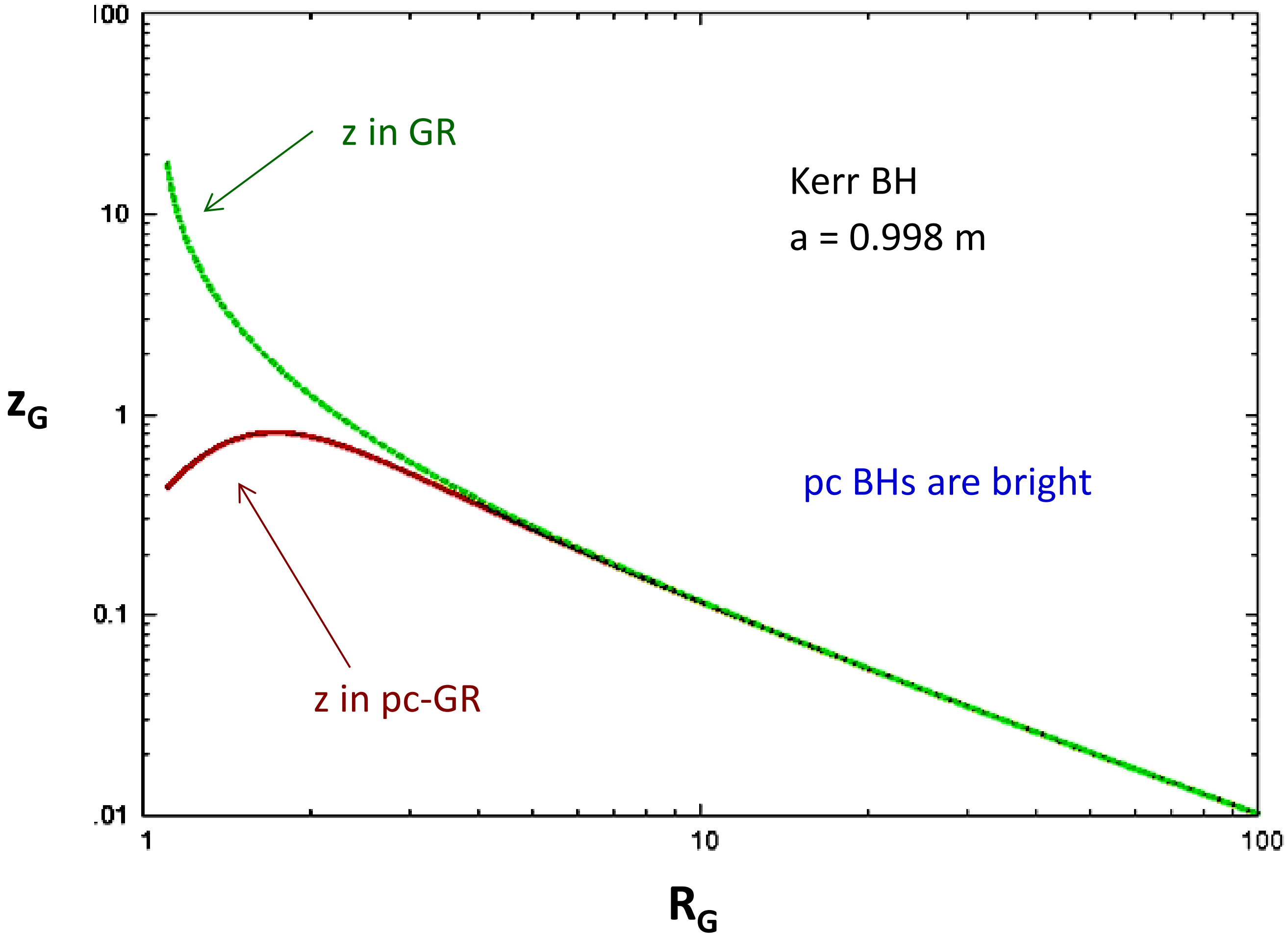
time derivative gives flux $$d_{|r}\omega\pm = d_{|r}\frac{c}{-a\pm\sqrt{\frac{2r}{h(a,m)}}} \sim flux$$



orbital frequency is reduced in pc-GR

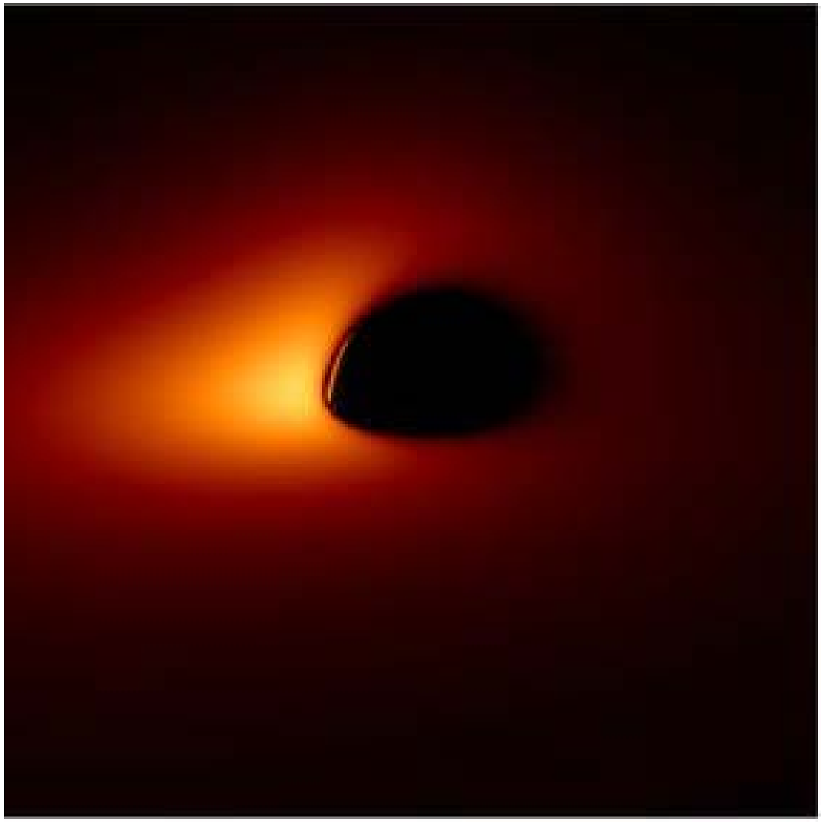
for the mass of the GC a maximum frequency of 0.219c/m exists, corresponding to a orbital period of 9.4 min

gravitational redshift as a function of distance

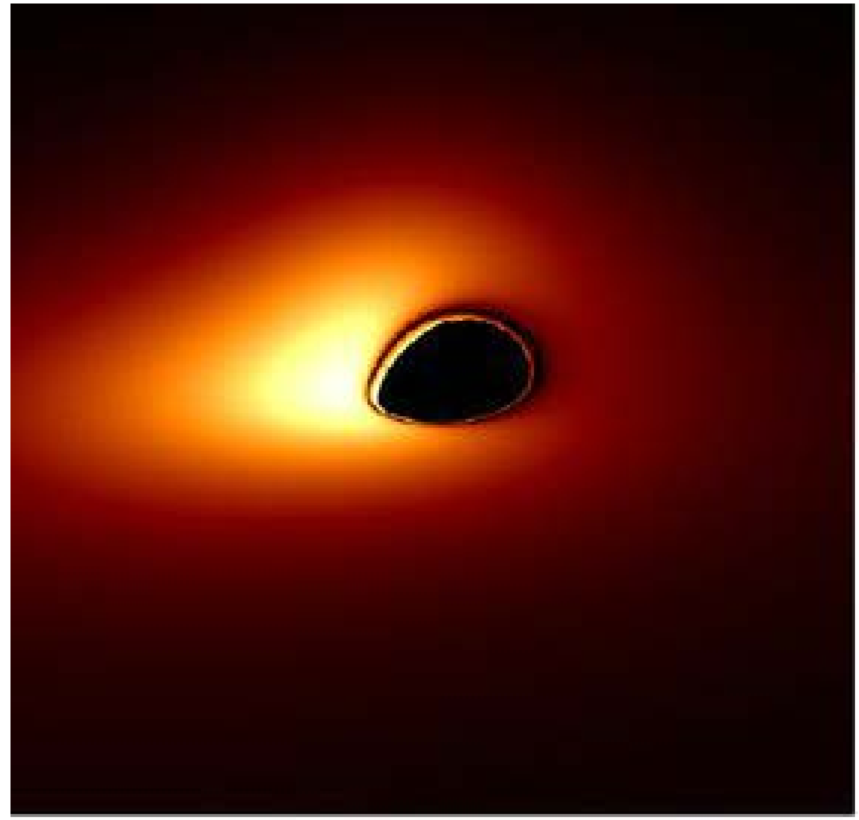


gravitational redshift is reduced in pc-GR

Geometrically thin accretion disc around a rotating compact object viewed from an inclination of 70°



(d) standard GR $a = 0.9m$

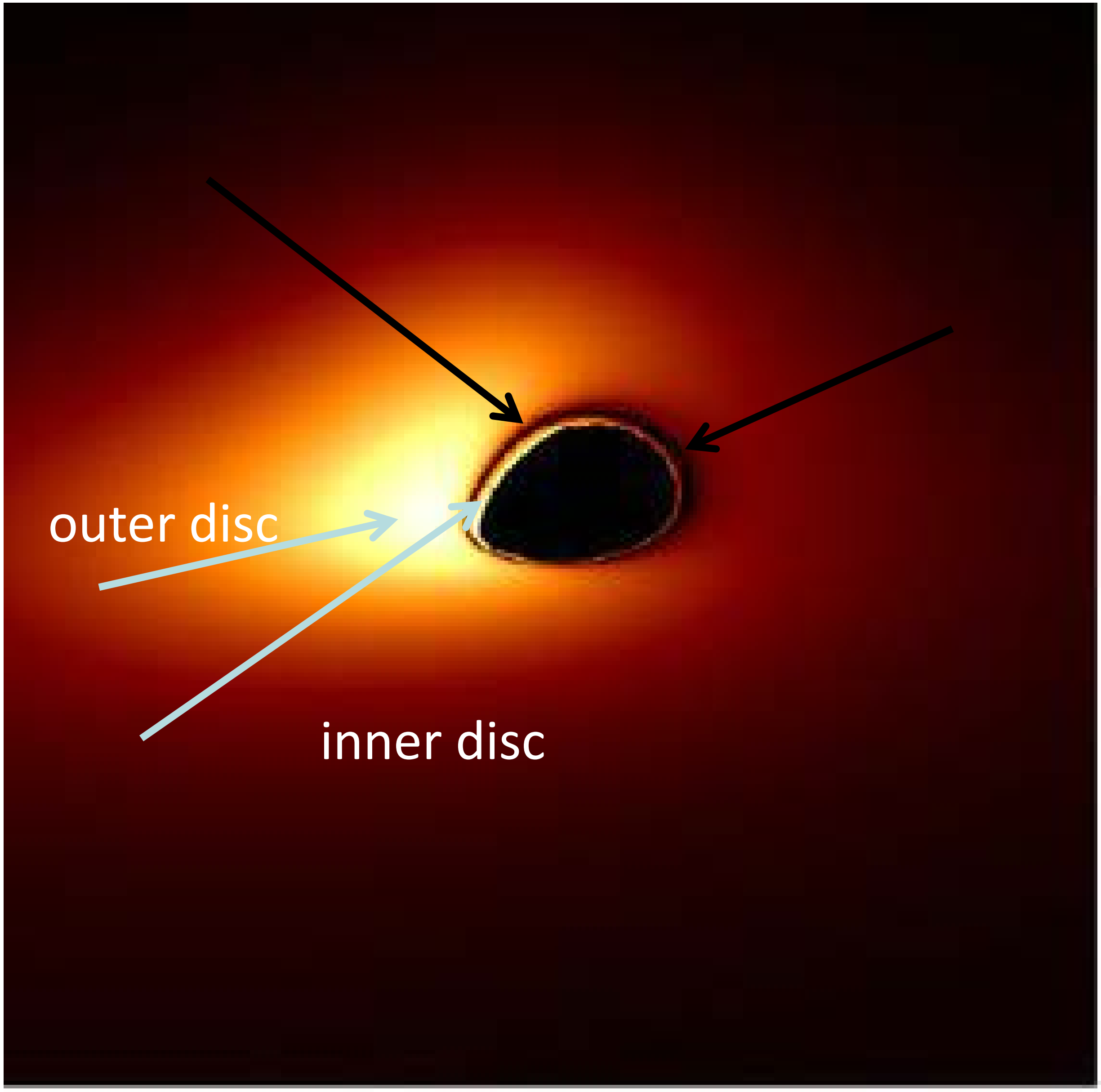


(d) pc-GR $a = 0.9m$

most prominent difference: pc-GR images are brighter

next significant difference: occurrence of a dark ring in pc-GR

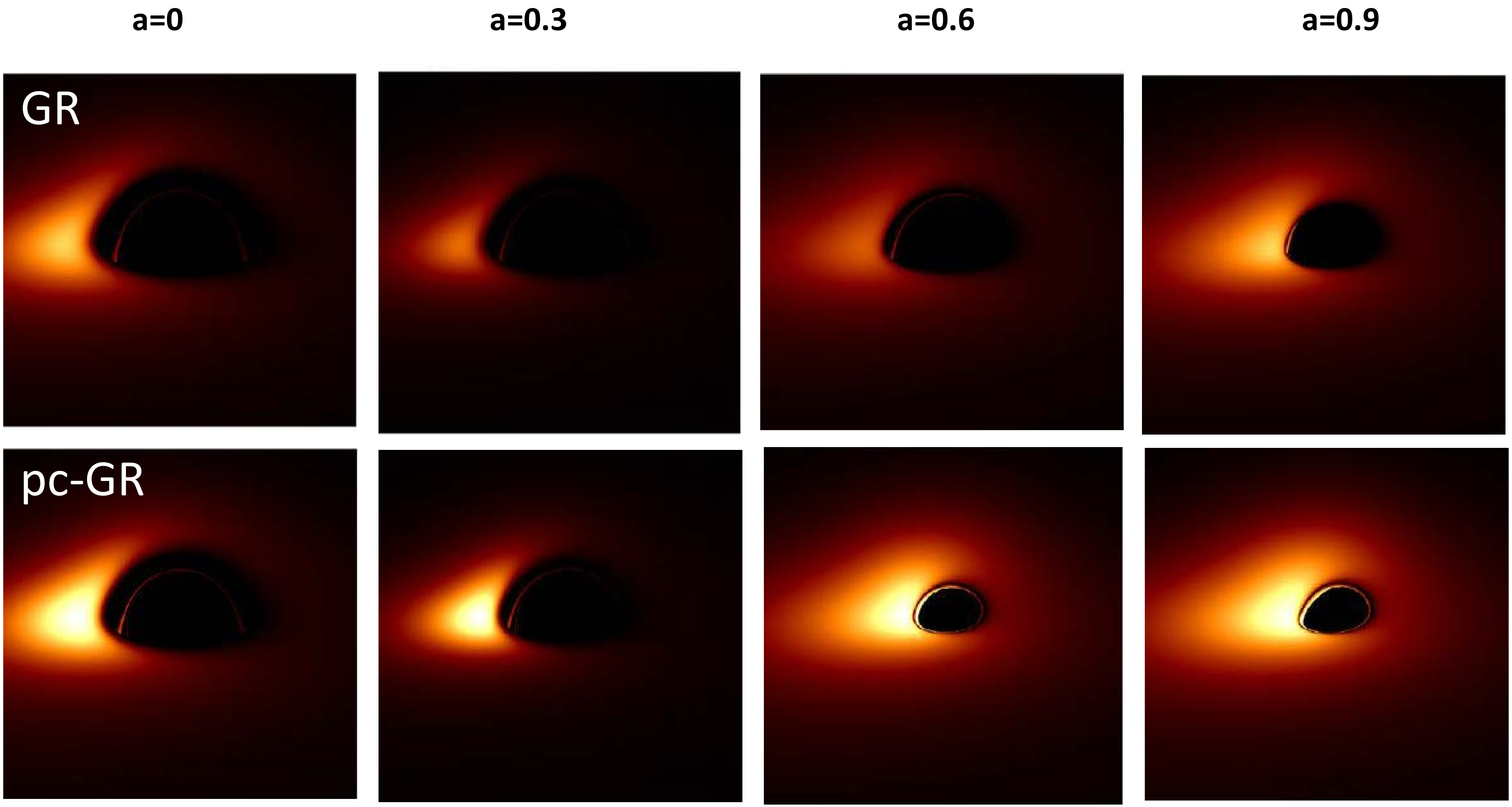
- the ring appears due to the fact that the angular frequency has a maximum at 1.72 m
- at 1.72m the flux vanishes, going further inside, the flux increases again, which is a new feature in pc-GR



(d) pc-GR $a = 0.9m$

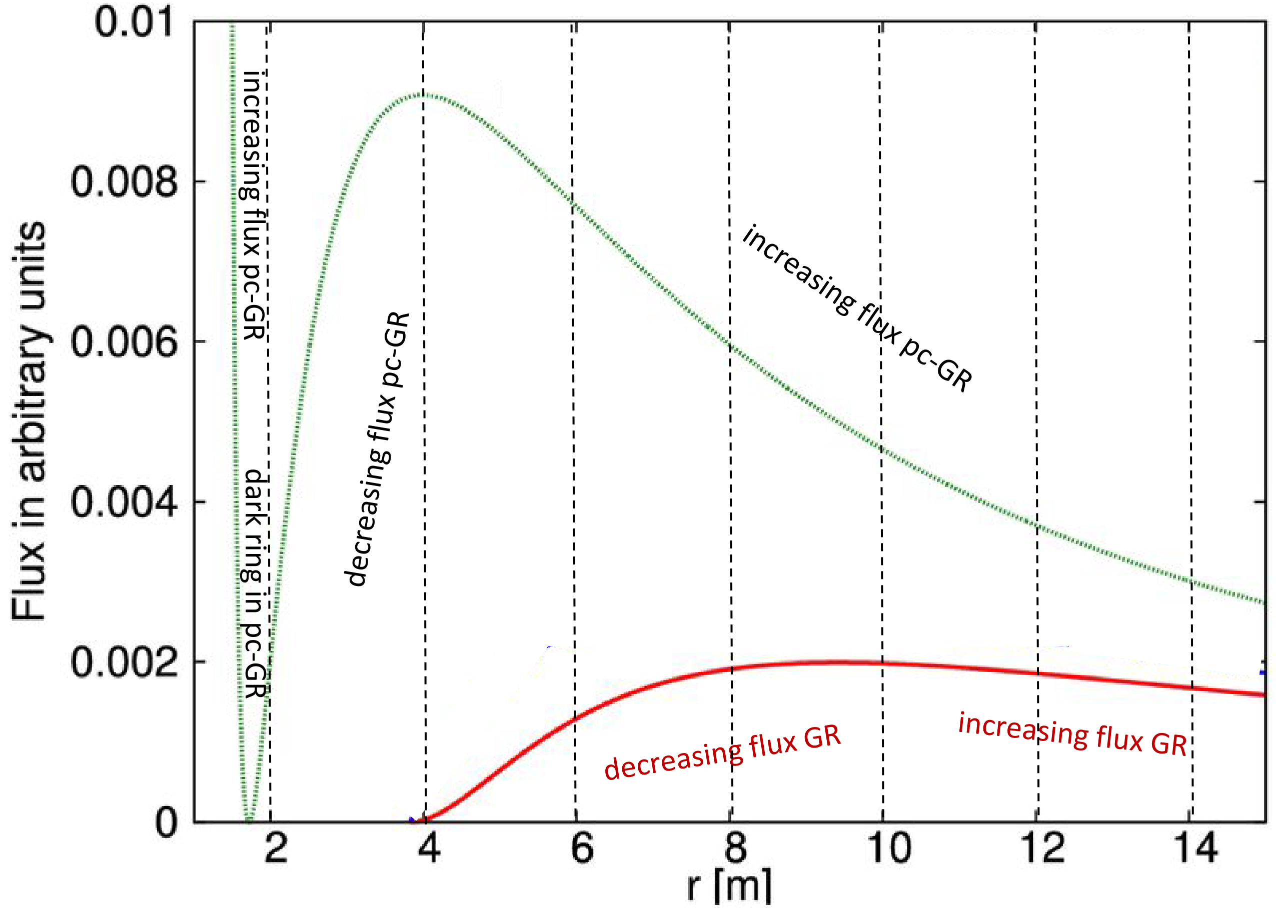
dark ring at 1.72m as new feature of pc-GR

ray-tracing in GR and pc-GR



most prominent difference: pc-GR images are brighter
next significant difference: occurrence of a dark ring in pc-GR

OBSERVED EHT intensity slices will provide robust GR test

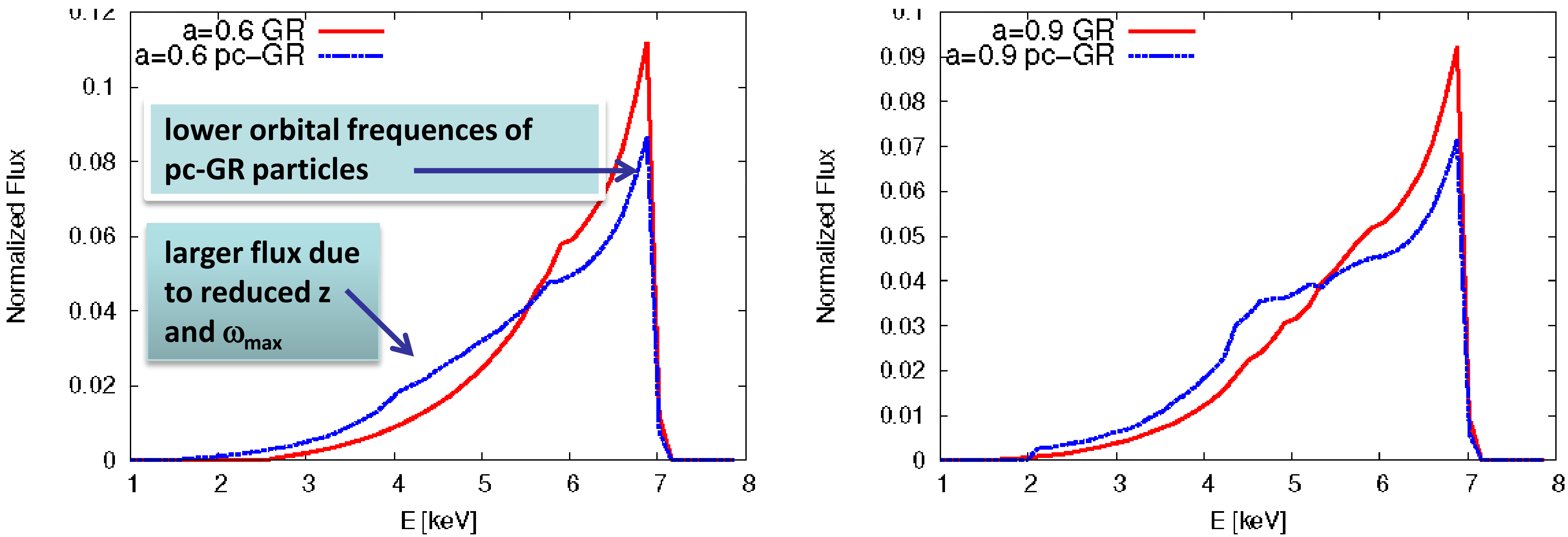


$I_\nu^{obs} = g^3 \; I_\nu^{rest}$

$$g \equiv \frac{1}{1+z} = \frac{\upsilon_{obs}}{\upsilon_{em}} = \frac{\hat{p}^t_{obs}}{\hat{p}^t_{em}}$$

$$\frac{I_\upsilon^{obs}(pc) \quad (m)}{I_\upsilon^{obs}(GR) \quad (m)} \sim 100..1$$

relativistic Fe K line differences



(c) $a = 0.6$ (d) $a = 0.9$

as pc-GR discs are brighter, the integreated line flux is larger in pc-GR

the line profiles are clearly different from standard GR

this offers a second robust measurements to test pc-GR versus GR

GR tests on Galactic binaries

a handful of stellar mass-black holes with

- dynamically constrained masses M
- relativistic Fe K lines
- QPO measurements

are known

GRO J1655-40	a= 0.92+-0.02	M=6.3+-0.5 [M_{sun}]	Miller[09], Green[01]
XTE J1550-564	a=0.5+-0.15	M=9.10+-0.61 [M_{sun}]	Steiner[10]
GX 339-4	a=0.93+-0.01	M>5.8 [M_{sun}]	Reis[08], Miller[08], Hynes[04]
XTE J1752-223	a=0.52+-0.11	M=9.8+-0.9 [M_{sun}]	Reis[10], Shaposhinikov[10]

Fe K and QPO emission radii are not consistent in GR

the **relativistic Fe K line** fitting, results in inner radii r_{in} of about **2 R_G**

the **QPO frequencies**, if associated with Keplerian, Vertical, and Radial motion, would place the QPOs at **10-50 R_G,** and not within 2 R_G

as these systems are not thought to have truncated disks at these high accretion rates, it is rather **puzzling to have this discrepancy between QPO frequency and the inner radius**

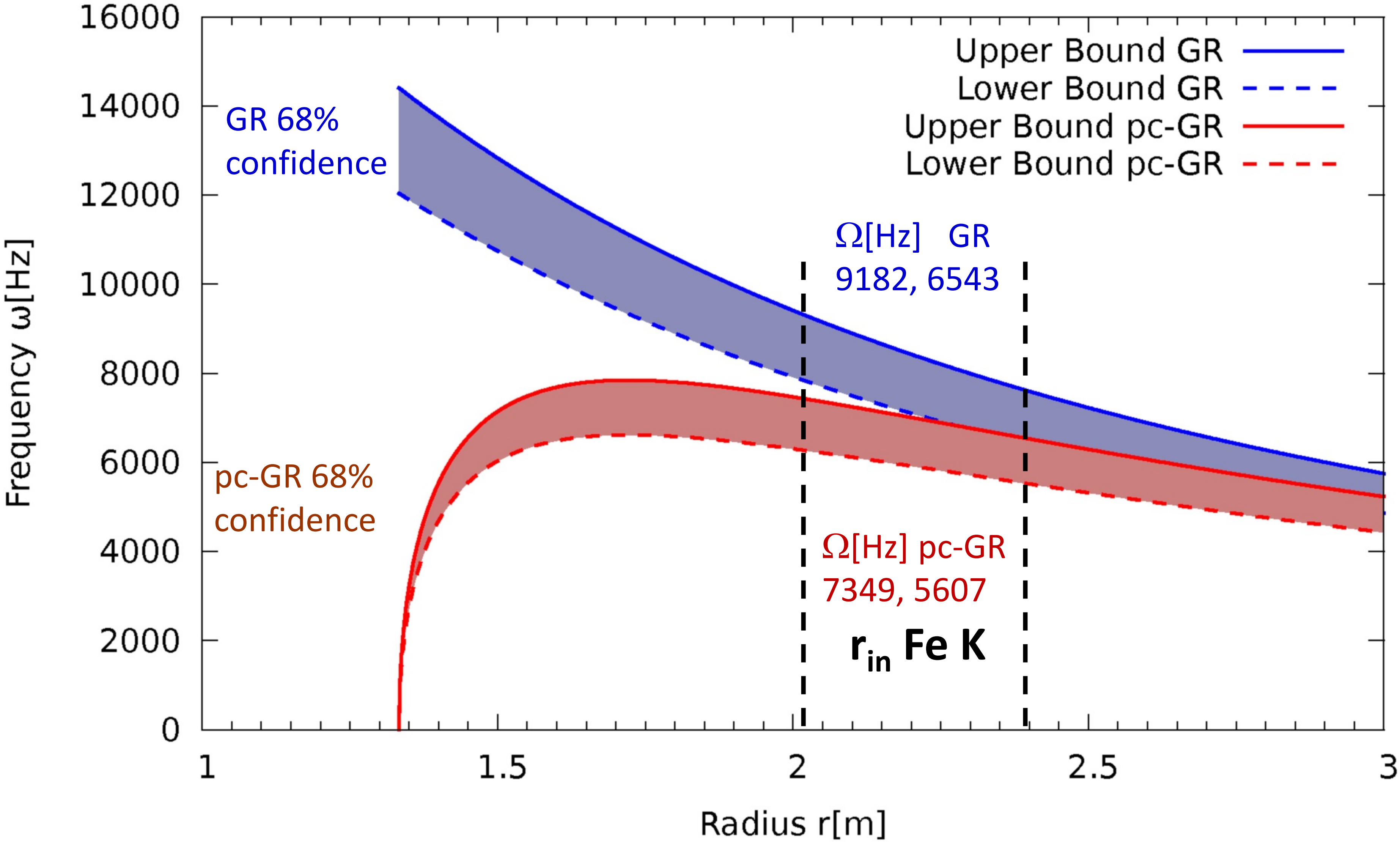
very little has been done beyond phenomenological description and this is all speculative and **there is no clear model** to explain this

the pc-theory might offer an solution, as it provides QPO frequencies that are consistent with Fe K emission

GRO J1655-40

$M = 6.30 \pm 0.5$

$a = 0.92 \pm 0.2$



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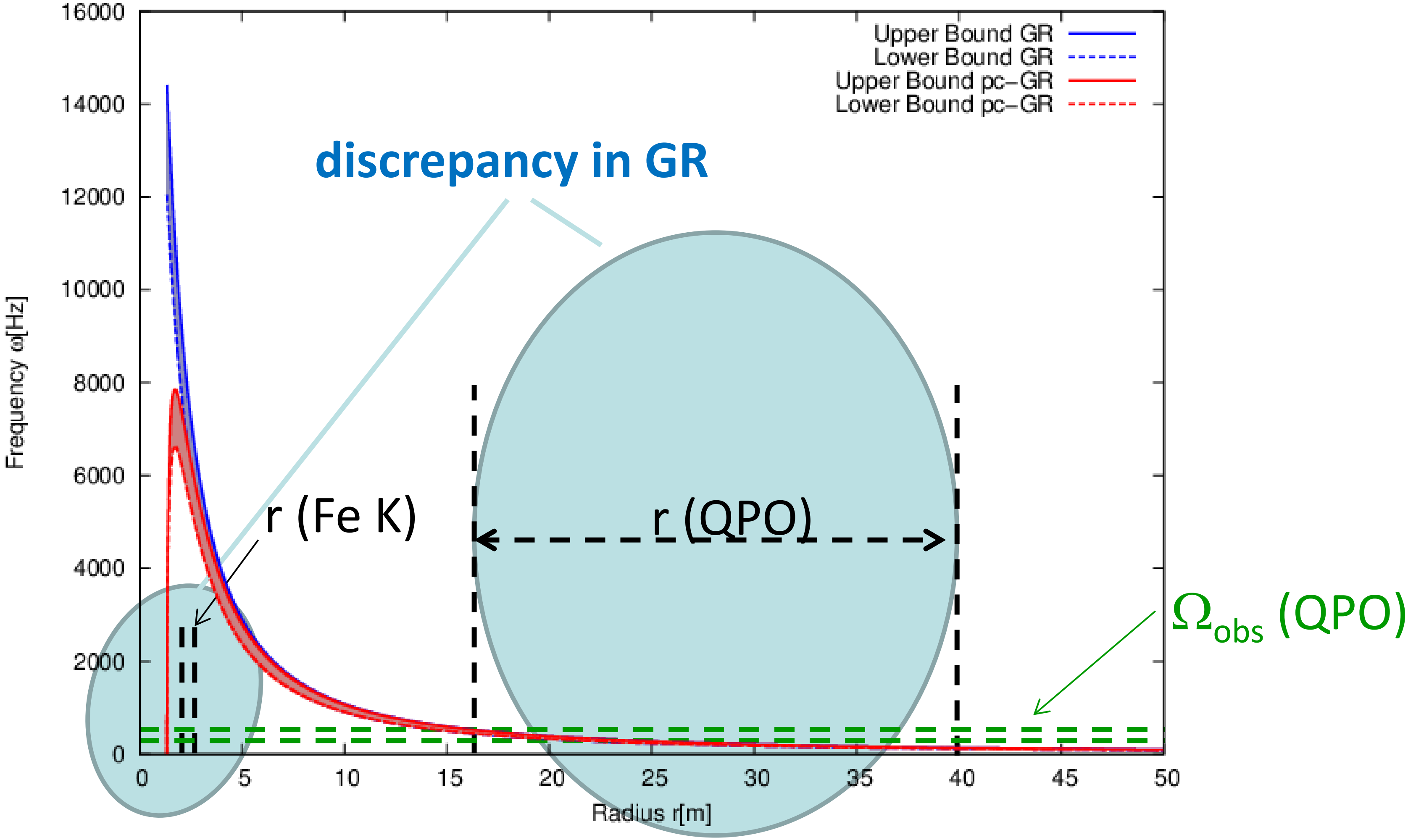
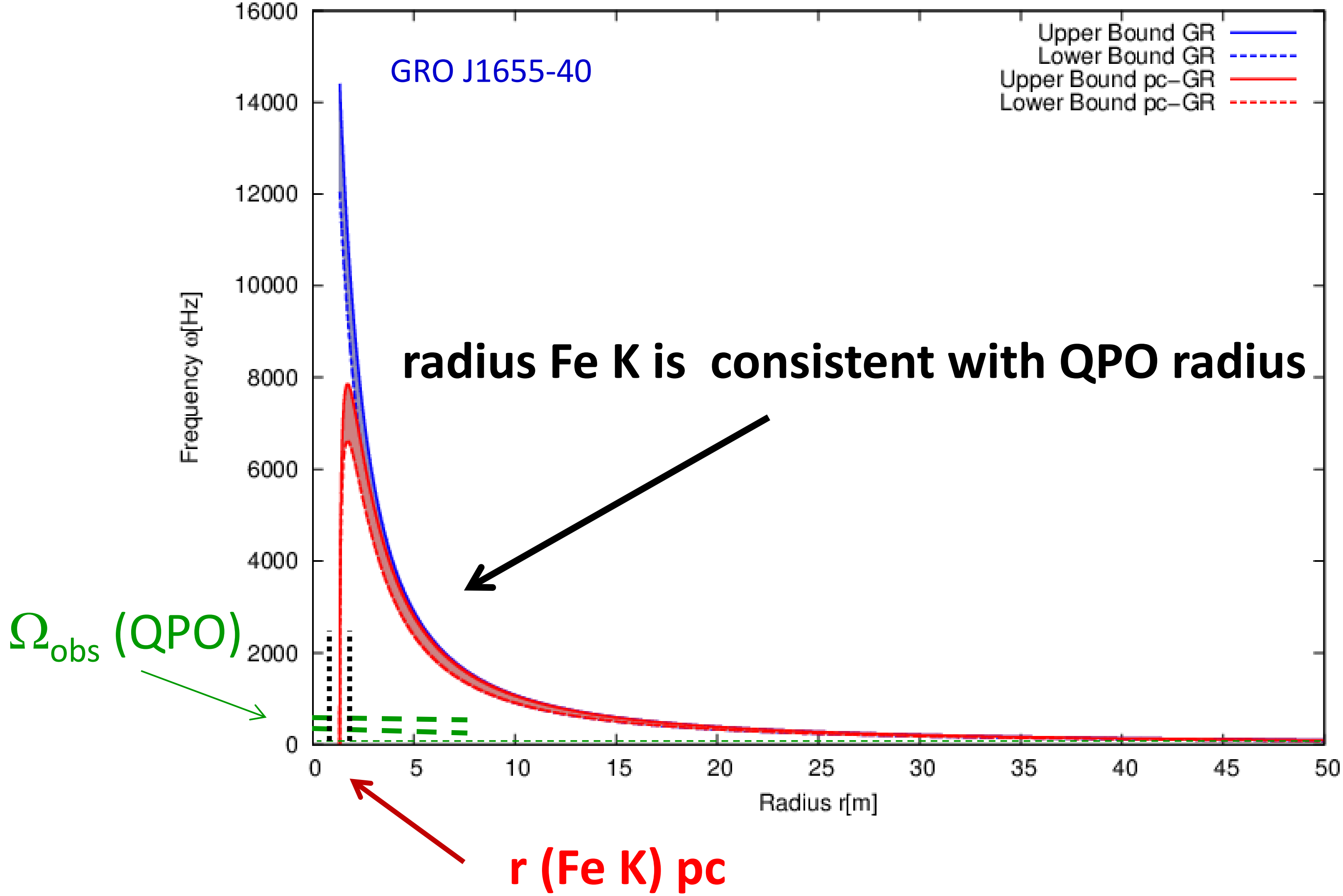


Galactic binaries in the pc-theory



Summary

motivated by the **upcoming EHT observations** of the BH in the GC and in M87, ray-tracing methods have been applied both to standard GR and pc-GR

the correction terms in pc-GR include:
- a modified concept of the ISCO, allowing particles to get closer to the BH
- a reducued graviational redshift and slower orbital motions
- the appearence of a maximum orbital frequency and a related zero flux emission at $d\omega/dt = 0$
- brighter accretion discs in pc-GR

the emissivity profiles of matter when approching the BH are different in GR and pc-GR allowing **a robust first test of GR and pc-GR**, especially to the appearance of a dark ring in pc-GR

the Iron **Kα emission-line profiles are also differen**t and those are good observables to test regions of strong gravity

the observable differences between GR and pc-GR are remarkable different and will provide new tests of GR going beyond the 4 classicial tests of Einsteins GR theory