Probing strong-field gravity: shadows, photon rings, flares, stars

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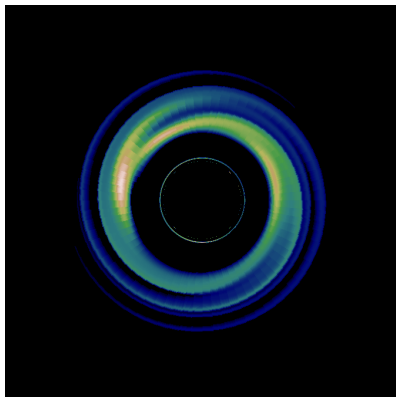
[1]CNRS/Observatoire de Paris/LESIA



1 Horizon-scale black hole observations

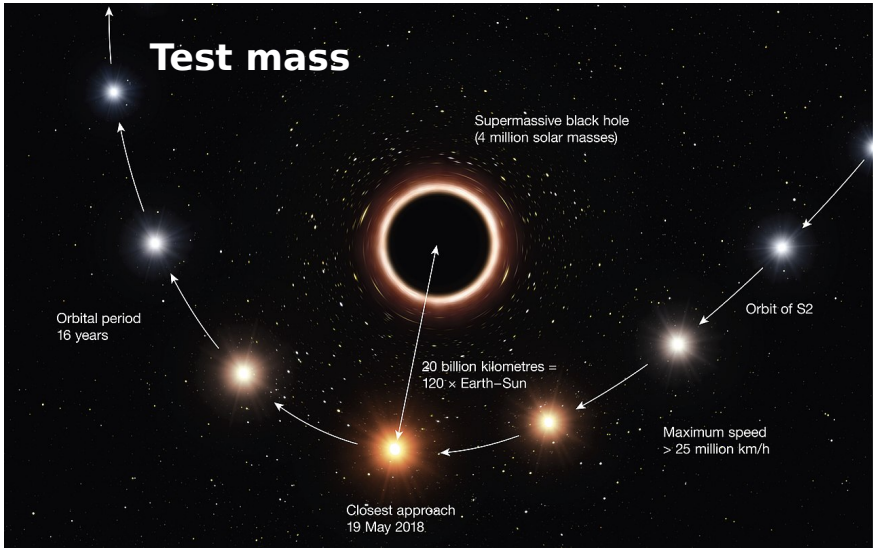
2 Photon rings and shadows
- Photon rings
- Shadows

3 Flares and stars
- Flares
- Stars

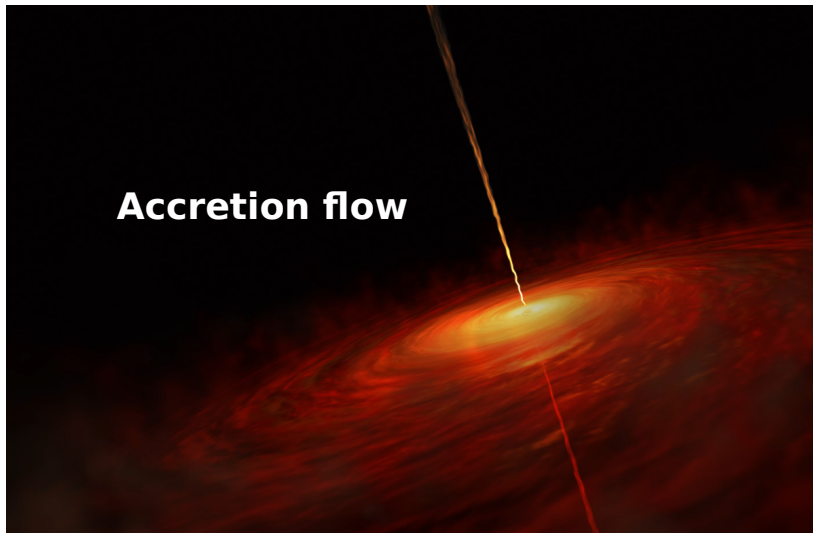
Testing Kerr hypothesis with SMBH?

- $\star$BH are better: curvature is higher
- EFT coupling cst *very* weak if relevant scale is Planck
- Does it make any sense?

- Strong-field GR is poorly tested: use all available probes!
- BHs are reasonable places to look for GR failure
- Uniqueness theorem can break in non-GR: SMBH $\neq \star$BH?
- Compact objects *very different from* BH
- The relevant scale of GR breaking might not be Planck
- $\rightarrow$ *Very relevant to check as much as we can!*

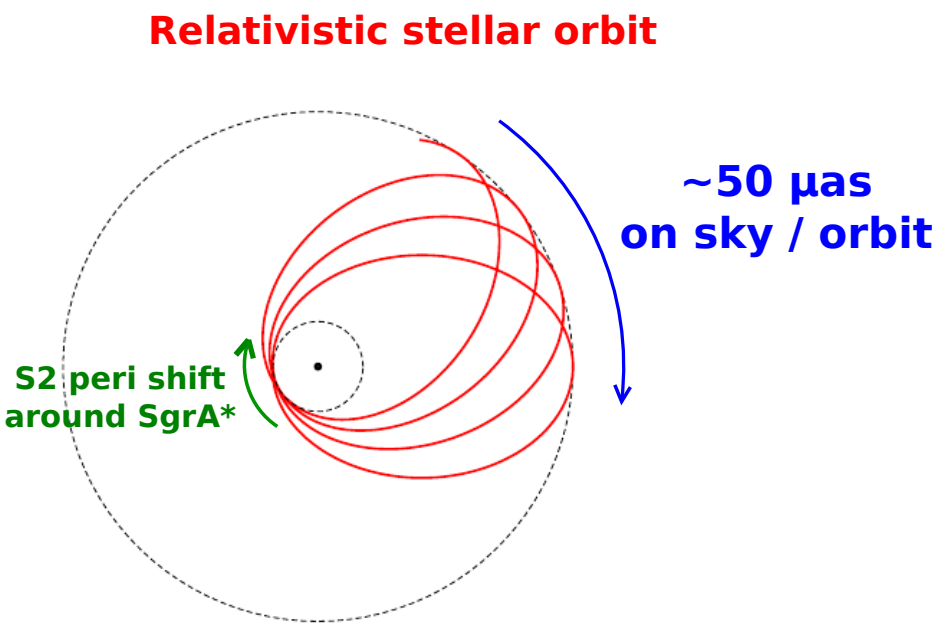


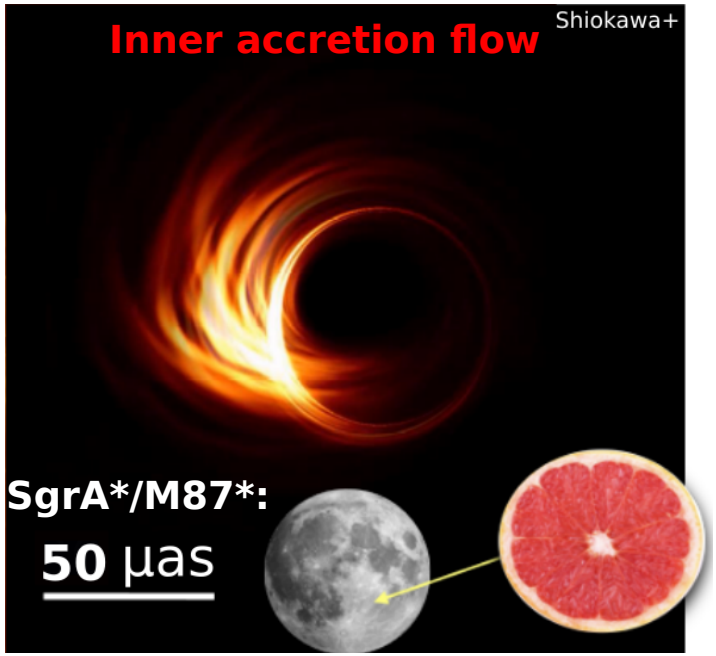
Credit: ESO



Electromagnetic probes of BH surroundings

- Star (test mass): clean, but far
- Accretion: close, but astrophysics-poluted

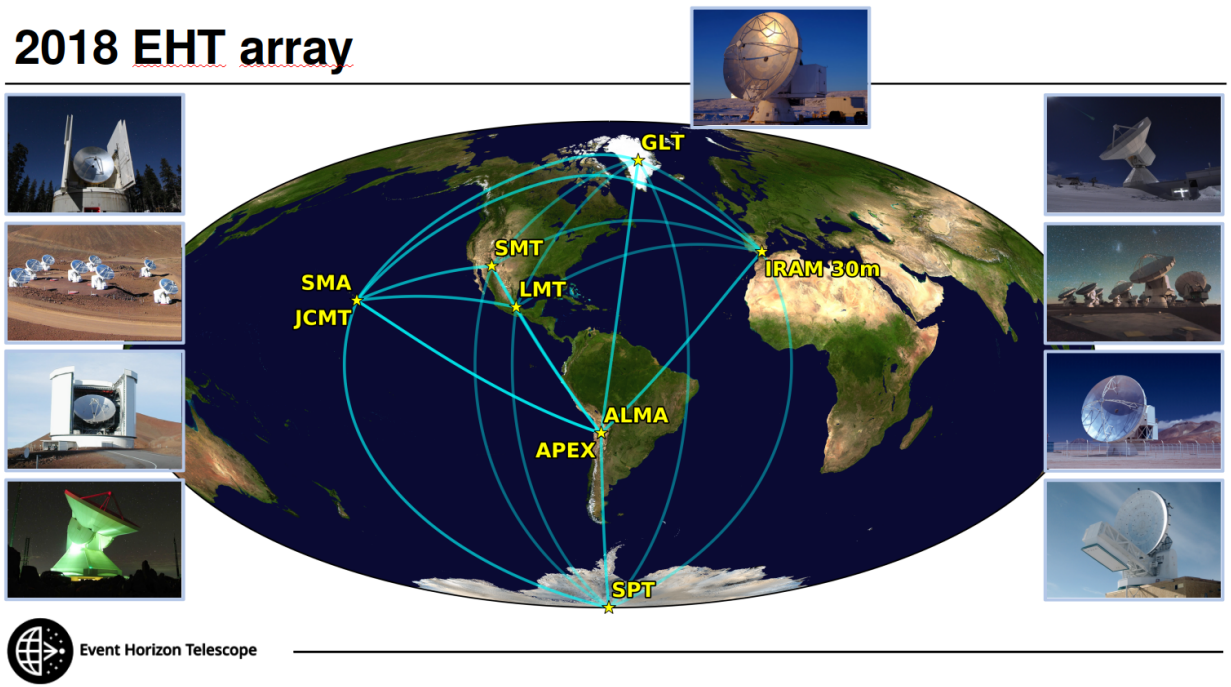


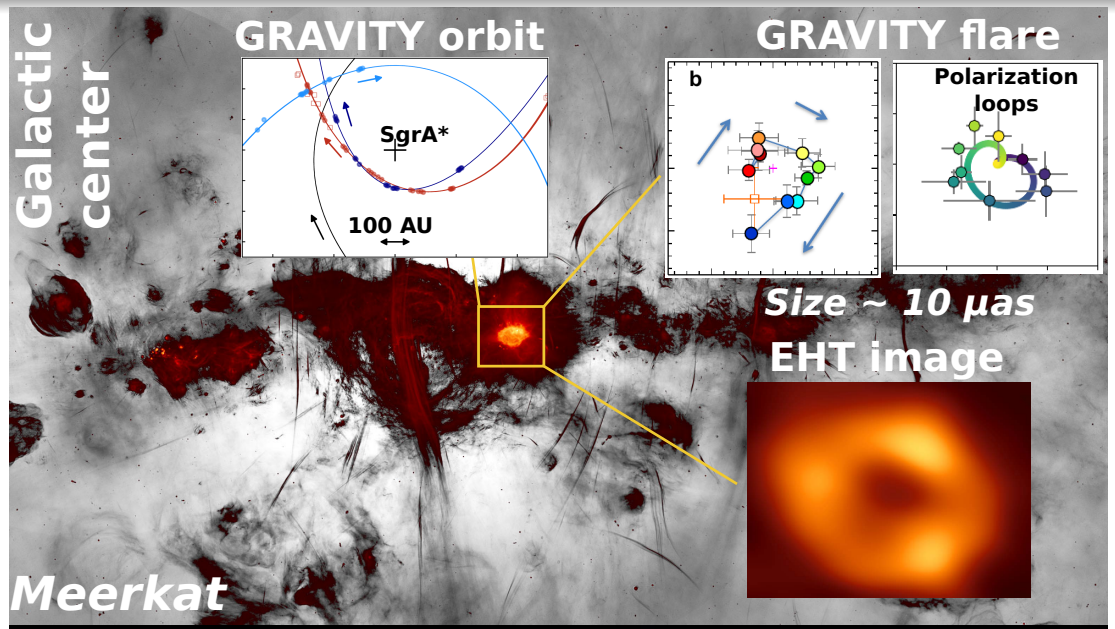


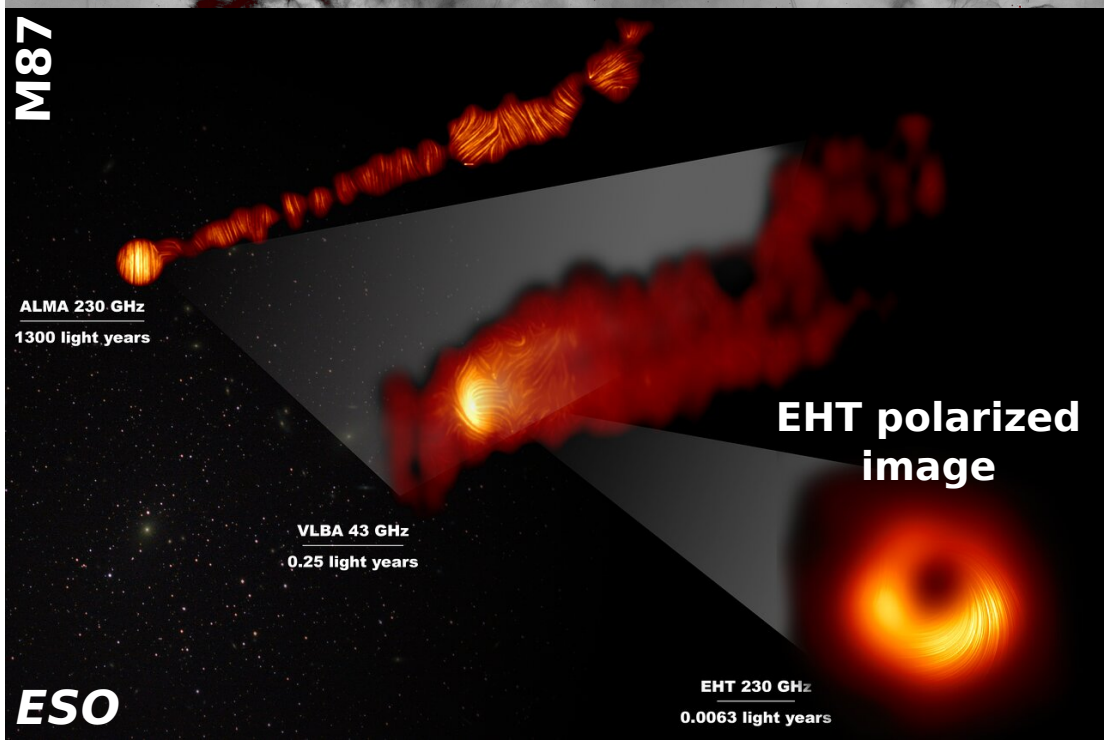
Strong-field test at SgrA*/M87*

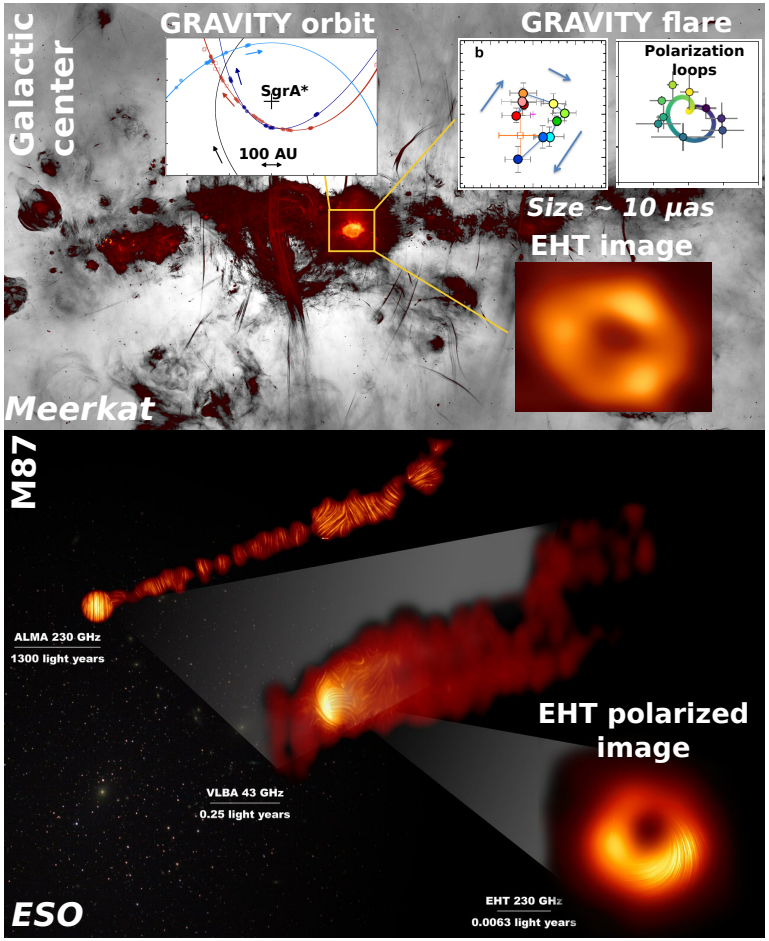
- Tens of μas scale astrometry / imaging
- $\rightarrow$ GRAVITY / EHT

VLTI/GRAVITY


2018 EHT array
GLT
SMT
LMT
SMA
JCMT
IRAM 30m
ALMA
APEX
SPT
Event Horizon Telescope


Galactic center
GRAVITY orbit
SgrA*
100 AU
GRAVITY flare
b
Polarization loops
Size ~ 10 μas
EHT image
Meerkat


M87
ALMA 230 GHz
1300 light years
VLBA 43 GHz
0.25 light years
EHT polarized image
EHT 230 GHz
0.0063 light years
ESO



Testing gravity?

- GRAVITY+EHT: fantastic probes of inner accretion flow
- What about testing gravity?

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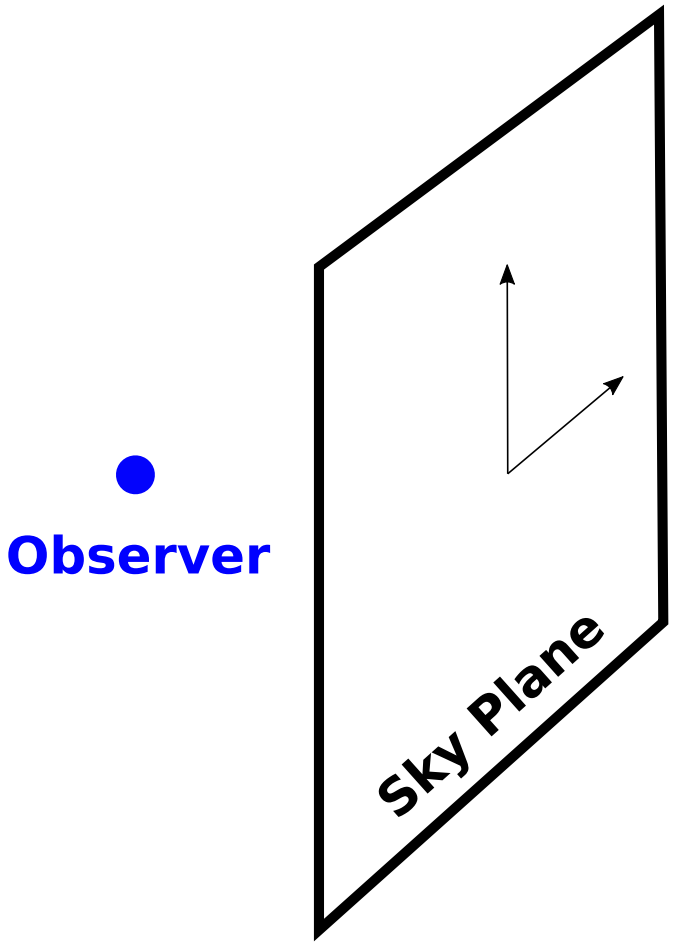
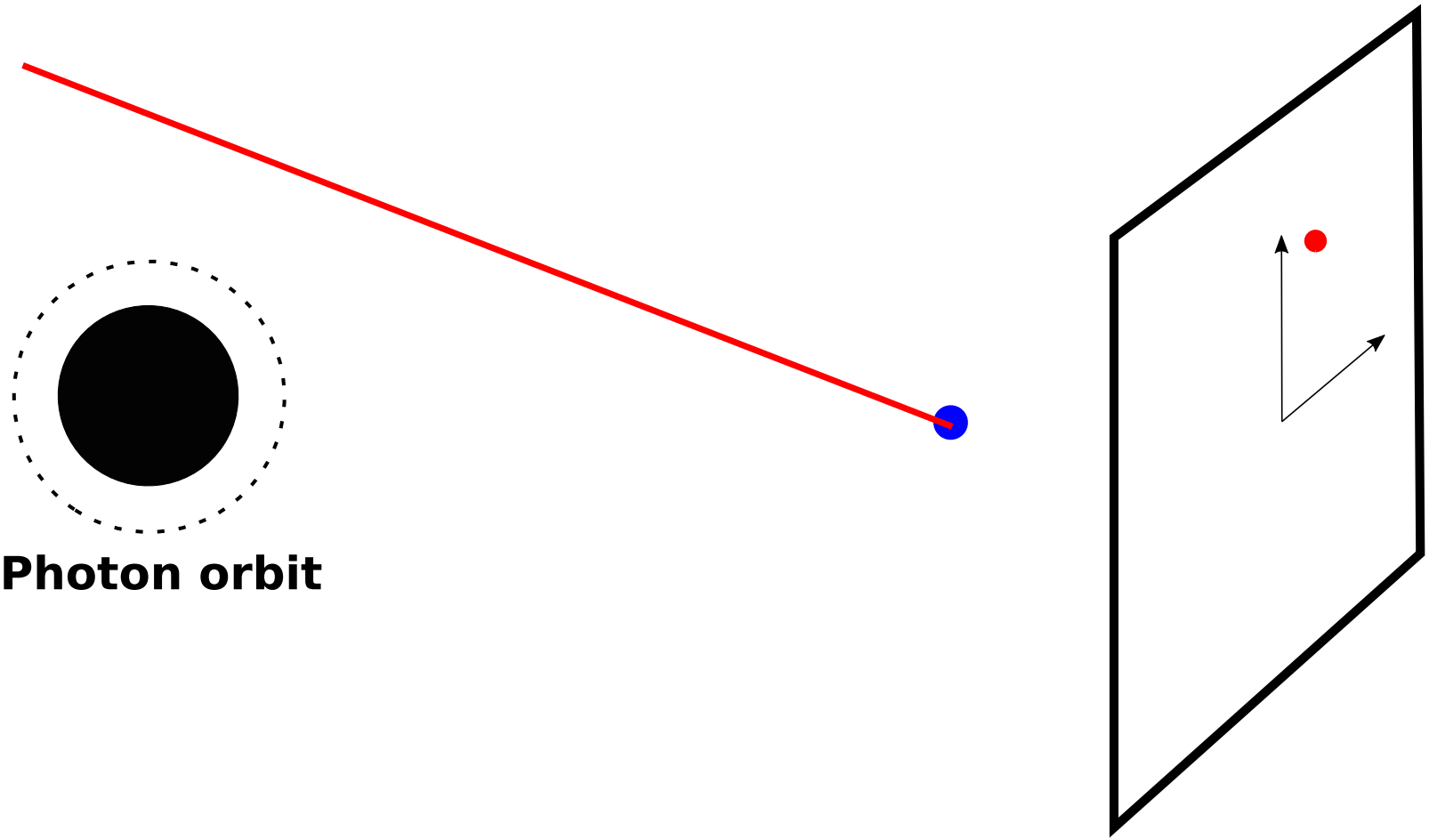
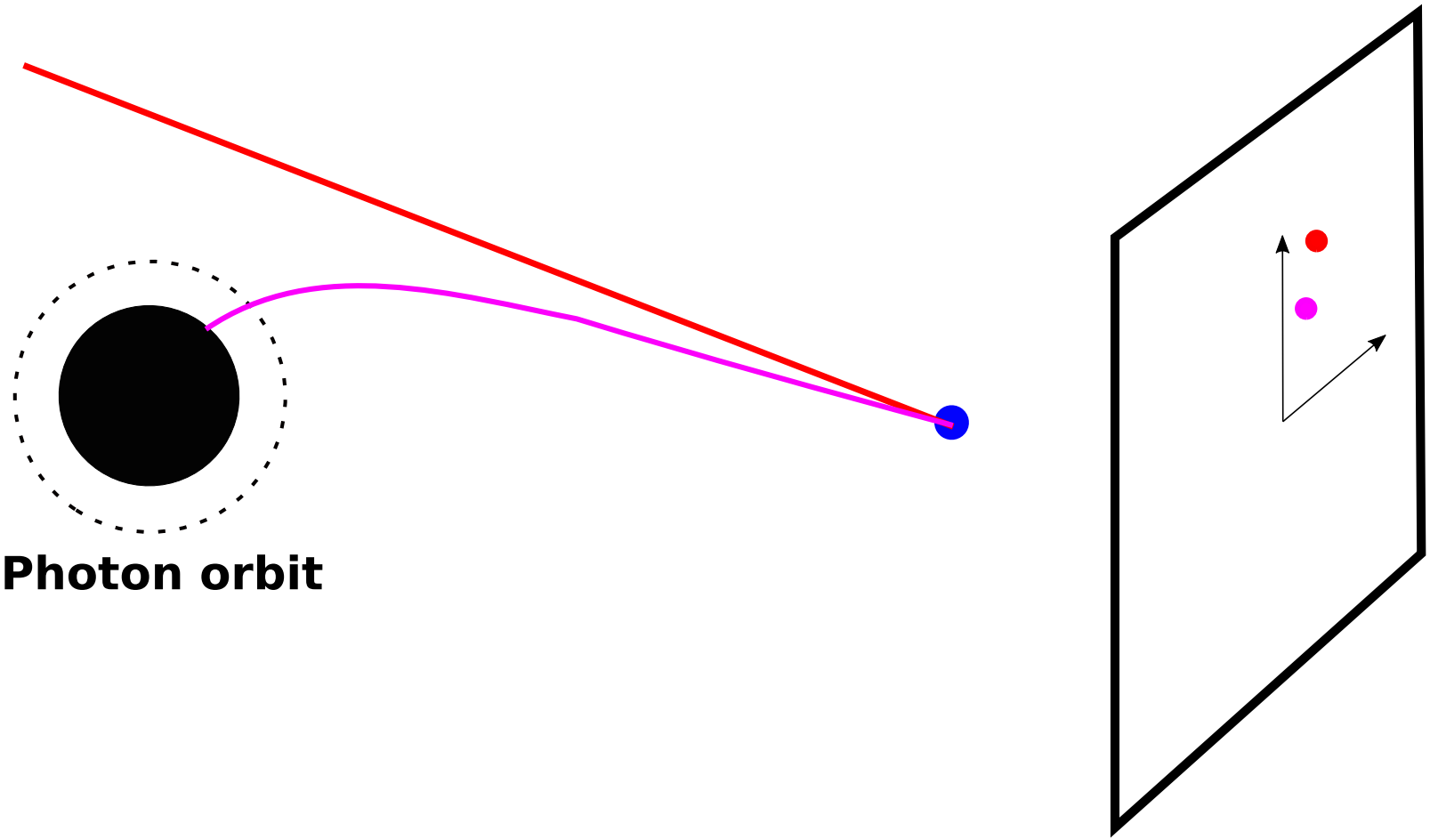
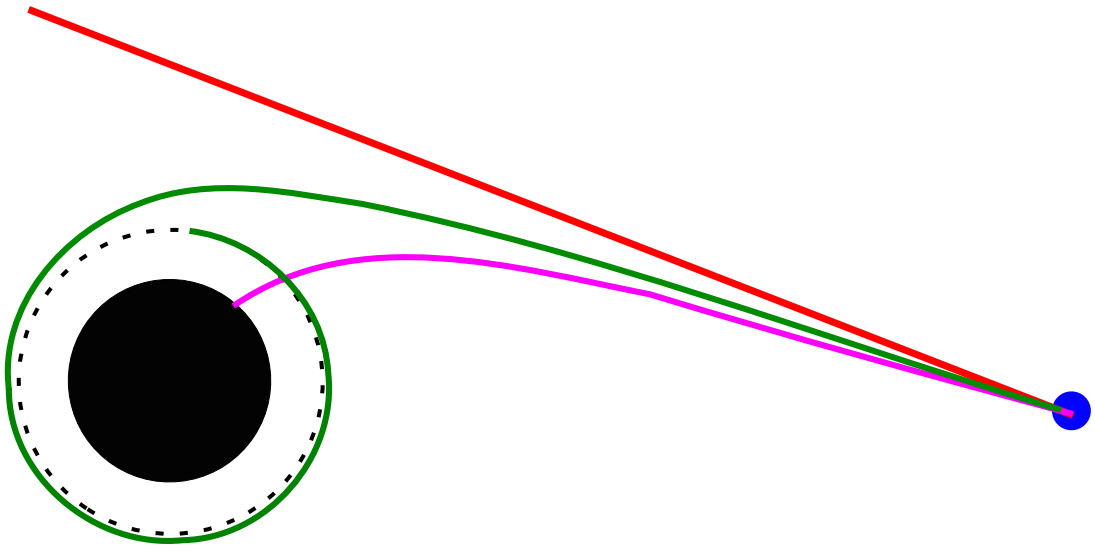
Photon orbit

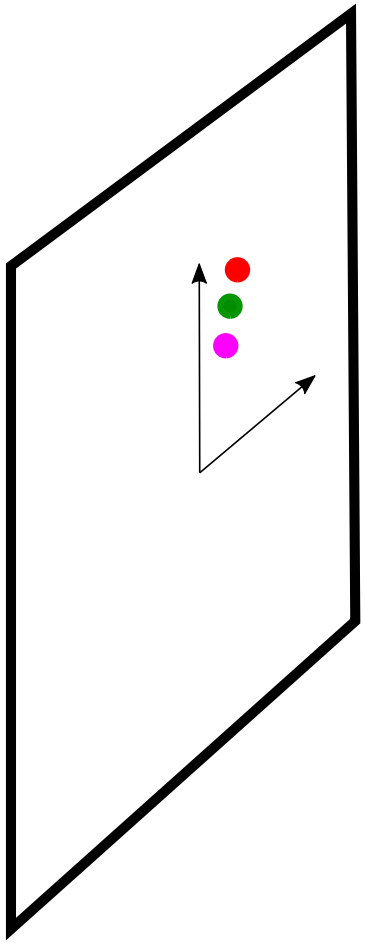


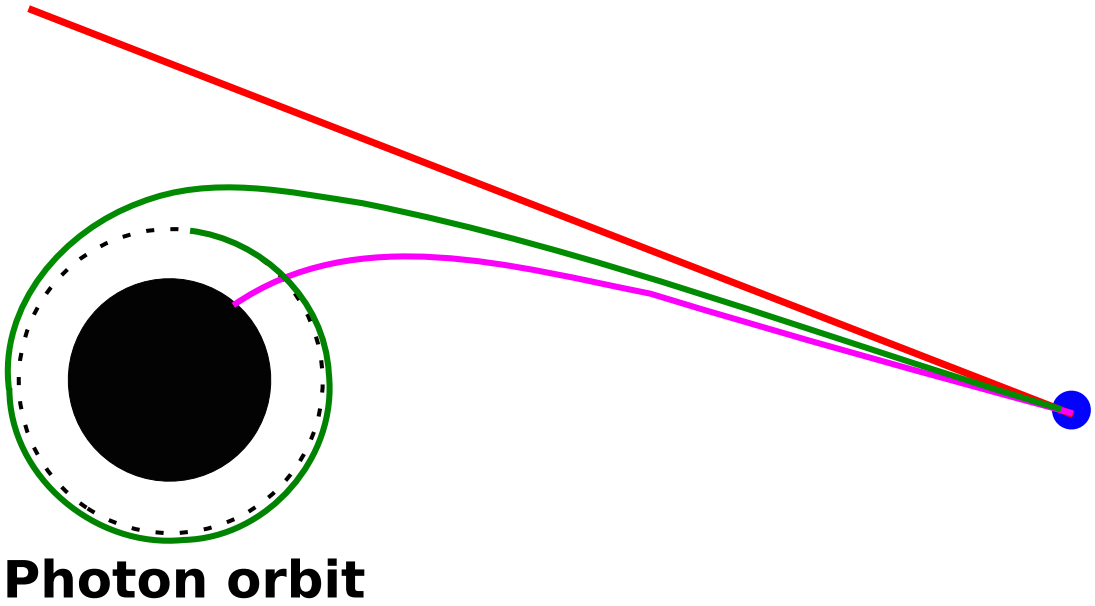

Photon orbit

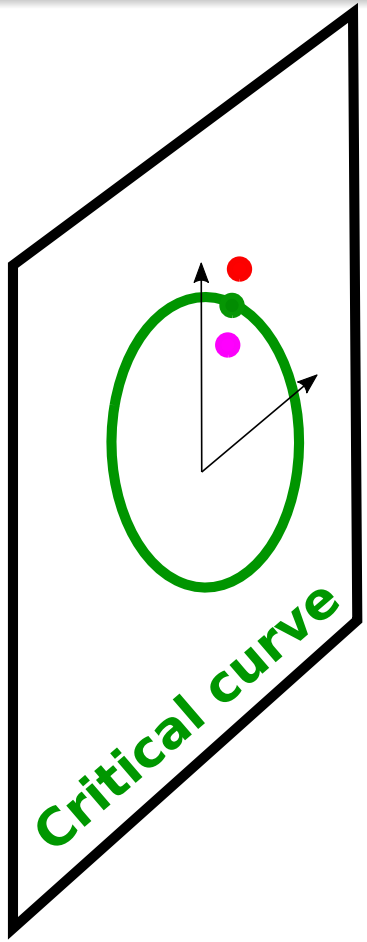

Photon orbit



Photon orbit

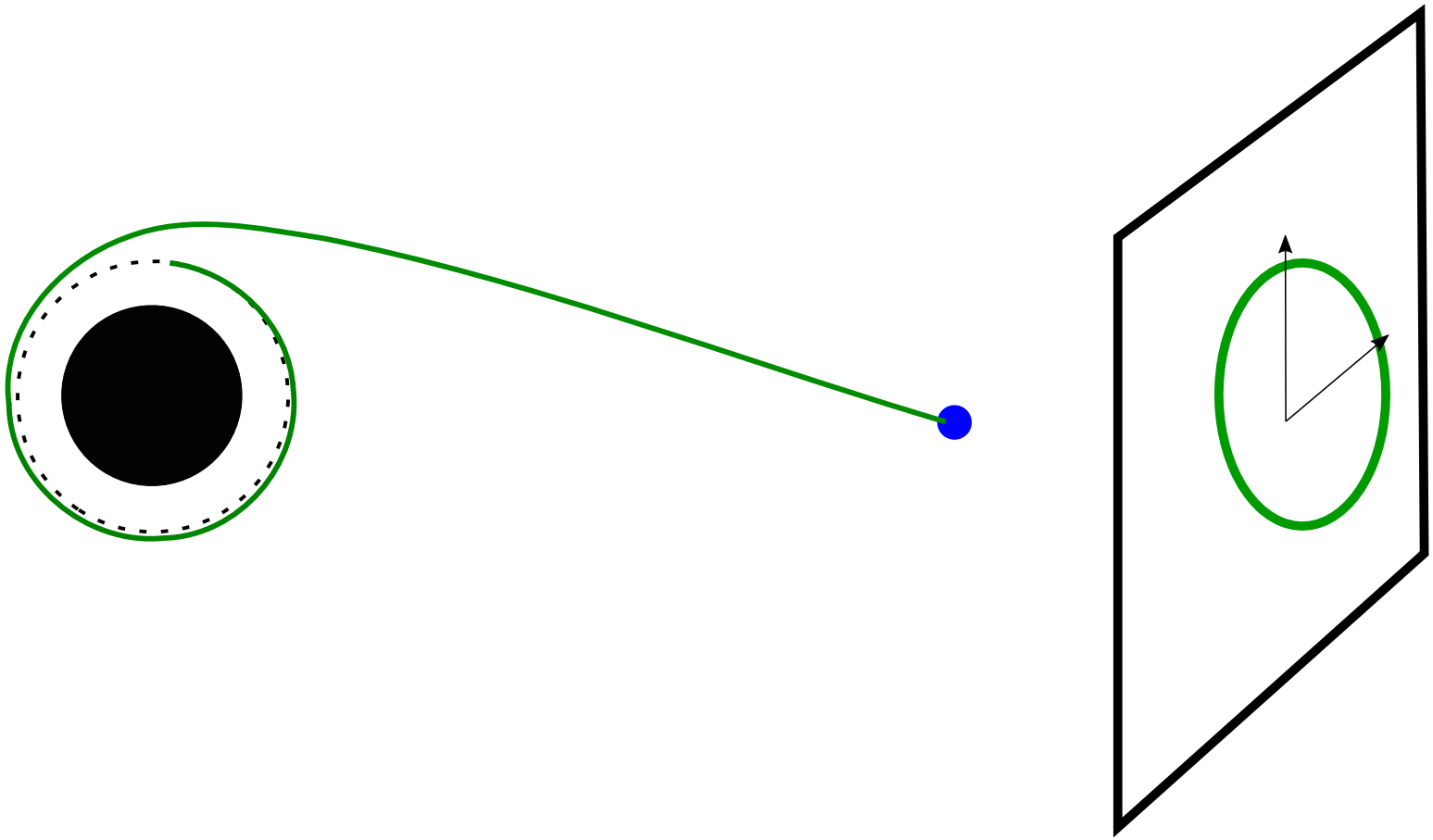


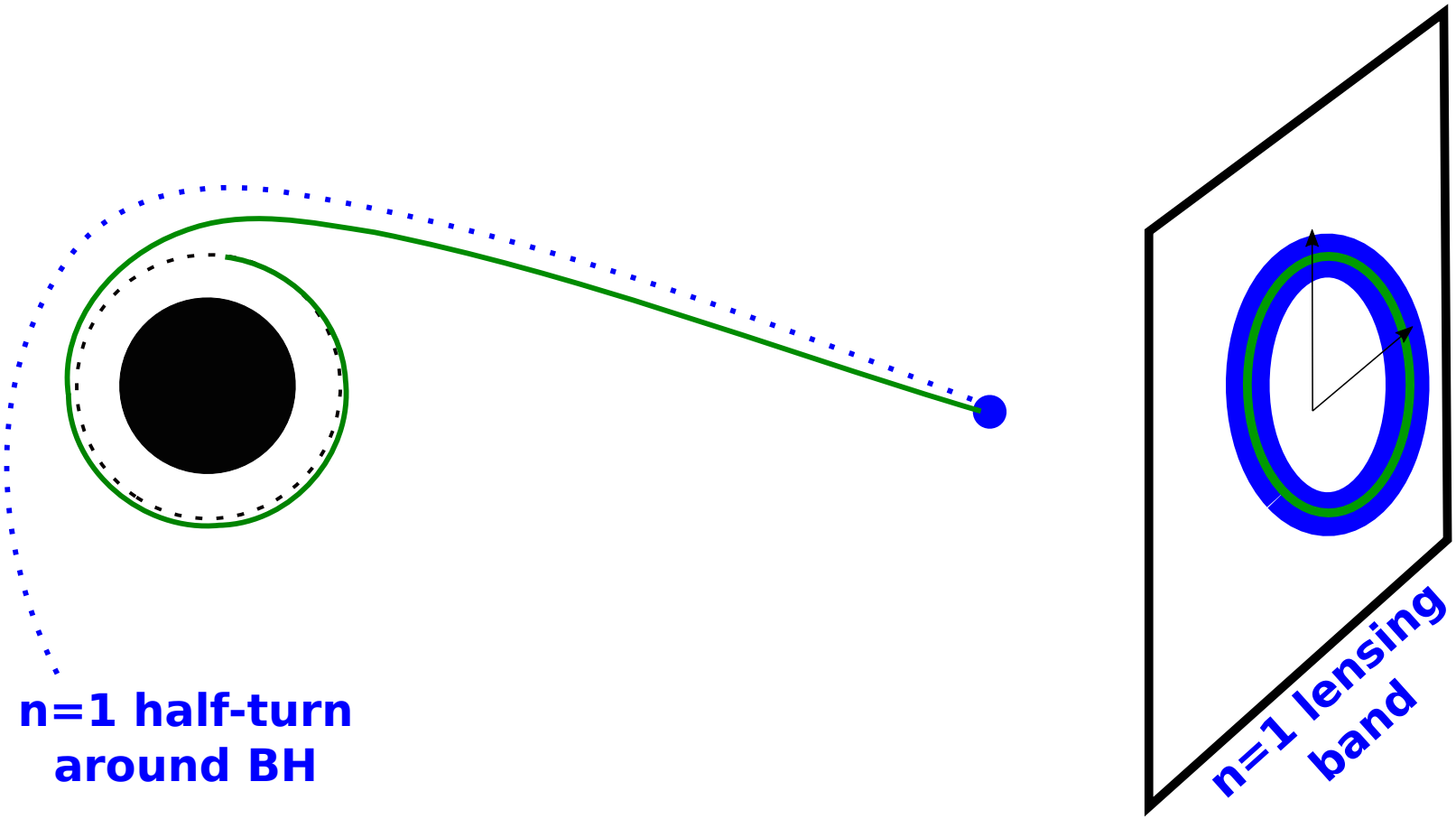


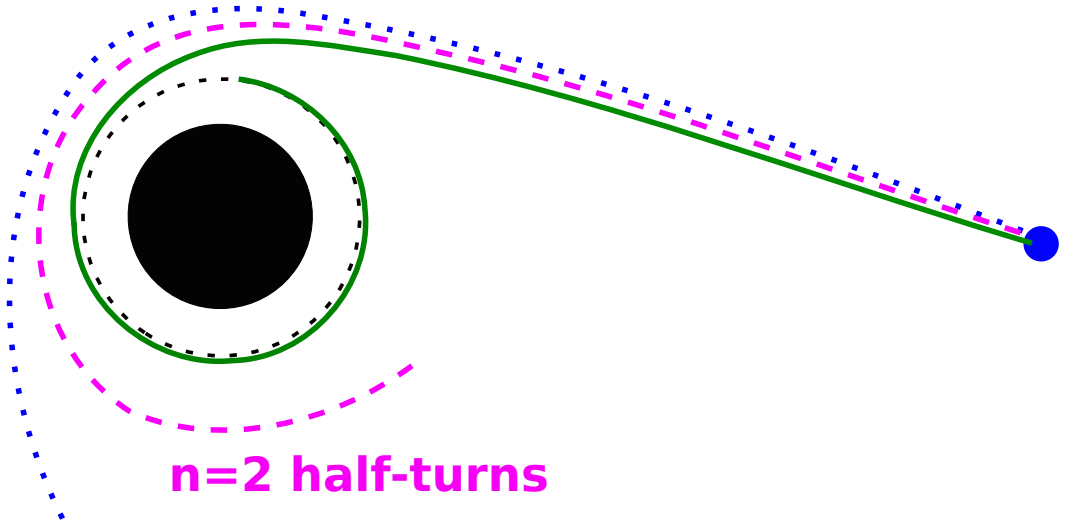


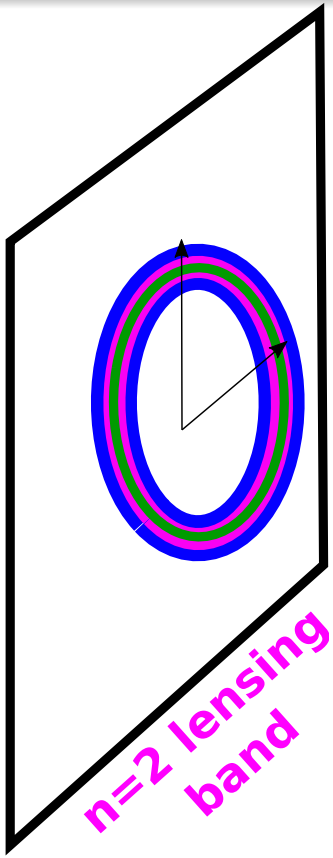
Critical curve

- **Spherical photon orbits** = Kerr bound null geodesics
- Its image = **Critical curve**, dictated by **gravity only**
- not observable! *Mathematical locus* on sky



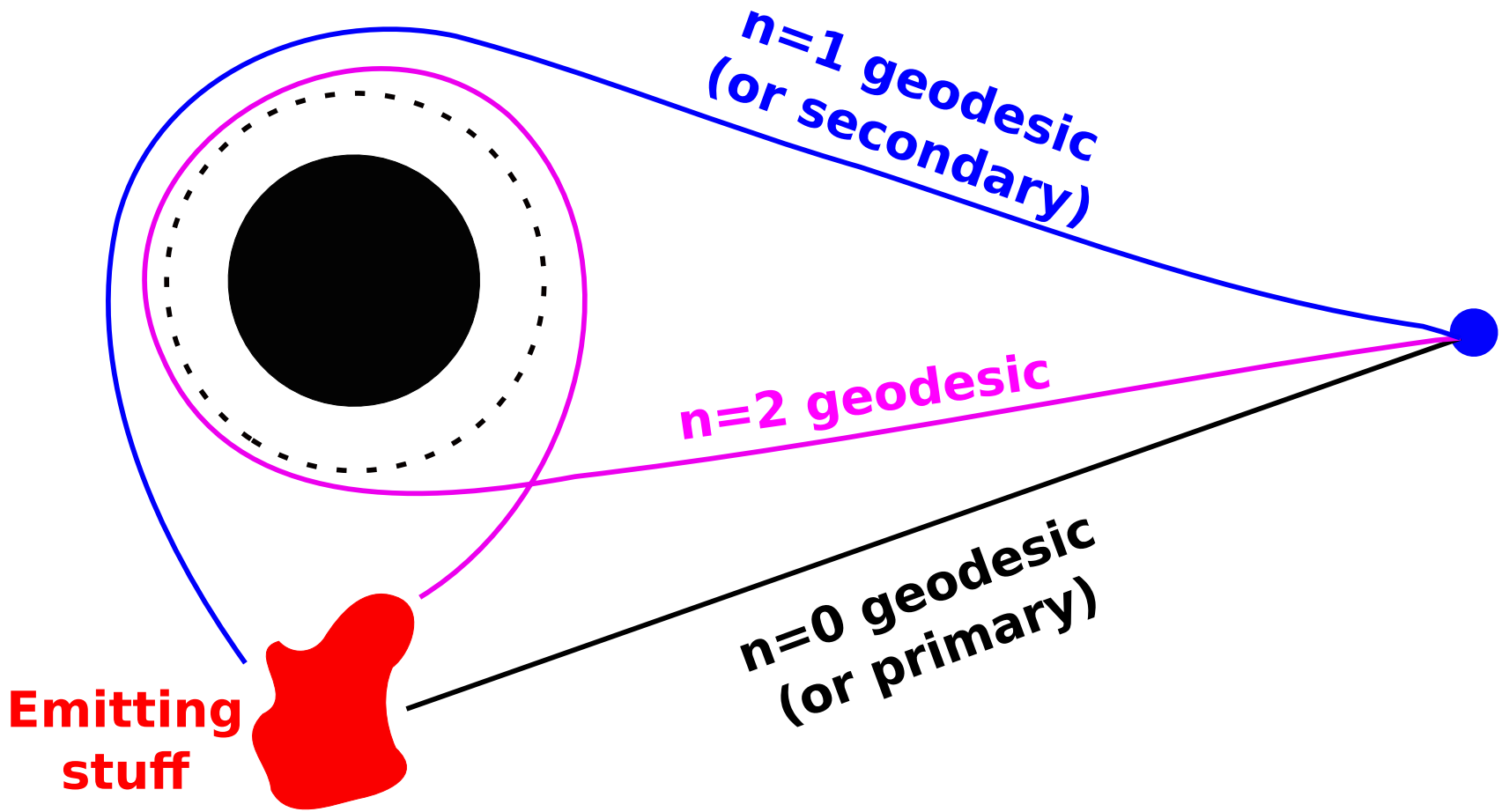

n=1 half-turn
around BH
n=1 lensing
band





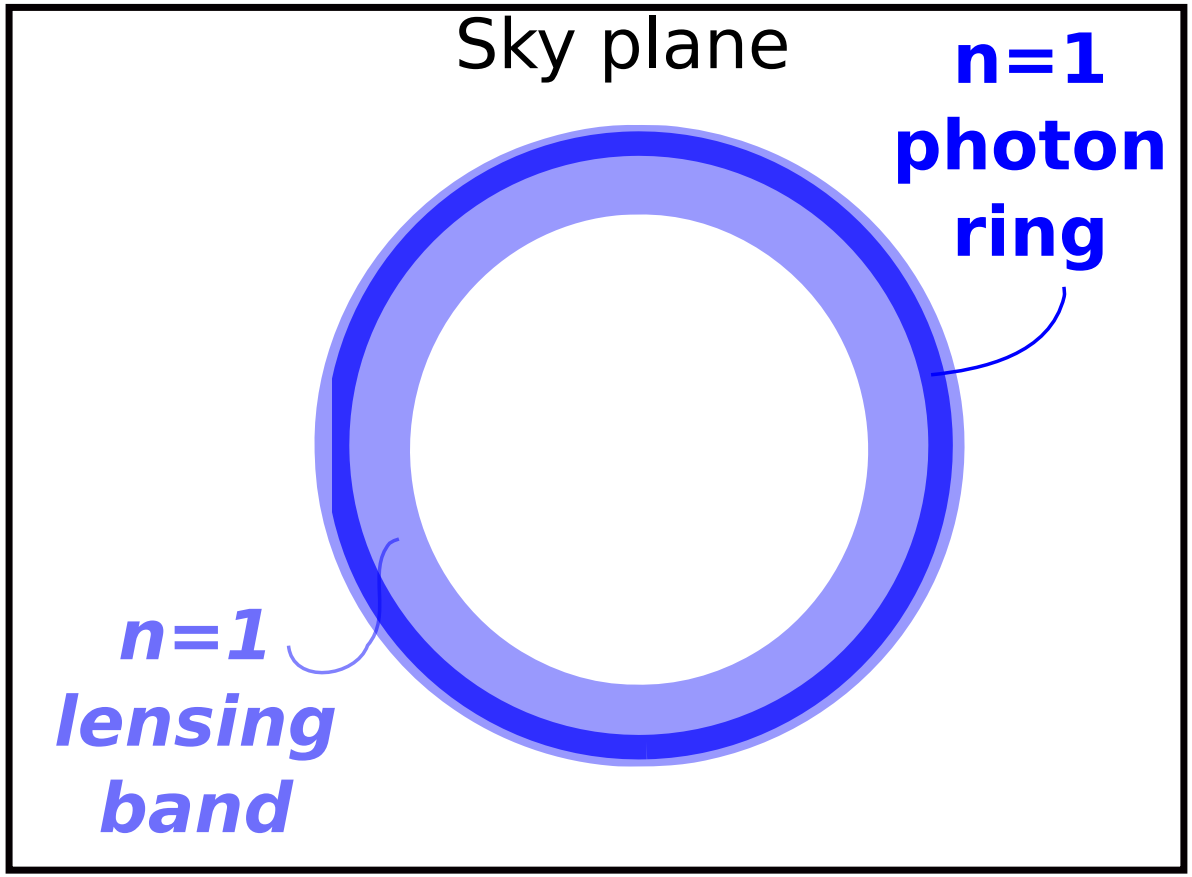
Lensing bands

- Locus on sky of geodesics that make n half turns: **lensing bands** $\rightarrow$ *nearly-bound* Kerr null geodesics
- Again not observable!
- No emission for the time being! Just shooting geodesics



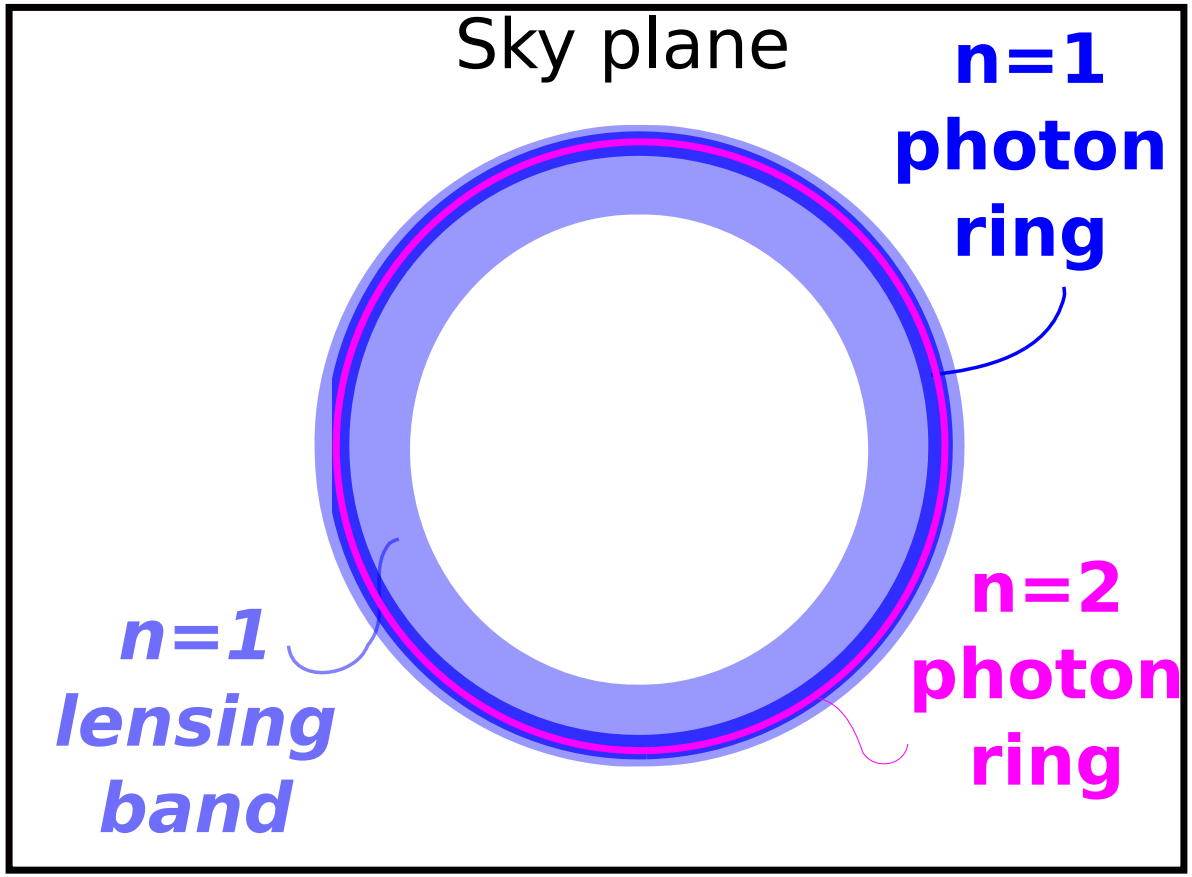
Adding astrophysics: emitting region

- Sequence of lensed images contained in lensing bands
- For each band, *some* part contains *some* flux
- These images are the (astro-dependent) observables



Photon rings

- Bright part of lensing band = **photon rings** = *observable*
- Infinite sequence of such rings
- Depends on **gravity + astro**



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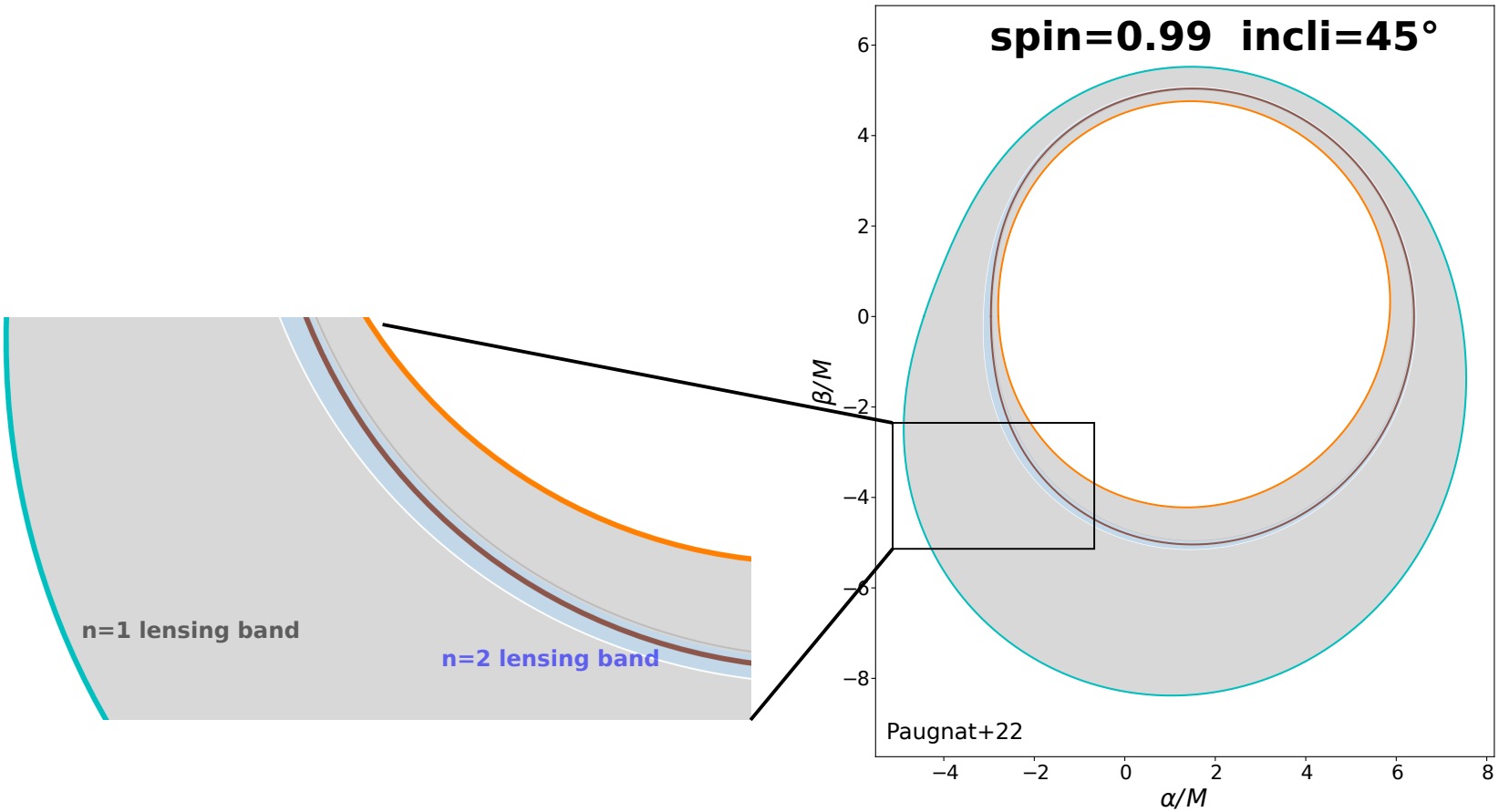
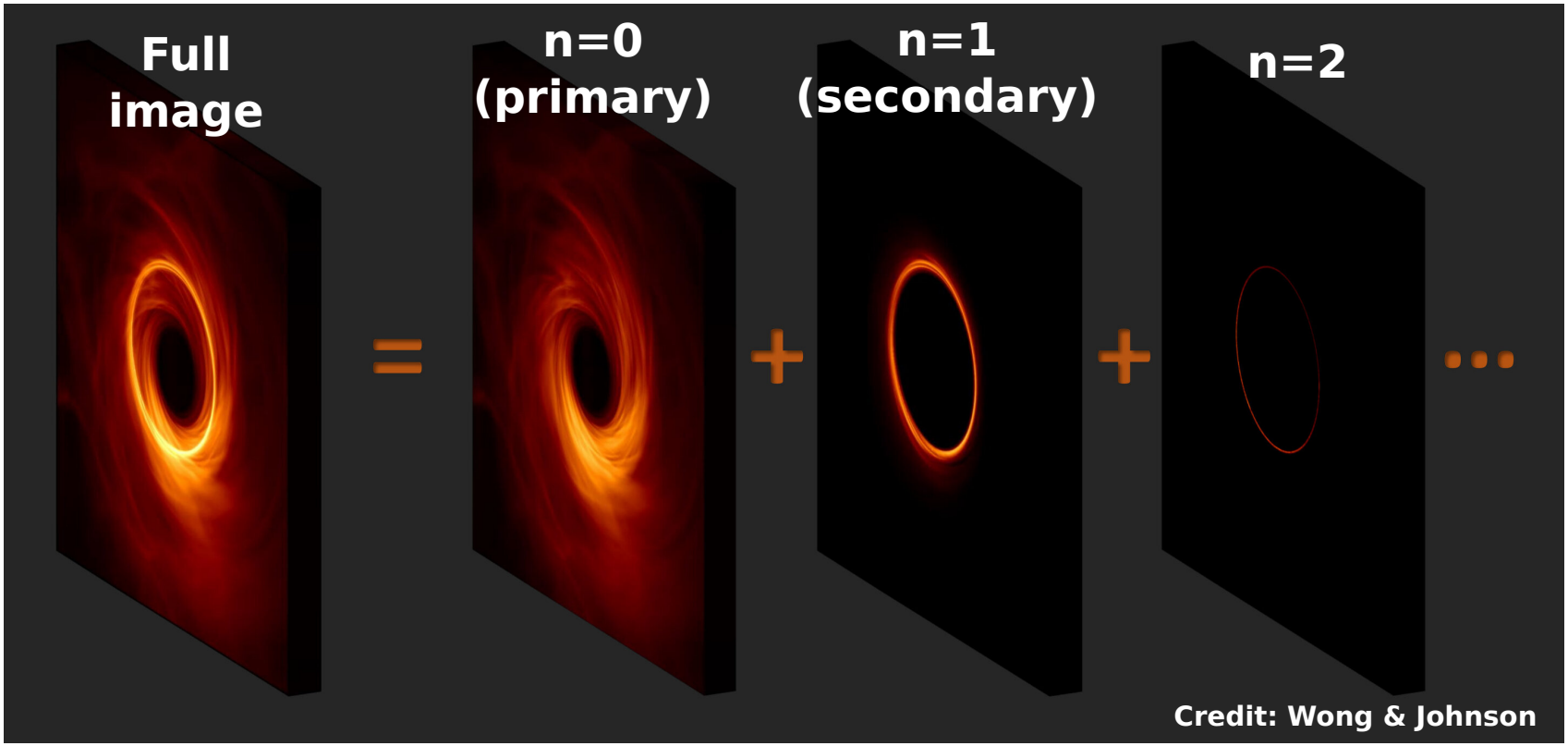


Lensing bands in real life



Photon rings in real life

- Rather thin stuff to detect!

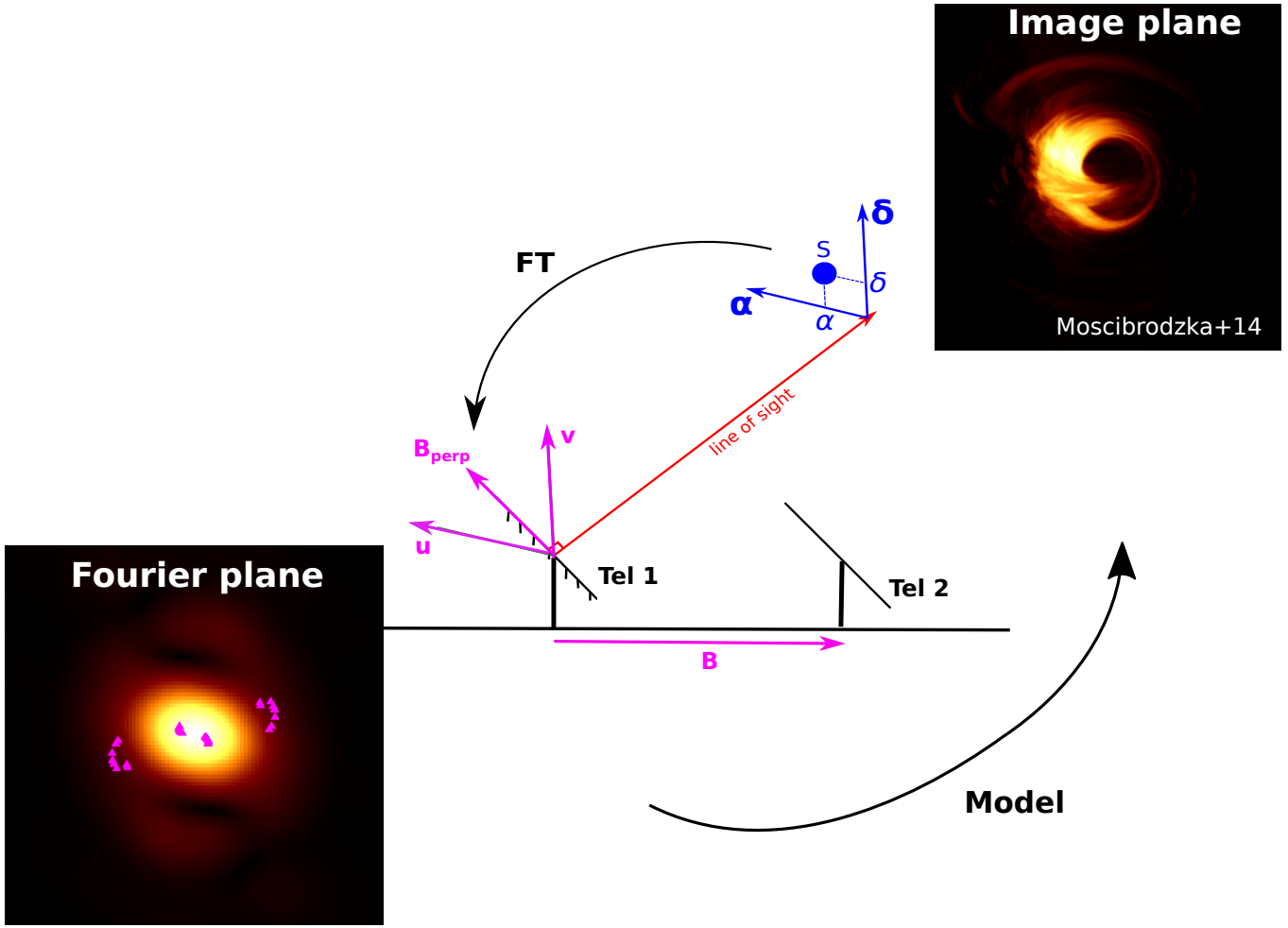
Photon ring conditions

- Optically thin
- Localized emission (disk, jet, blob; not spherical shell)
- $\rightarrow$ rather generic!

Photon ring properties

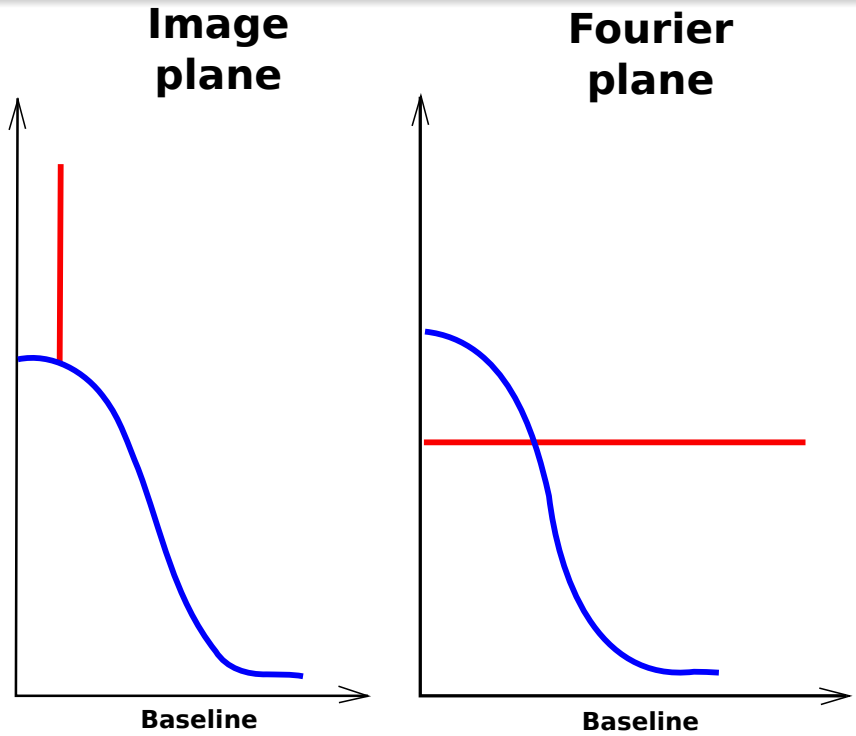
- Logarithmic divergence of intensity close to critical curve
- Exponential convergence to critical curve, and decreasing ring width: $w_{n+1} = e^{-\gamma} w_n$, $\gamma =$ *Lyapunov exponent*

- See Johnson+20, Gralla & Lupsasca 20, Paugnat+22, Lupsasca+24 (*arxiv:2402.01290*)



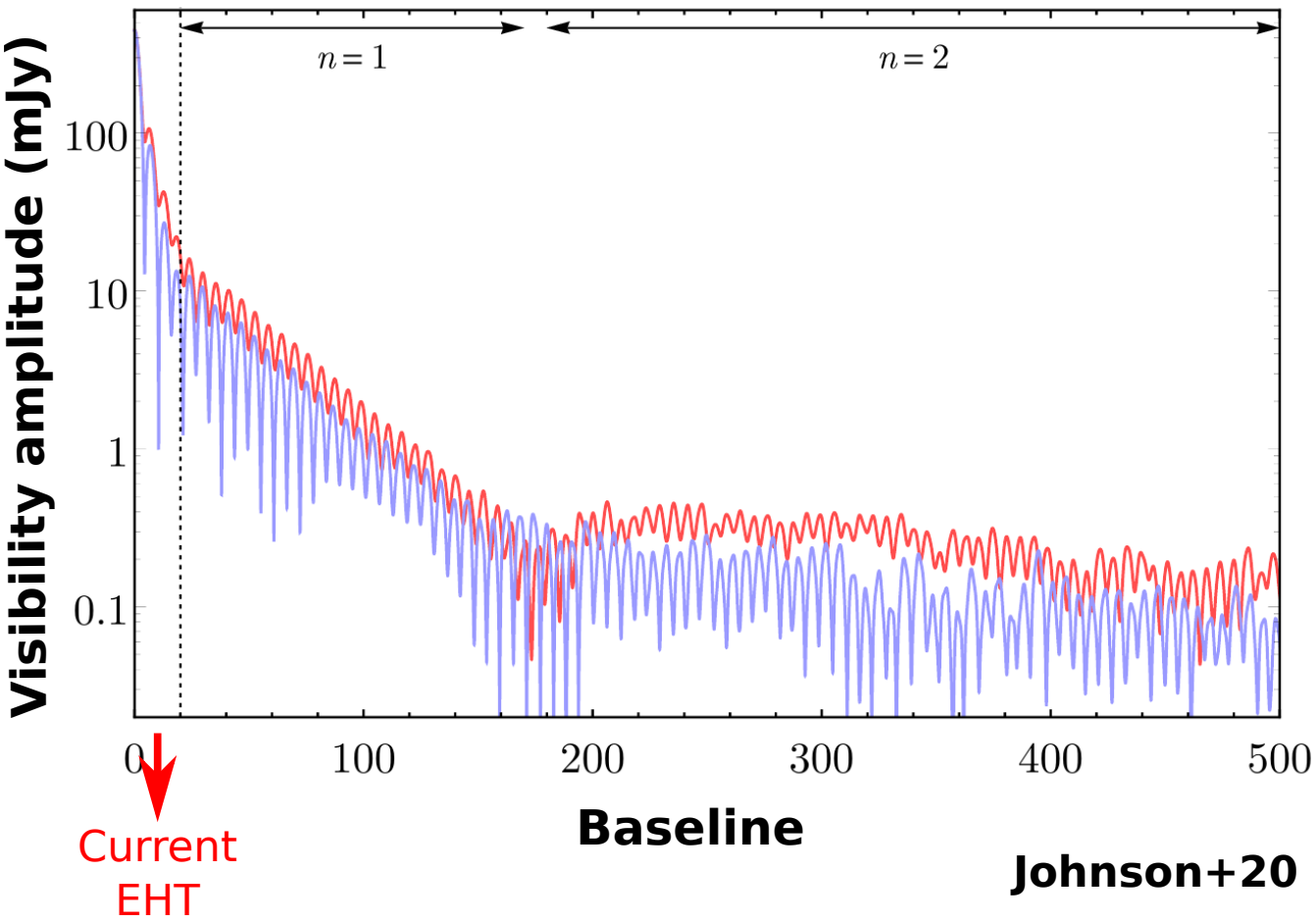
Observable

- Complex visibility: FT of image
- Sampled by interferometry



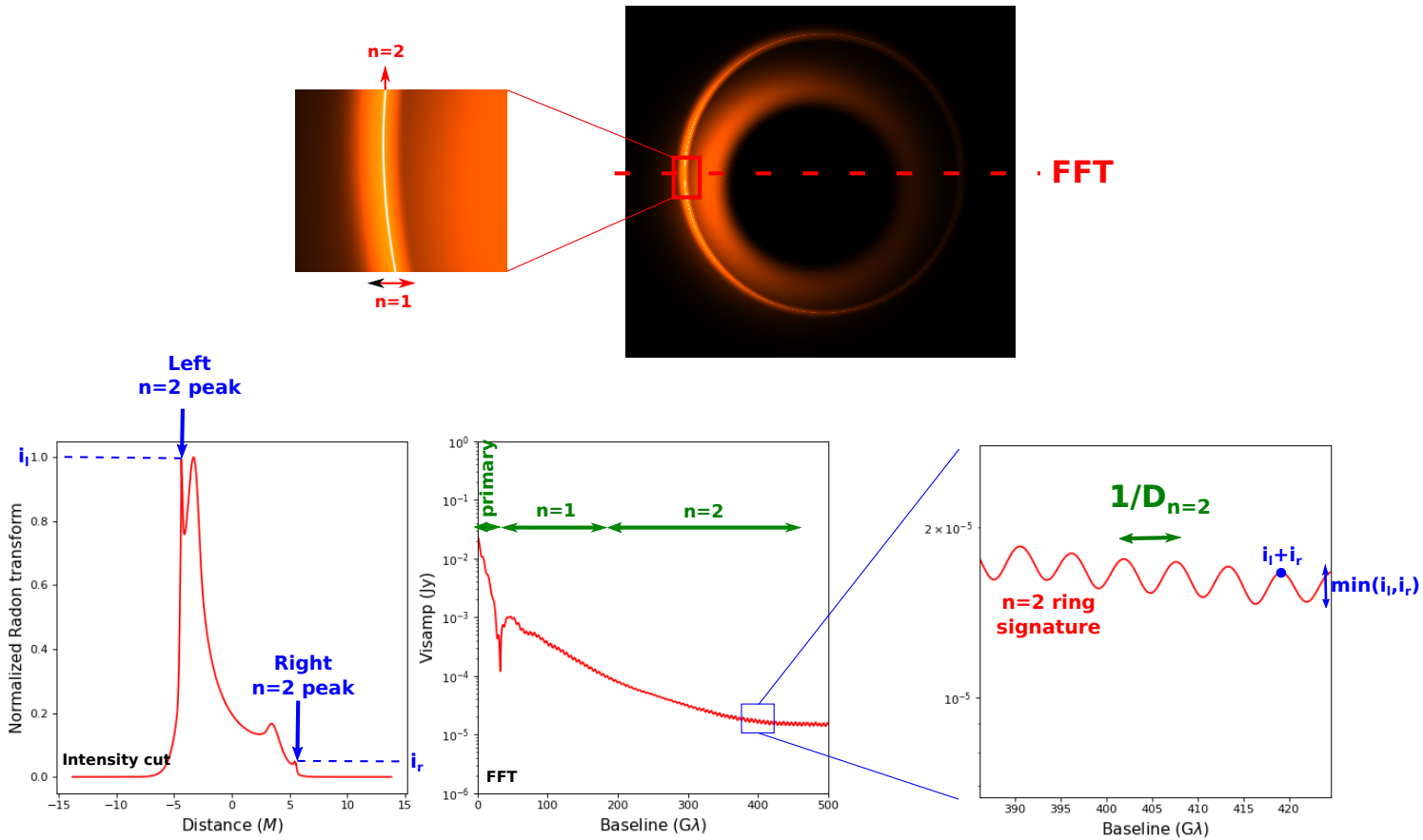
Detecting sharp features (photon ring!)

- Image = Gaussian + Dirac
- FT = Gaussian + constant
- The sharper in image plane, the further you survive in Fourier freq
- So **sharp feature should dominate at high Fourier freq!**



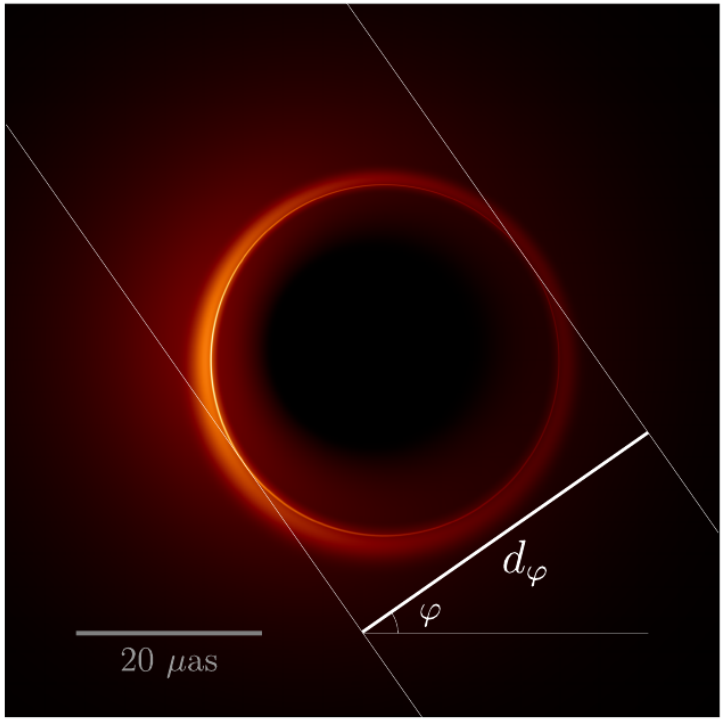
Photon ring visibility signature

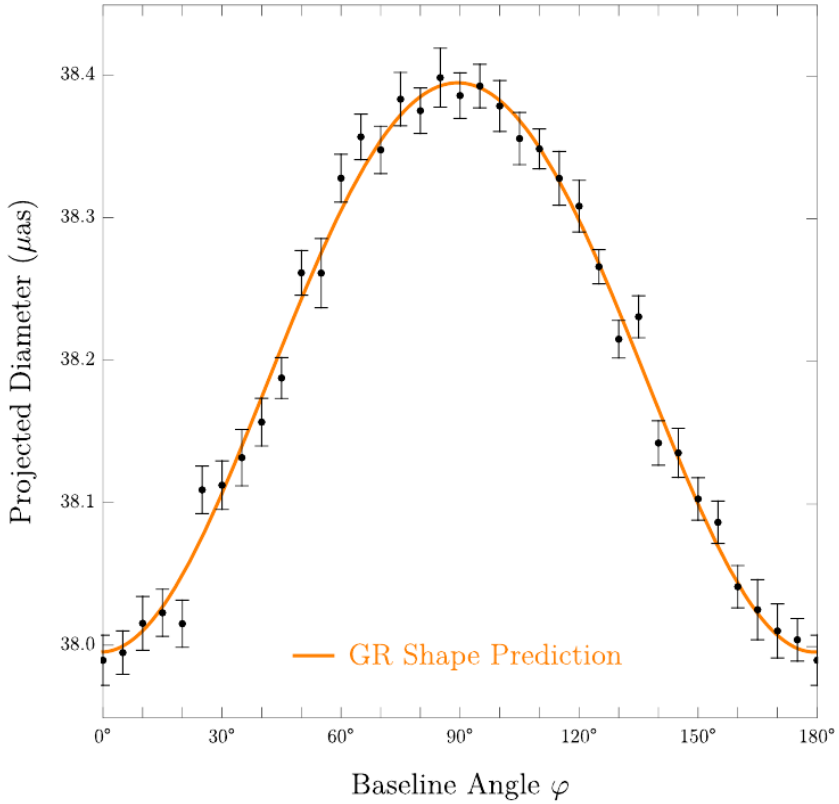
- Various rings dominate at higher and higher freq



Photon rings diameters

- Measure $D_n \rightarrow$ Kerr test??





Gralla, Lupsasca, Marrone, 2020

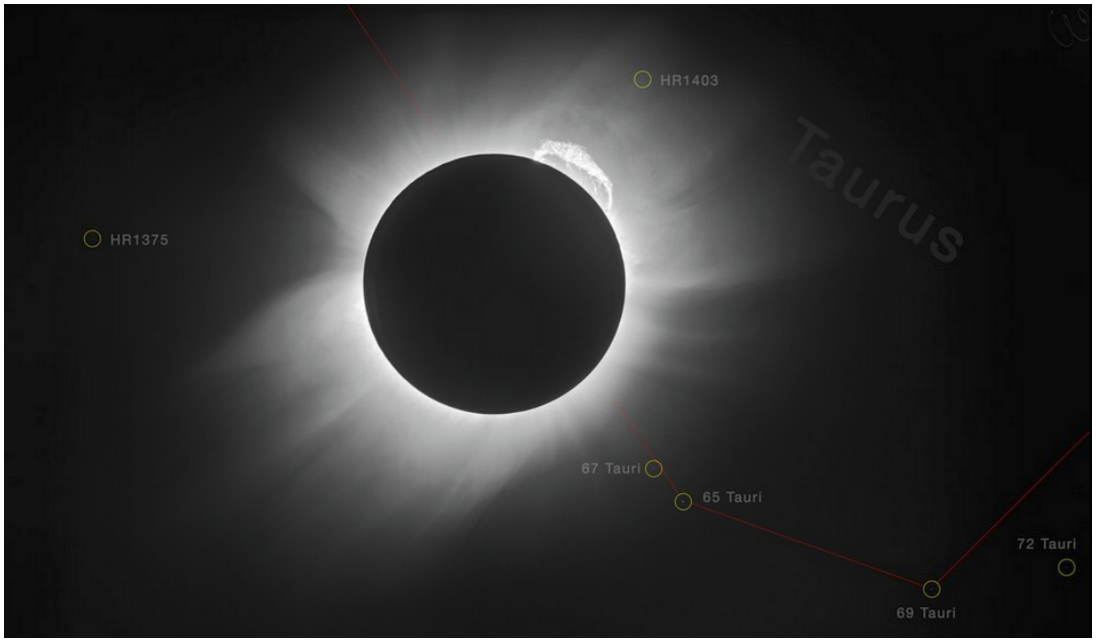
- $d(\varphi) \to$ astro-independent shape in Kerr (*circlipse*)
- "Universal observable property" of $n = 2$ photon ring
- Kerr test!

What kind of test?

- **Consistency** test: what we observe is in agreement with Kerr (but likely with many other things as well)
- **Discriminatory** test: what we observe is more in agreement with Kerr (Bayesian meaning) than with alternatives

Caveat!

- **Degeneracy** astro/geometry: a discriminatory test should be sure to break it
- “Theory A + Astro model B” can lead to same observables as “Theory B + Astro model A”...
- Very difficult given our poor knowledge of the flow



29 May 1919 solar eclipse
"Eddington experiment":
an example of a discriminatory test

REVOLUTION IN SCIENCE.

NEW THEORY OF THE UNIVERSE.

NEWTONIAN IDEAS OVERTHROWN.

Yesterday afternoon in the rooms of the Royal Society, at a joint session of the Royal and Astronomical Societies, the results obtained by British observers of the total solar eclipse of May 29 were discussed.

The greatest possible interest had been aroused in scientific circles by the hope that rival theories of a fundamental physical problem would be put to the test, and there was a very large attendance of astronomers and physicists. It was generally accepted that the observations were decisive in the verifying of the prediction of the famous physicist, Einstein, stated by the President of the Royal Society as being the most remarkable scientific event since the discovery of the predicted existence of the planet Neptune. But there was differ-

***The Times*, 7 Nov 1919**

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Gralla+21, PRD, 103, 024023

- No test of GR with EHT; astro uncertainties

EHT6 on SgrA*, ApJ, 925, 119 (2022)

- Discuss $\alpha_1 = d_{\rm ring}/d_{\rm crit}$; testing what?

Bauer+22, ApJ, 925, 119

- Departure to GR (parametric) leads to very weak features ($\ll$ astro)

Staelens+23, PRD, 107, 124026

- Lyapnunov exponent (width ratio) better probe than shape

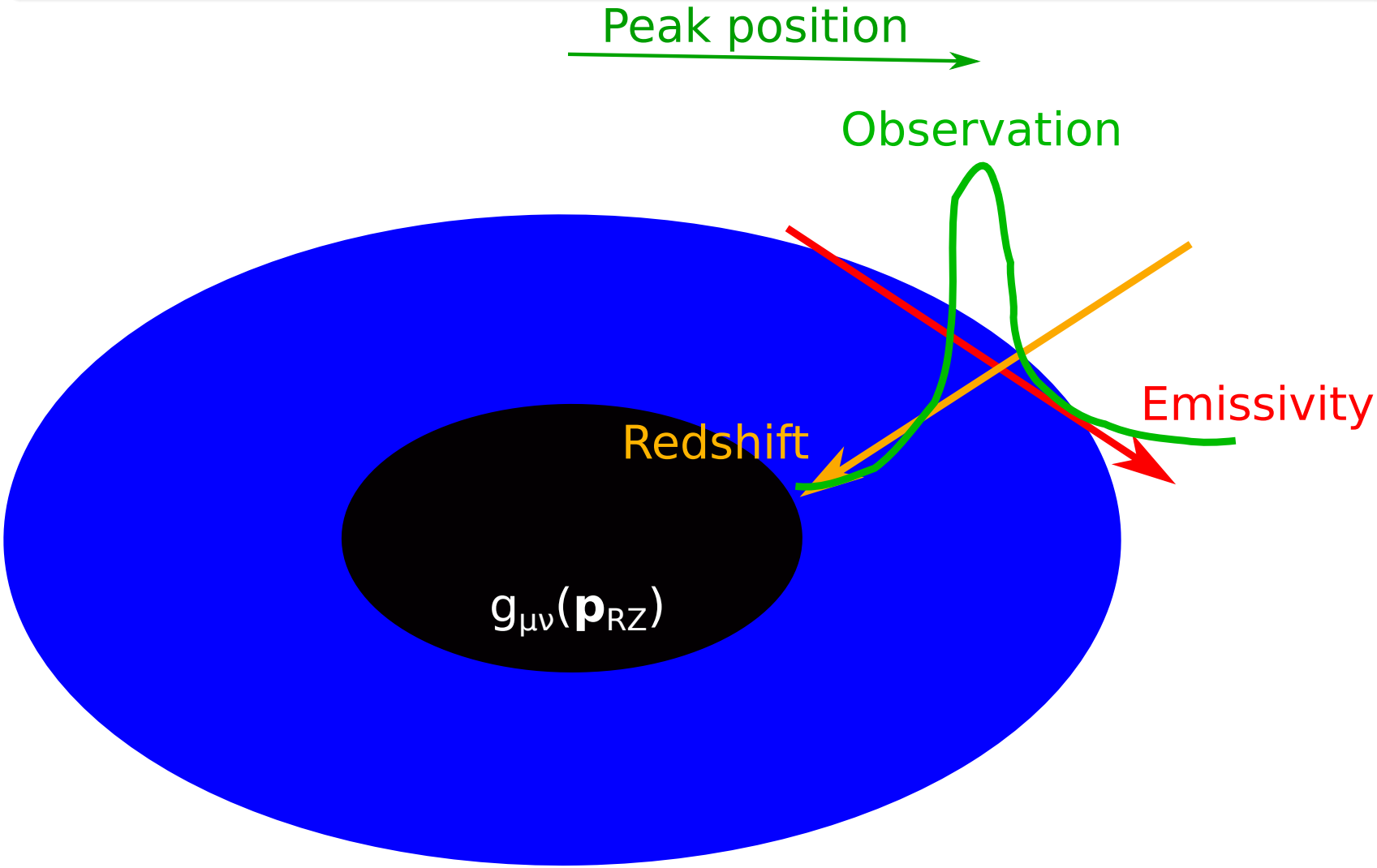
Cardenas-Avendano+23, PRD, 108, 064043

- $n = 1$ photon ring already follows a circlipse shape

Carballo-Rubio+24, JCAP, 05, 103

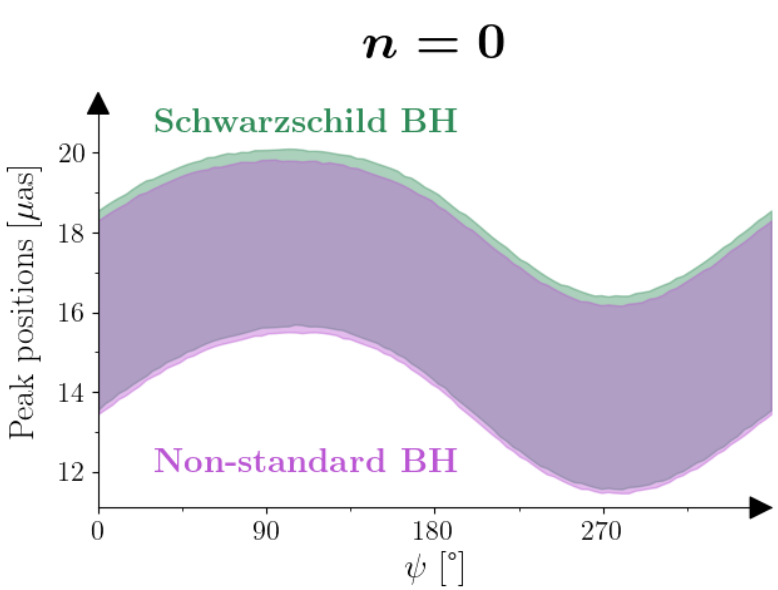
- On photon ring detection prospect

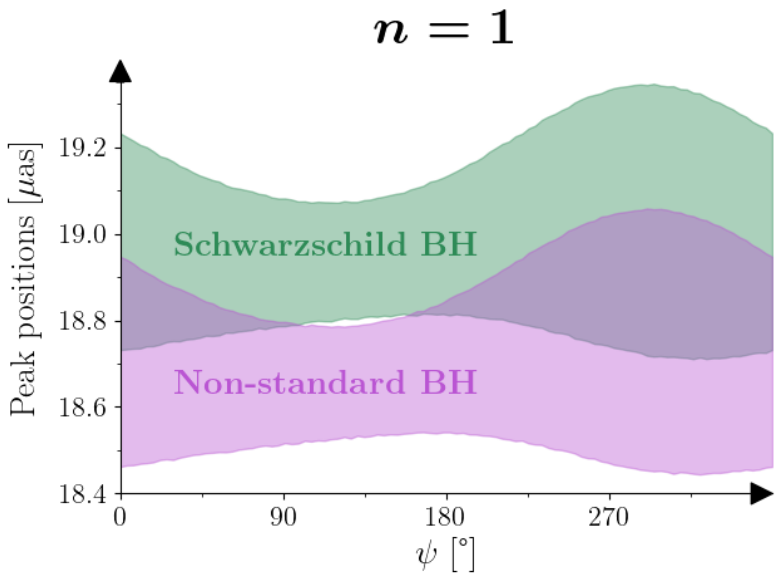
Urso+24 in prep: Preliminary results

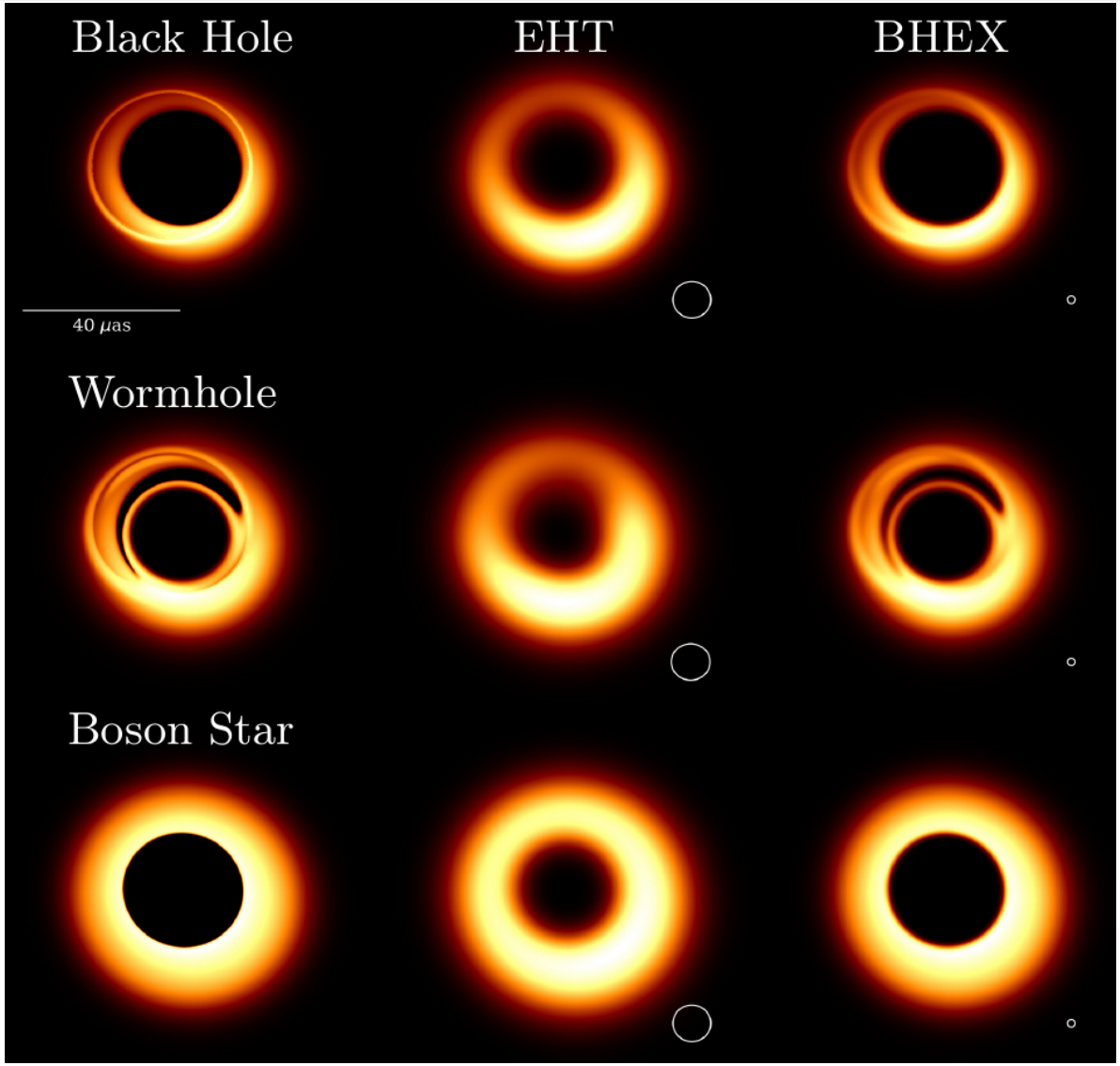


Urso+24 in prep: Preliminary results

- $n = 0$ image **completely degenerate**
- Total degeneracy for the width of the $n = 1$ photon ring
- **Geometry** and **astrophysics disentanglable** with the $n = 1$ **peak**







Future? **BH Explorer** (NASA proposed space-VLBI mission)

So much about photon rings!

What about BH shadows??

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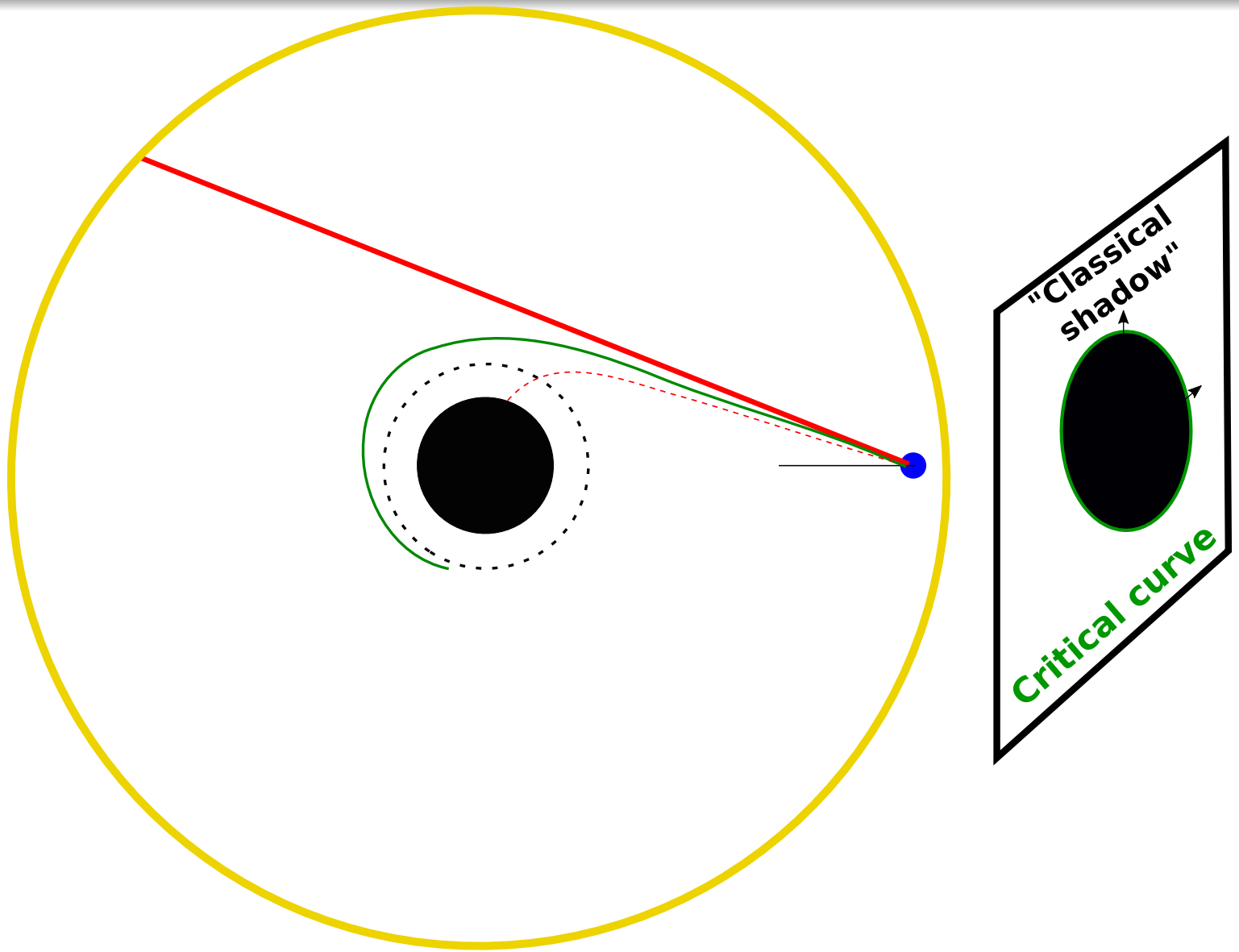
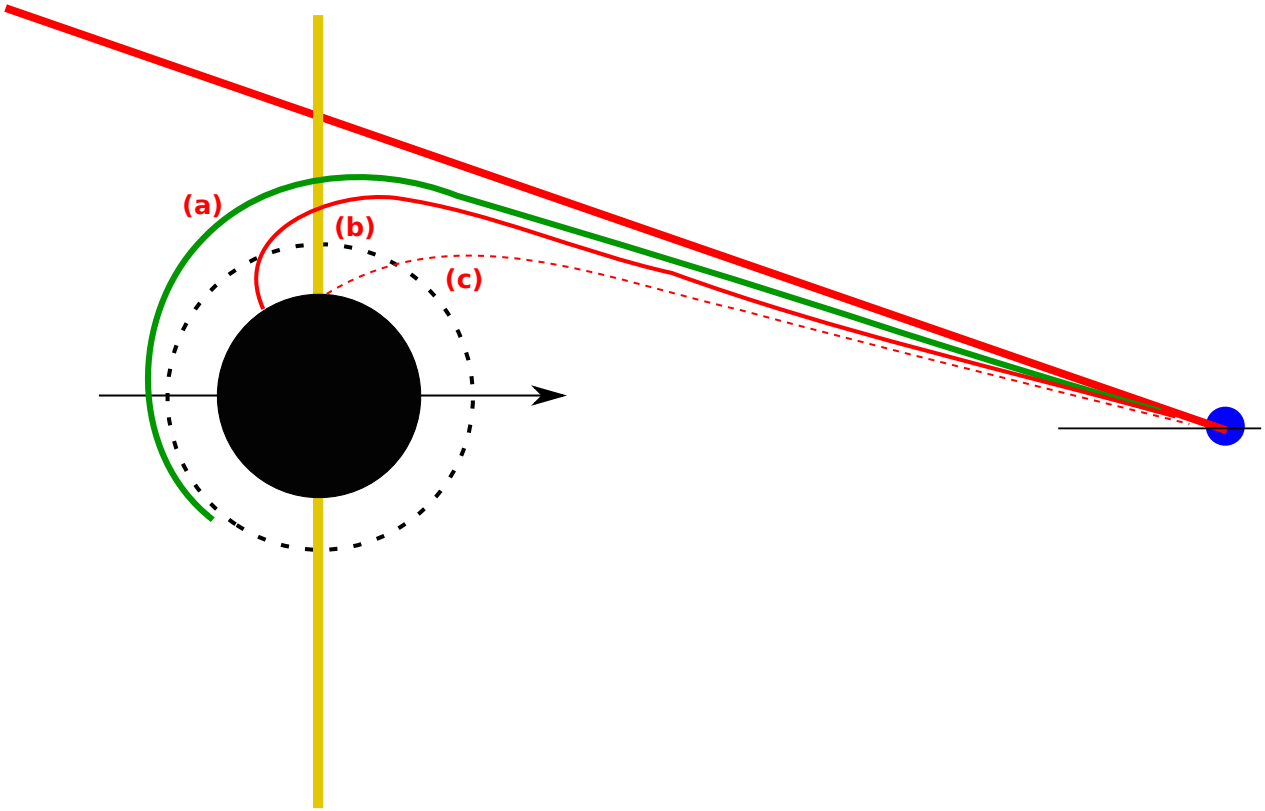
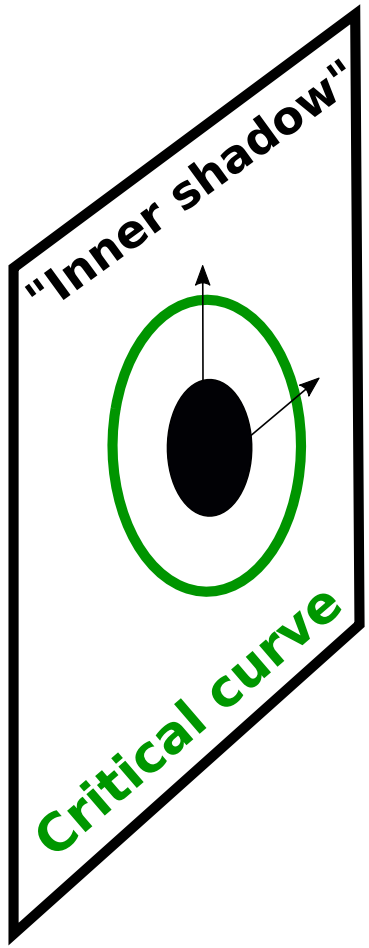


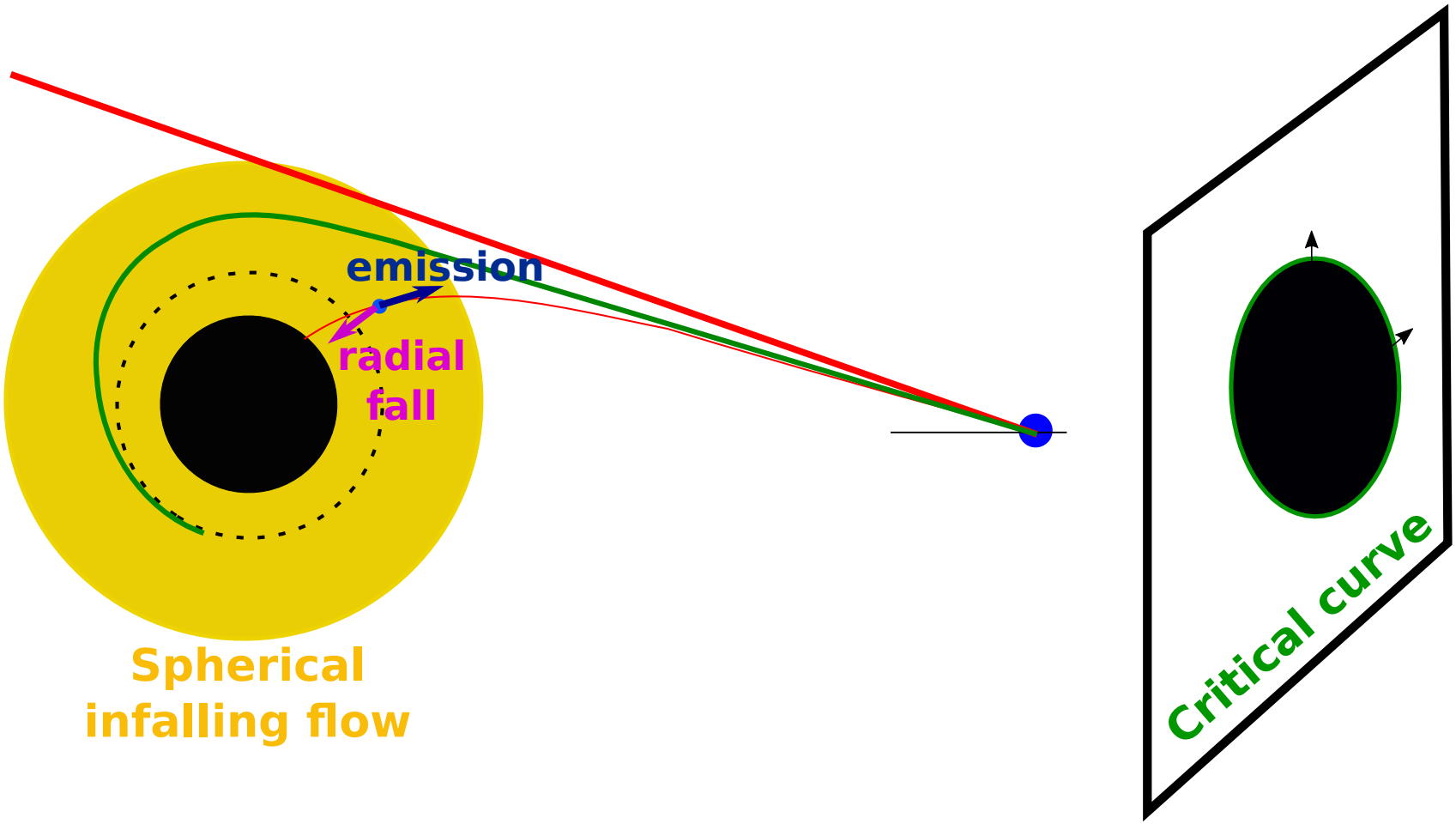
Classical shadow = inside of critical curve



Equatorial orbiting flow



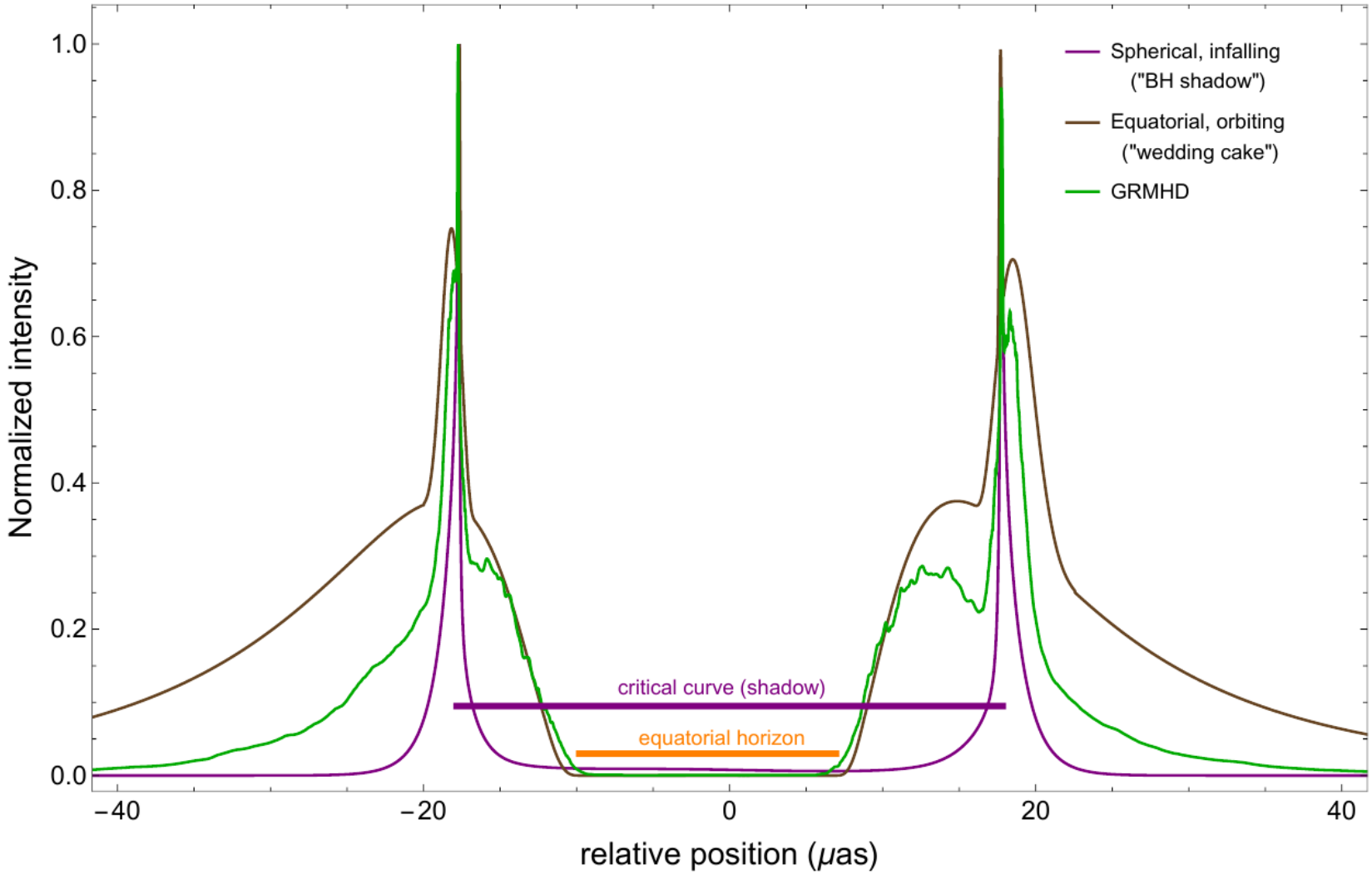
Inner shadow = image of equatorial horizon



“Special-relativistic shadow”

Black hole shadow

- Very astrophysics-dependent
- Can be dominated by special-relativistic effects
- No “universal feature” as for the photon ring
- Obviously interesting feature, but likely less promising than photon ring for theory testing


Spherical, infalling
("BH shadow")
Equatorial, orbiting
("wedding cake")
GRMHD
critical curve (shadow)
equatorial horizon
Normalized intensity
relative position (μas)
1.0
0.8
0.6
0.4
0.2
0.0
−40
−20
0
20
40

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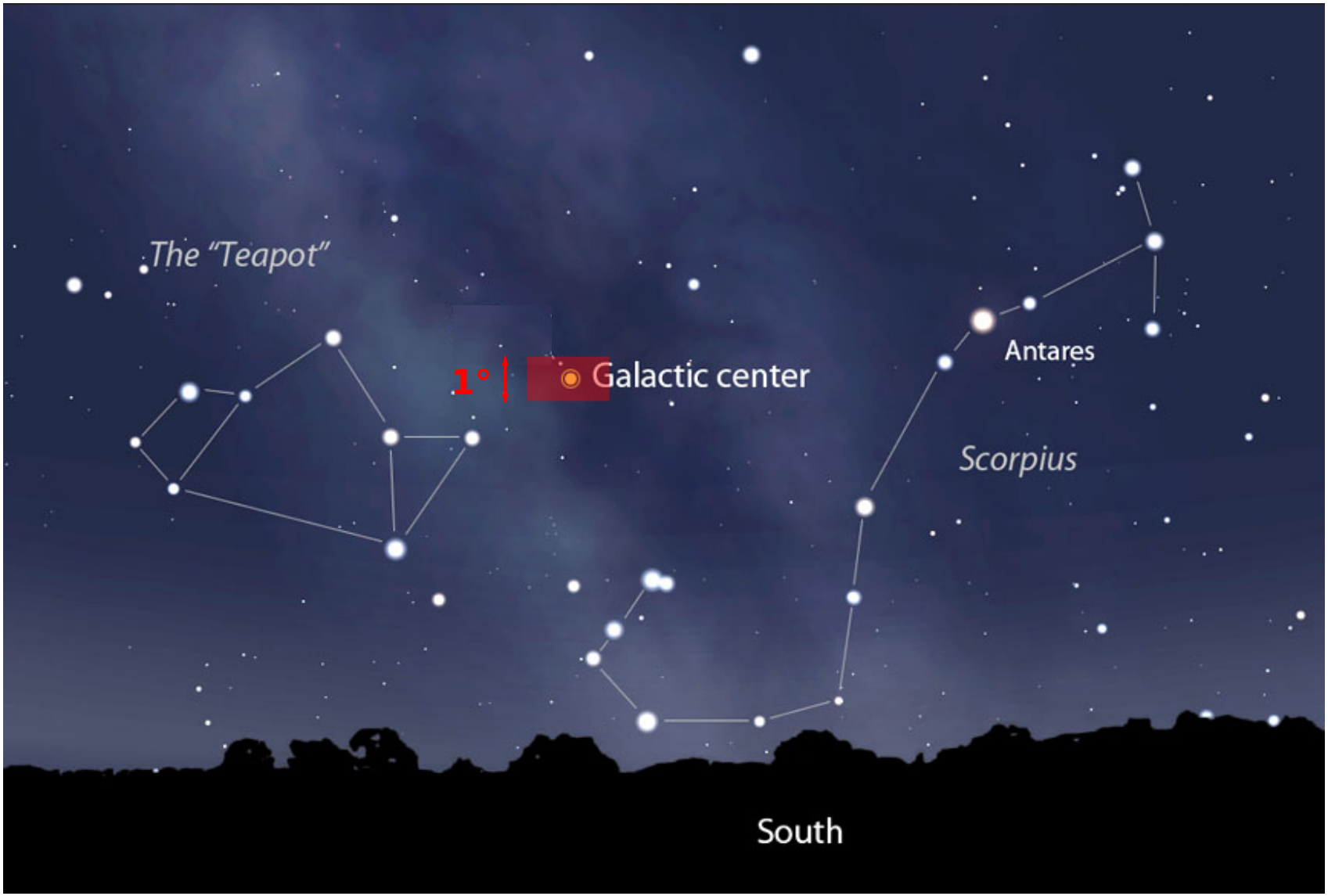
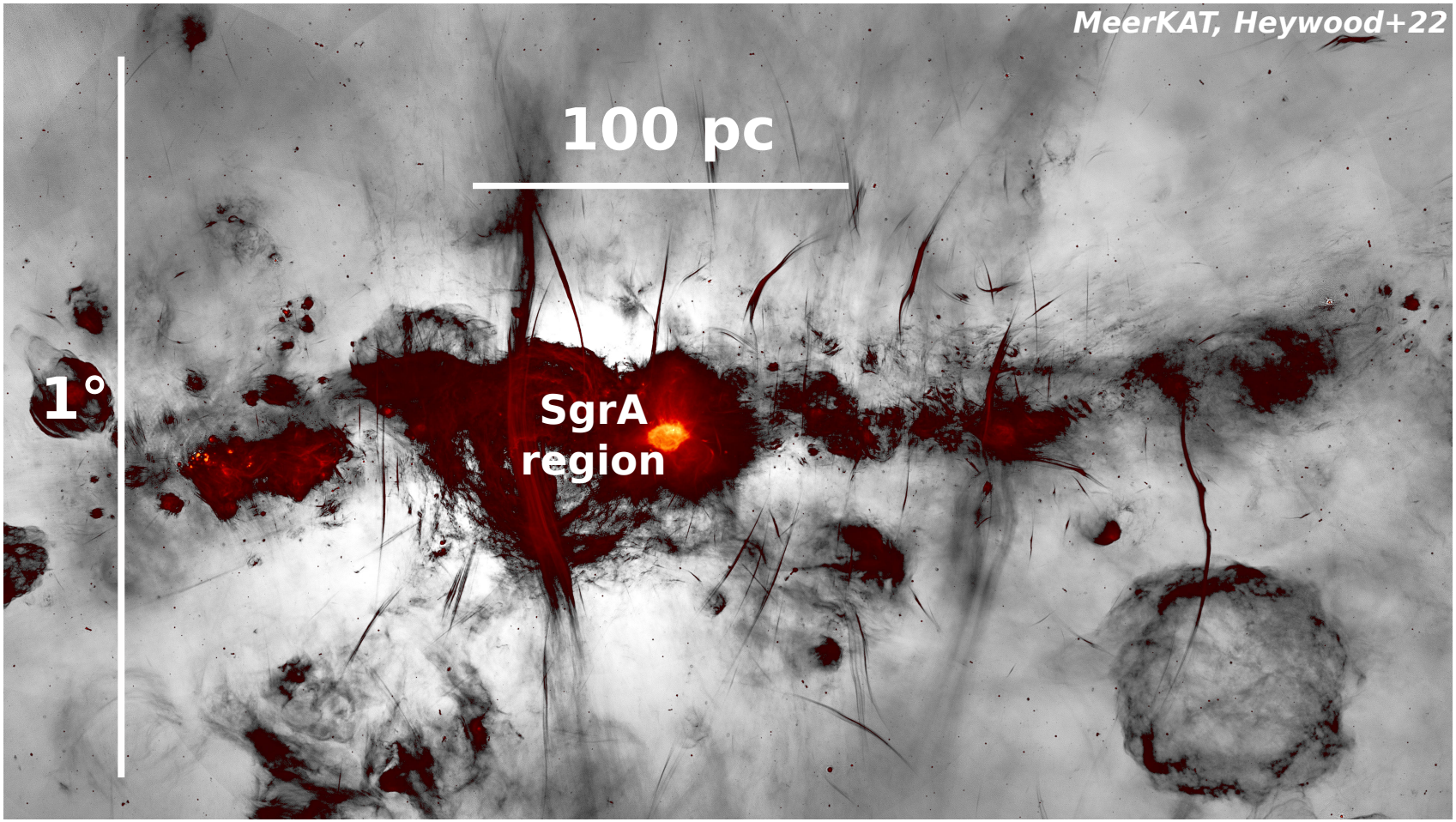
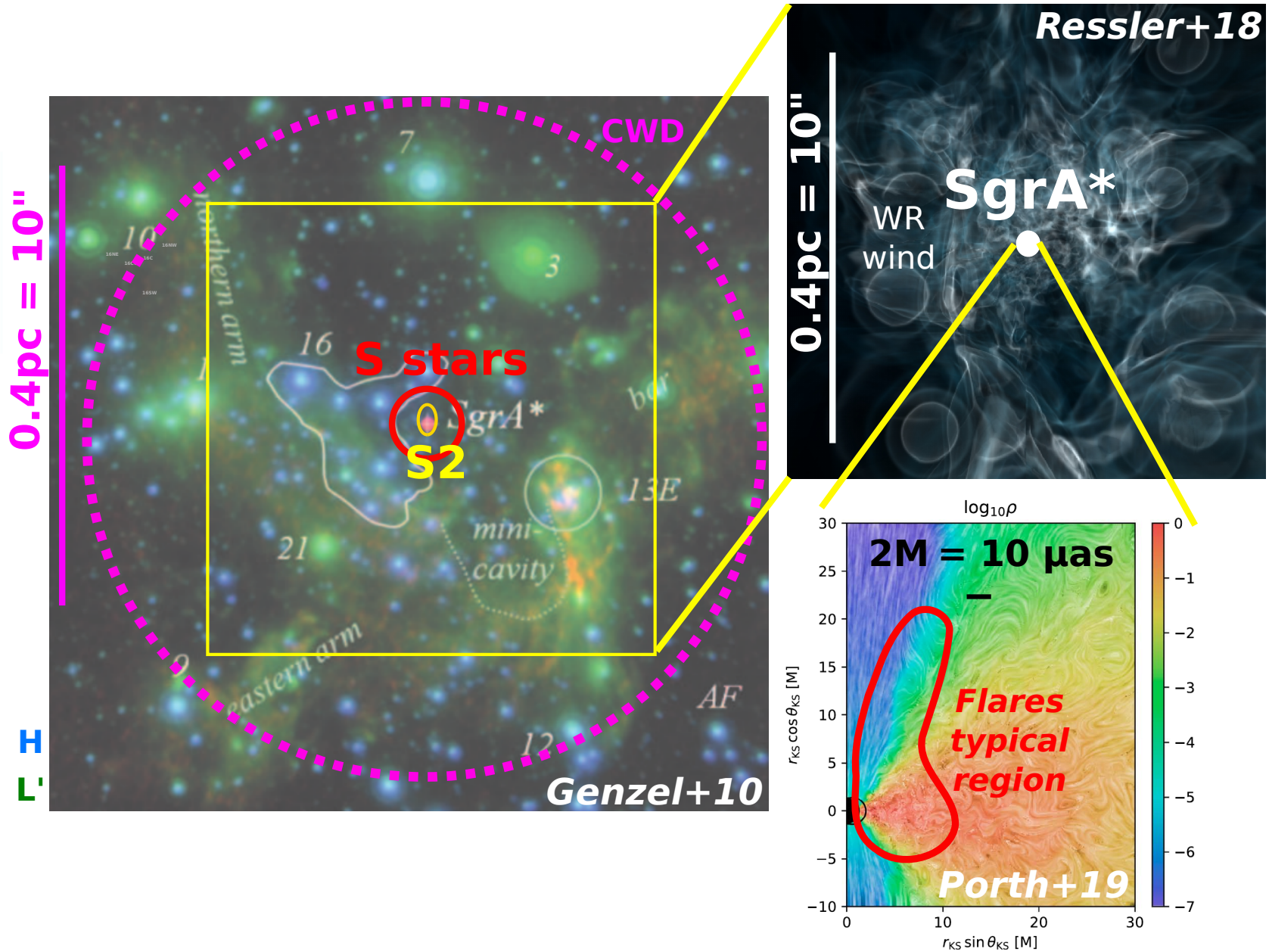
- Flares
- Stars


The "Teapot"
1°
Galactic center
Antares
Scorpius
South

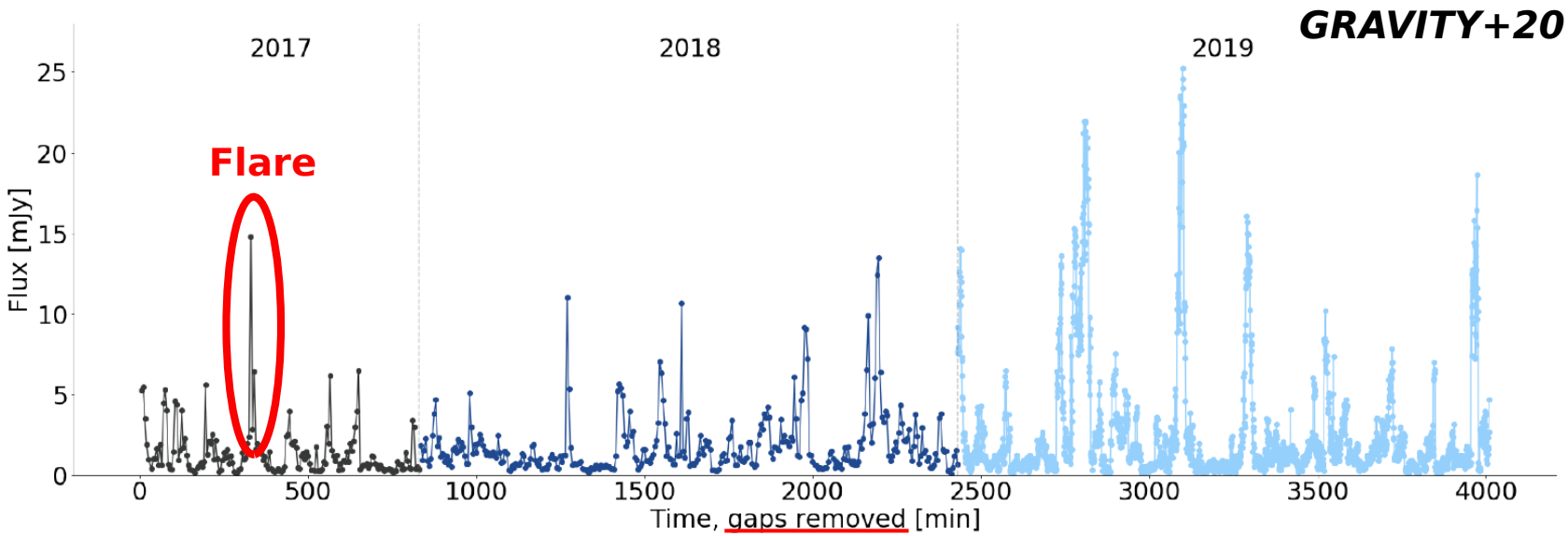

MeerKAT, Heywood+22
100 pc
1°
SgrA
region


0.4pc = 10"
CWD
S stars
SgrA*
S2
H
L'
Genzel+10
Ressler+18
0.4pc = 10"
WR
wind
SgrA*
log10ρ
2M = 10 μas
Flares
typical
region
Porth+19
rKS cos θKS [M]
rKS sin θKS [M]

1 Horizon-scale black hole observations

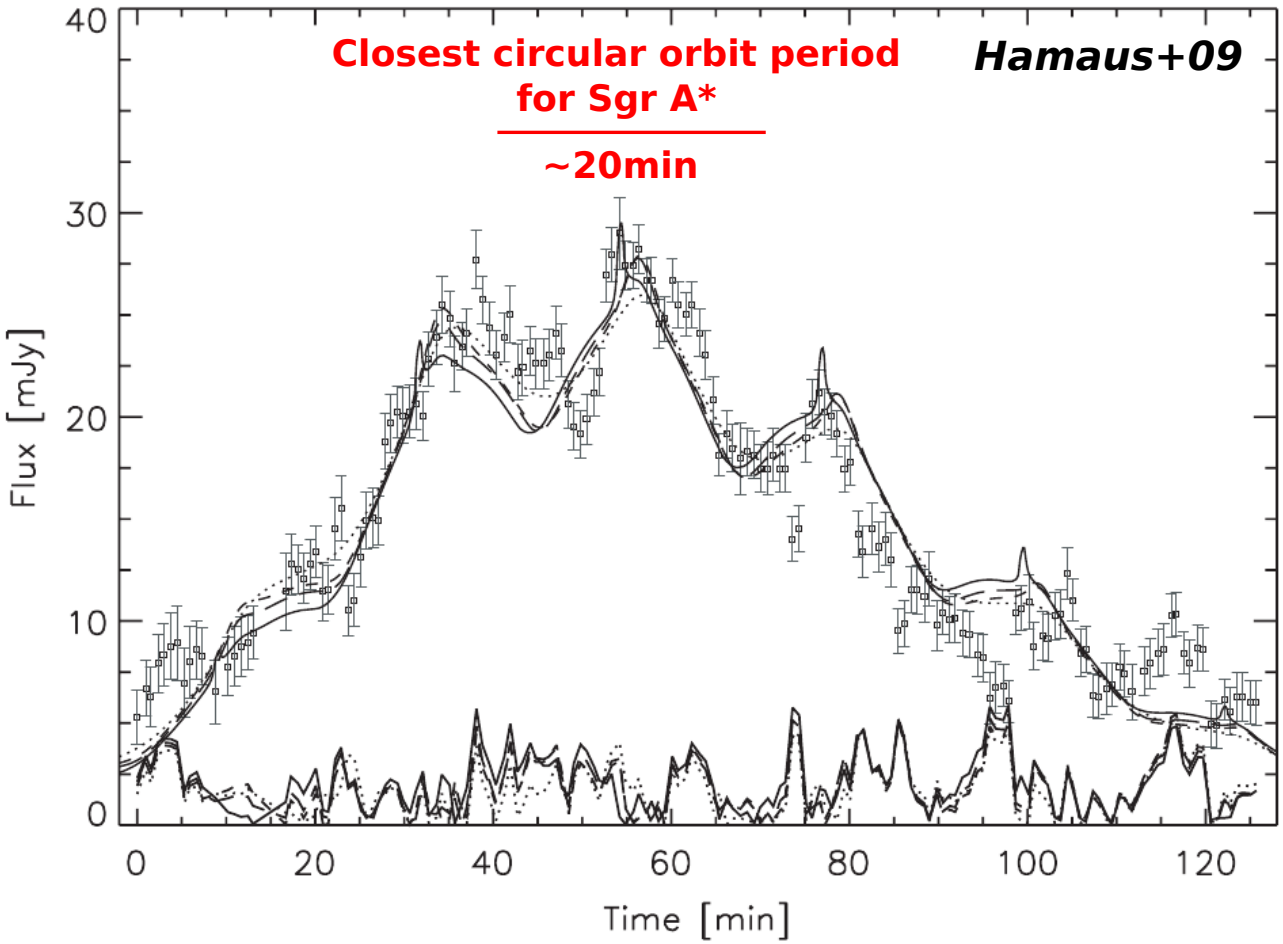
2 Photon rings and shadows
- Photon rings
- Shadows

3 Flares and stars
- Flares
- Stars



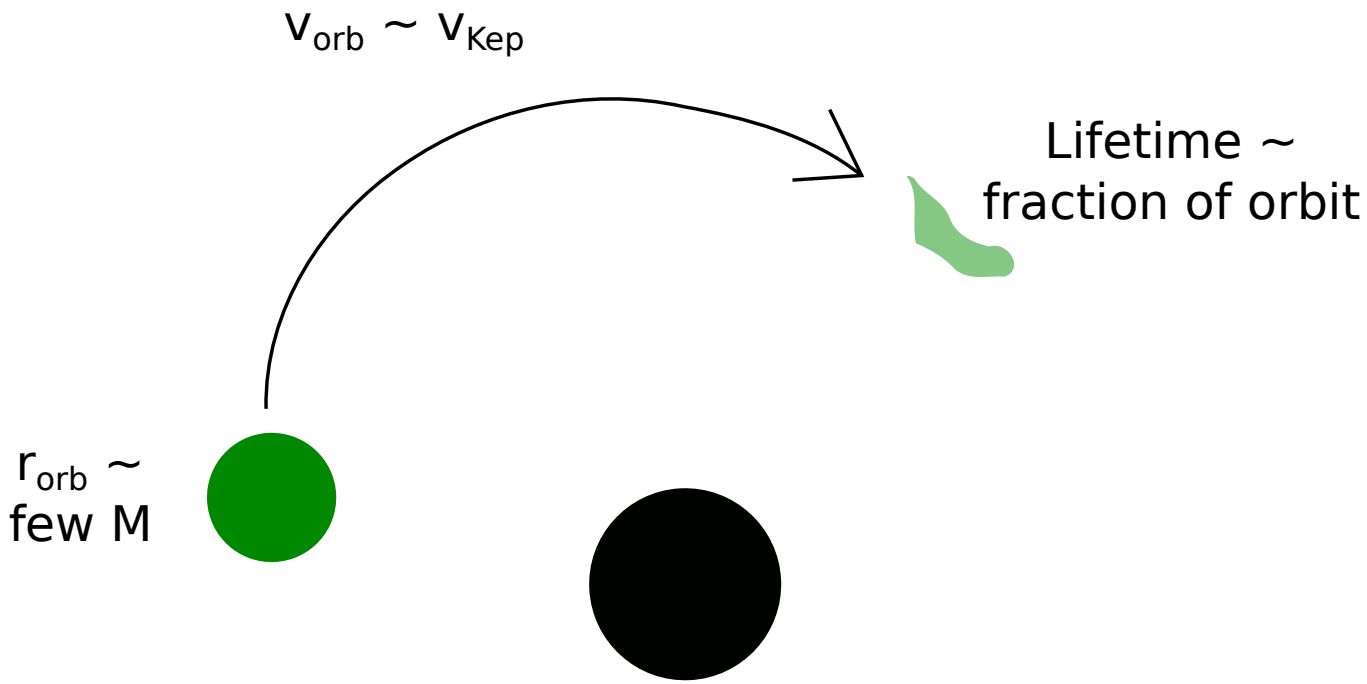
Observations

- Flare = **transient peaks** of flux on daily basis (4/day in IR)



Observations

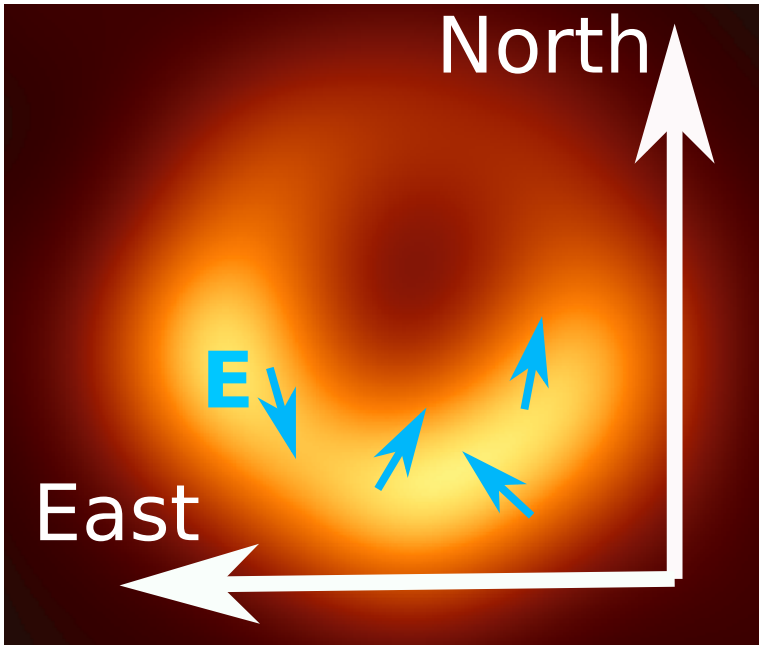
- IR light curve **pseudo period** (at least some events)
  (So likely very close to BH!)



Modeling: **hotspot**

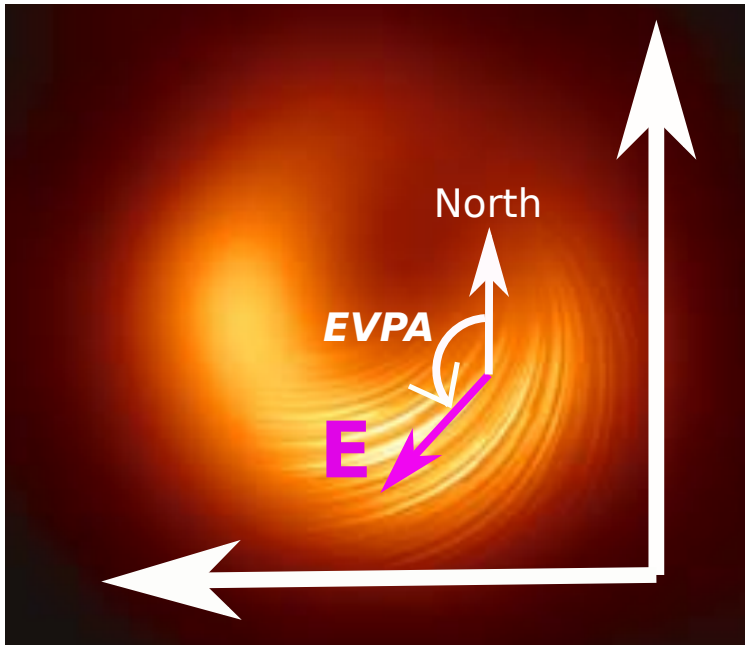
- Transient, compact, magnetized parcels of energized plasma, orbiting/ejected close to BH
- Emitting (polarized) non-thermal synchrotron radiation

Non-polarized



$I = E^2$

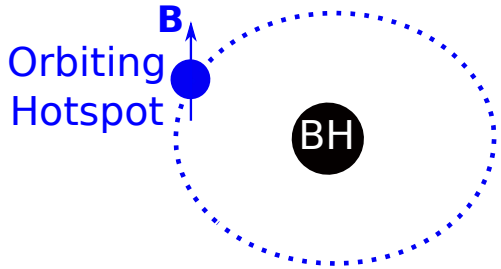
Polarized

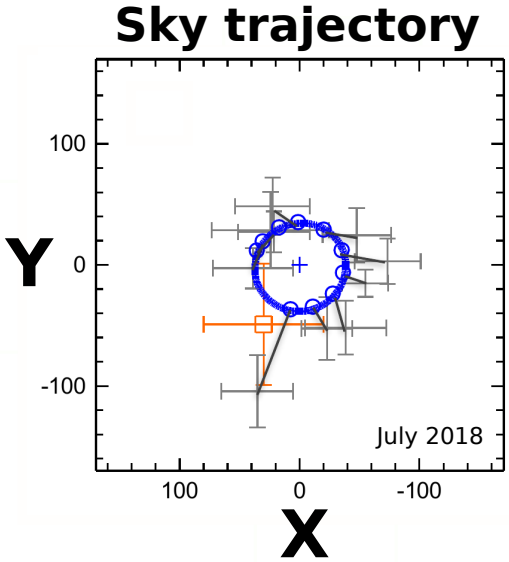


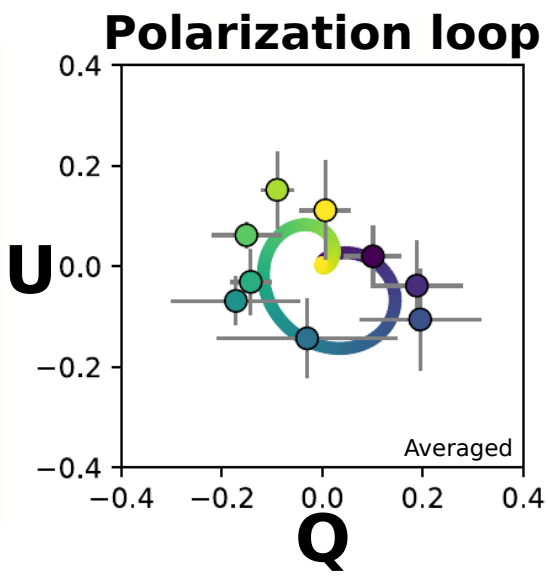
$I = E^2$
+EVPA

(I, EVPA) ⟷ Stokes (Q,U)

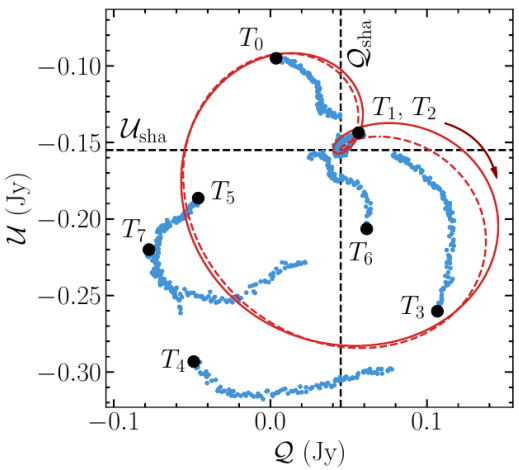
- Details on polarized radiation in curved spacetime: Aimar+24 *arxiv:2311.18802*







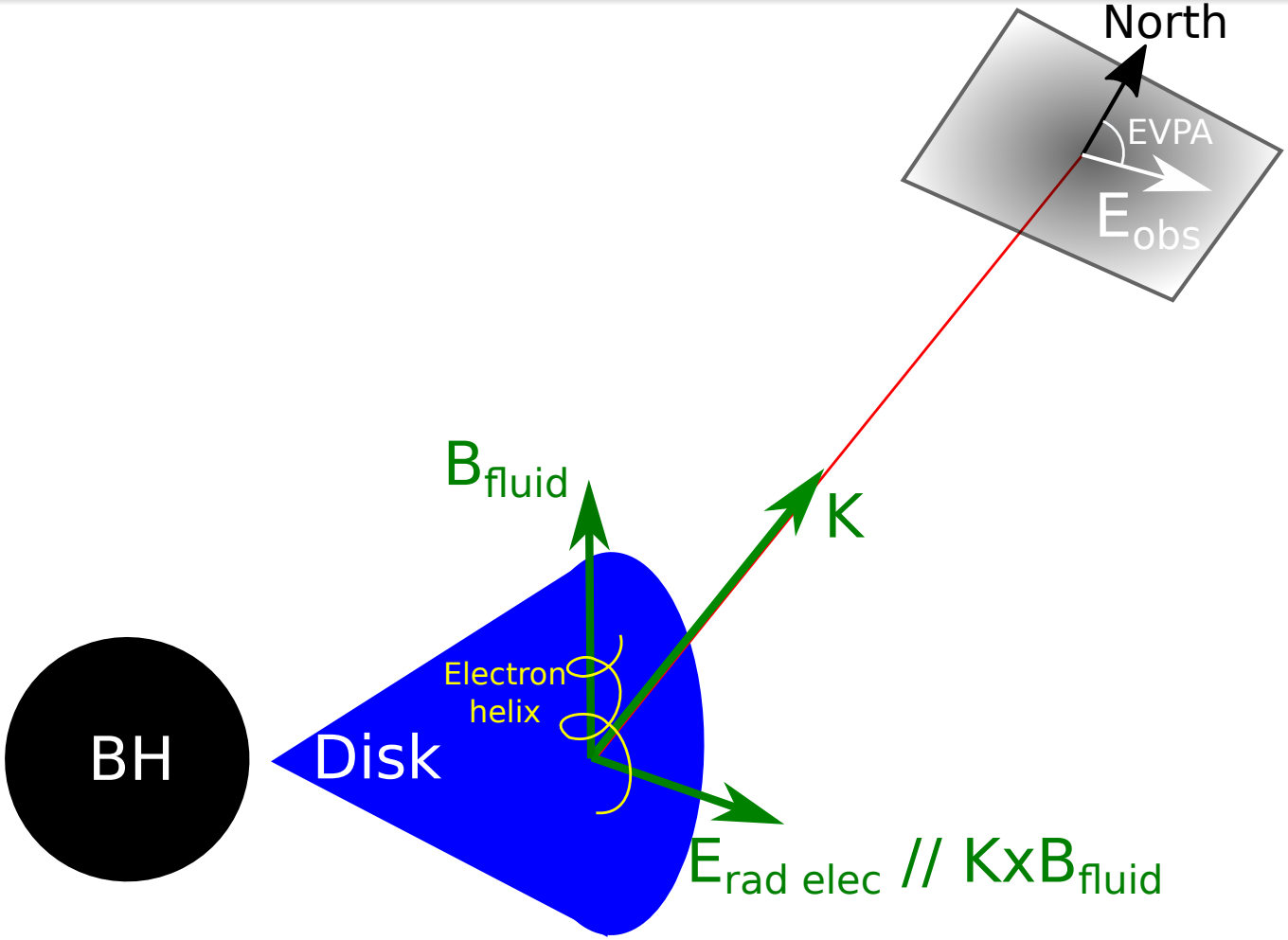
GRAVITY Coll. 2018,23



ALMA/Wielgus+22

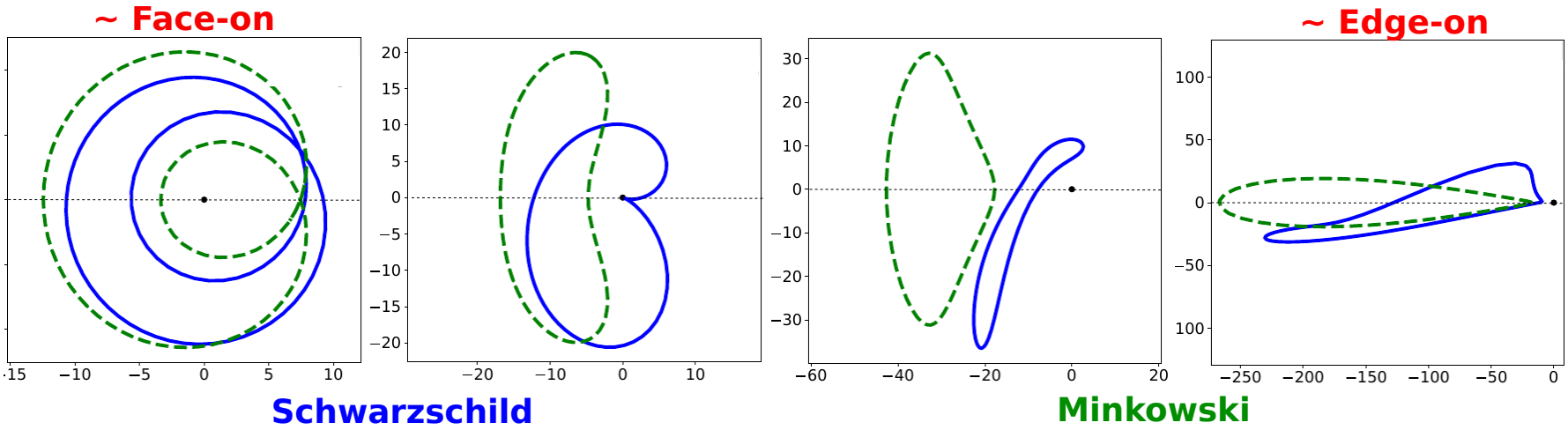
Observed polarized flares

- Astrometry: close to BH ($r \lesssim 10M$)
- Polarization loops: vertical B-field



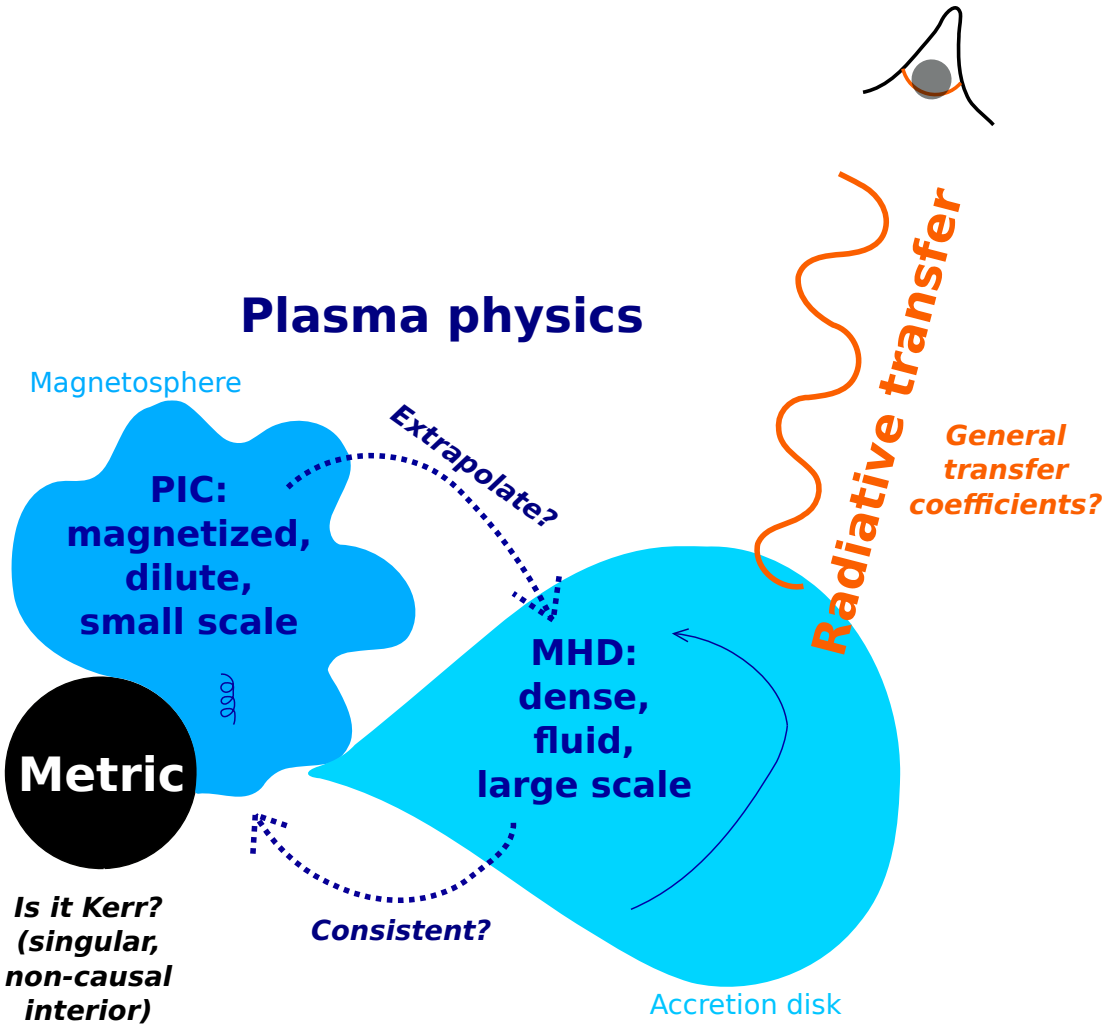
Why do we care about EVPA?

- Constraint on B field geometry
- Any use for testing the geometry?



Polarization loops and curvature probing

- Flat-spacetime: **mirror symmetry**
- Curved spacetime: **asymmetric loop** (from light bending)
- *Quantifying curvature?*
- → Vincent, Wielgus, Aimar, Paumard, Perrin A&A 2024

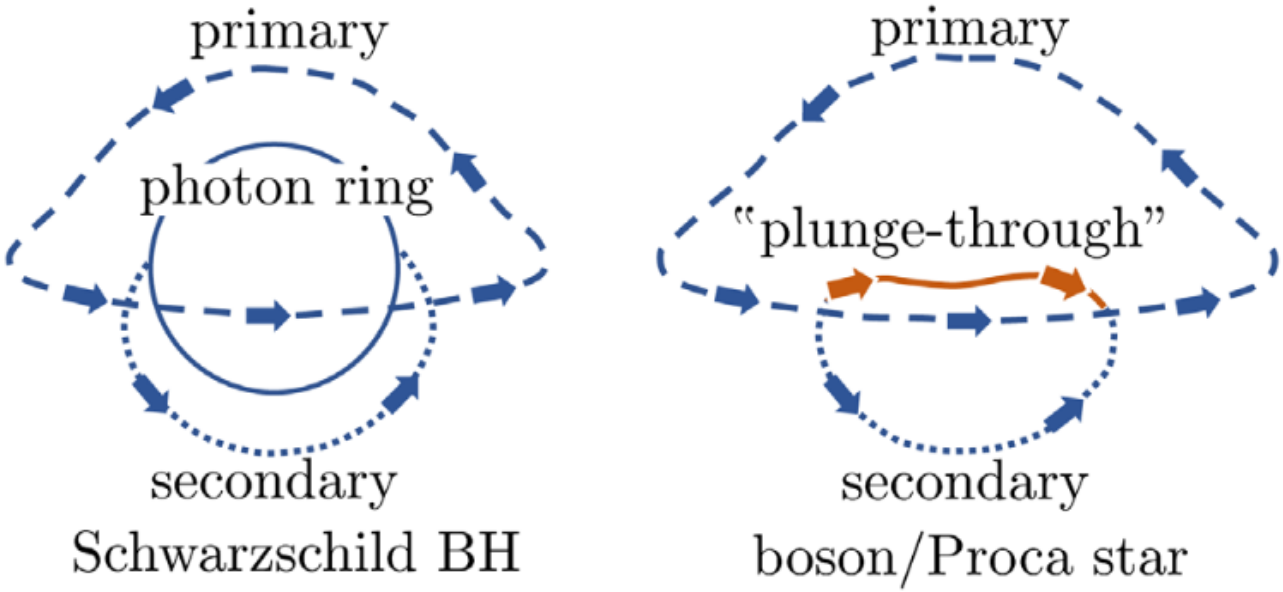


Remember! Plasma physics unknown

- Hopefully, averaging out astro complexity?

Rosa+22, PRD, 106, 044031

- Hotspots around horizonless objects



Chen+24, JCAP, 2024, 032

- Hotspots around naked singularities

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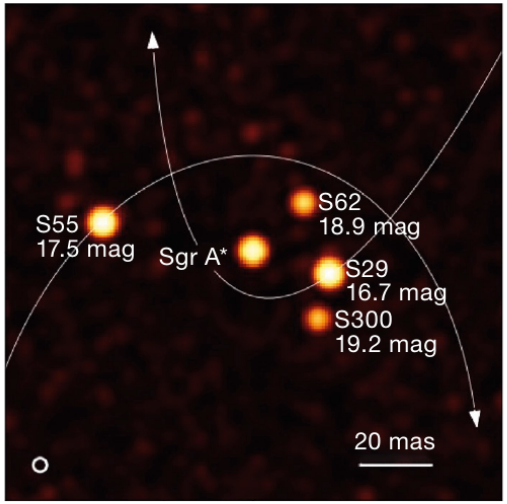
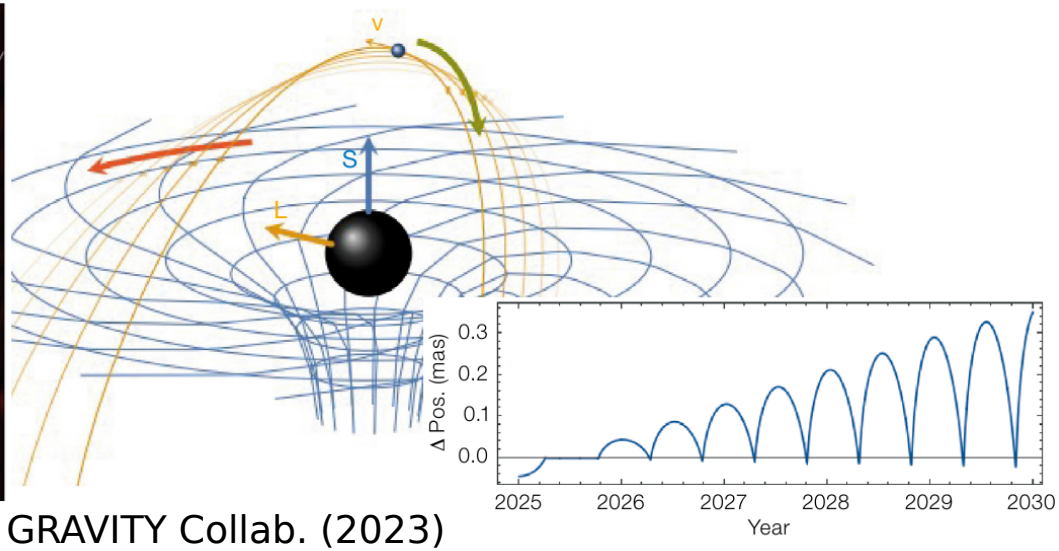
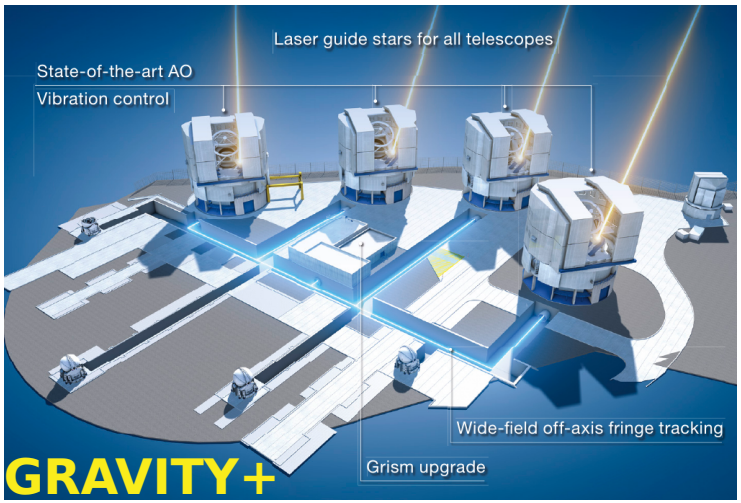




GRAVITY Collab. (2023)



Post-Newtonian orbit integration

$$\ddot{\mathbf{r}} = -\frac{Gm}{r^2}\mathbf{n}_{\rm orb} + \mathbf{a}_{\rm PN}$$

$$\mathbf{a}_{\rm PN} \approx \mathbf{a}_{\rm 2PN} = \mathbf{a}_{\rm Sch} + \mathbf{a}_{\chi} + \mathbf{a}_{Q}$$

Spin? Quadrupole moment??

More news soon: Abd El Dayem+24 in prep.

Conclusion

- GRAVITY+EHT allow to understand astro close to BH
- Next step: Probing gravity??

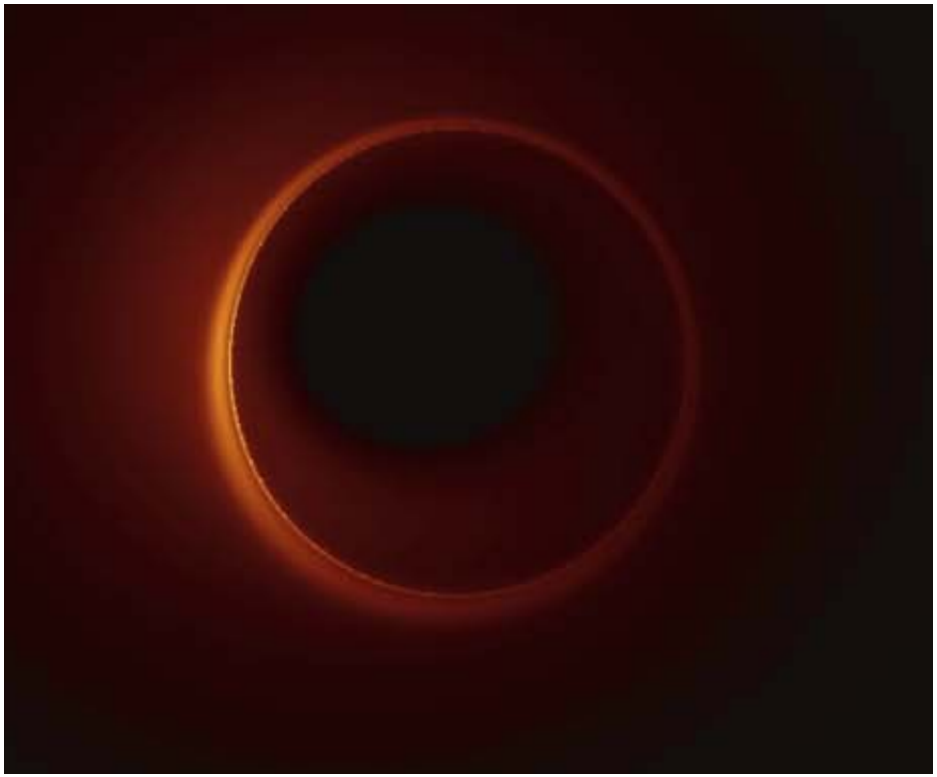
Probing gravity?

- **Photon rings**: great probe but degeneracy with astro;

  Space-VLBI needed!
- **Flares**: still a lot of astro unknowns.

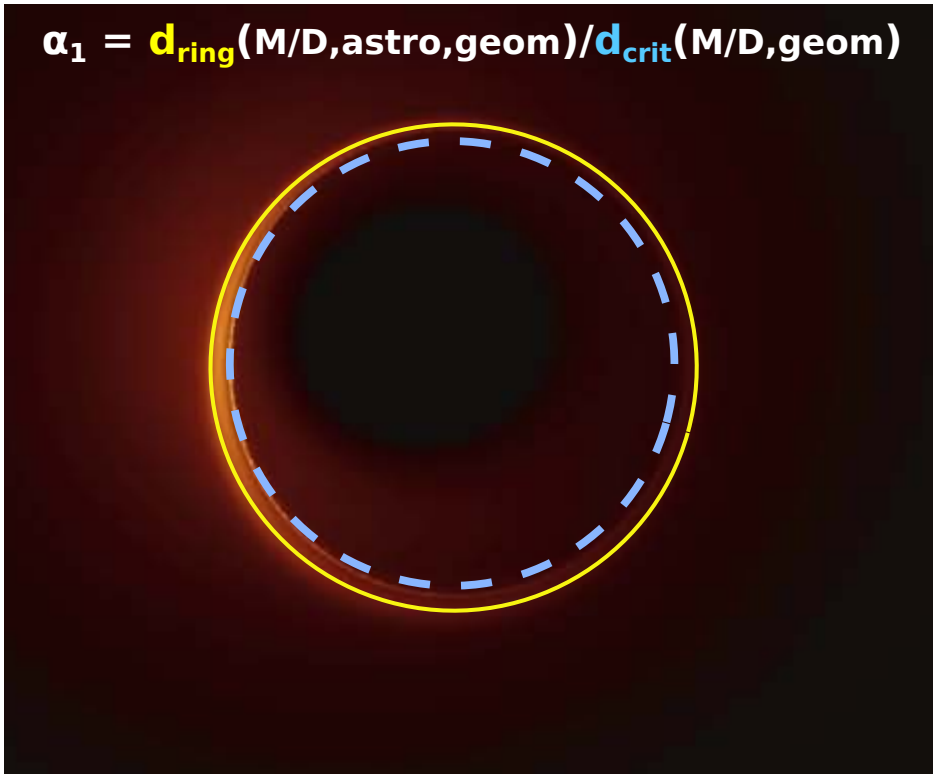
  Maybe averaging many events can help.

  More data needed!
- **Stellar orbits**: not discussed but promising if closer-in stars discovered! (GRAVITY+)



Diameter of BH shadow

- Scale emission ring to “shadow” (actually, critical curve)
  Compare to critical curve given M/D prior
  Advocate Kerr consistency test
- Can we trust the GRMHD prediction?



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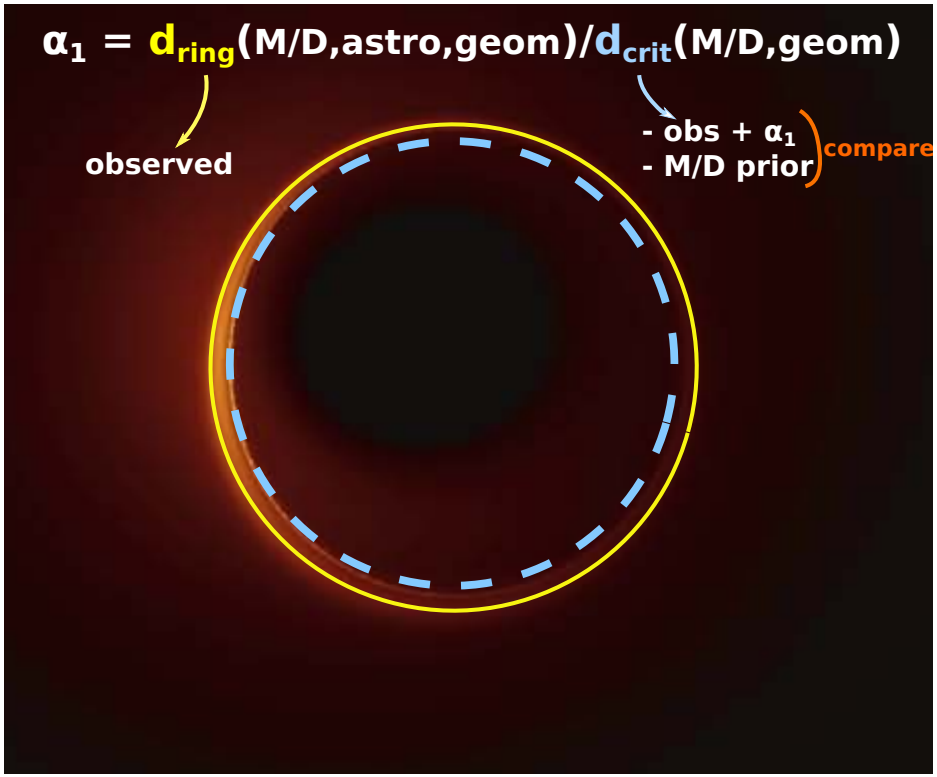

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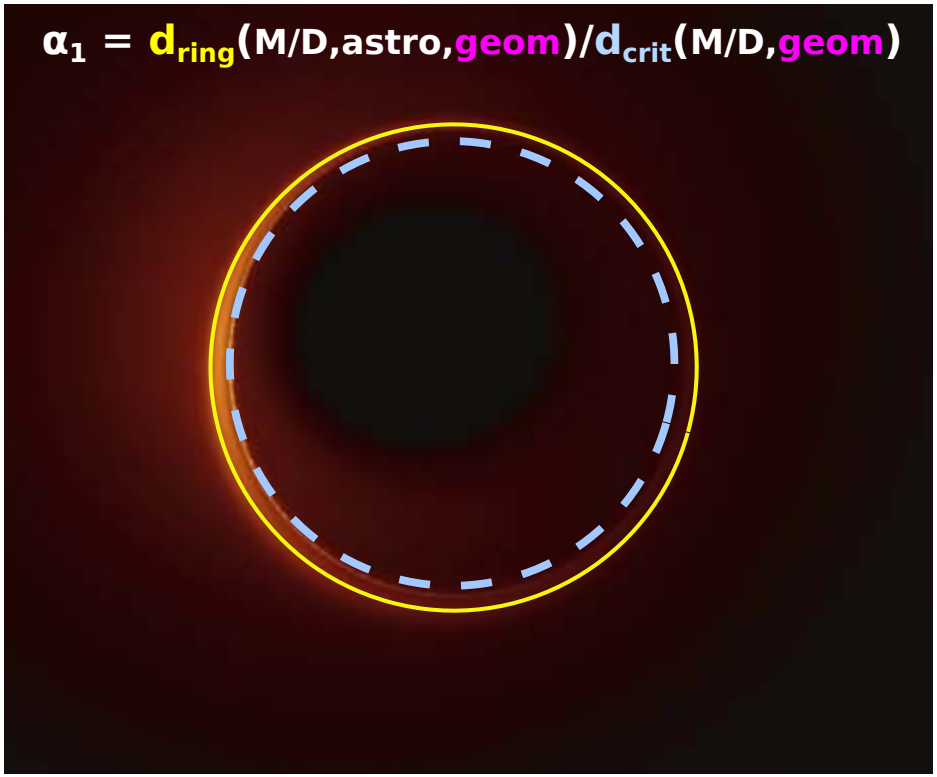

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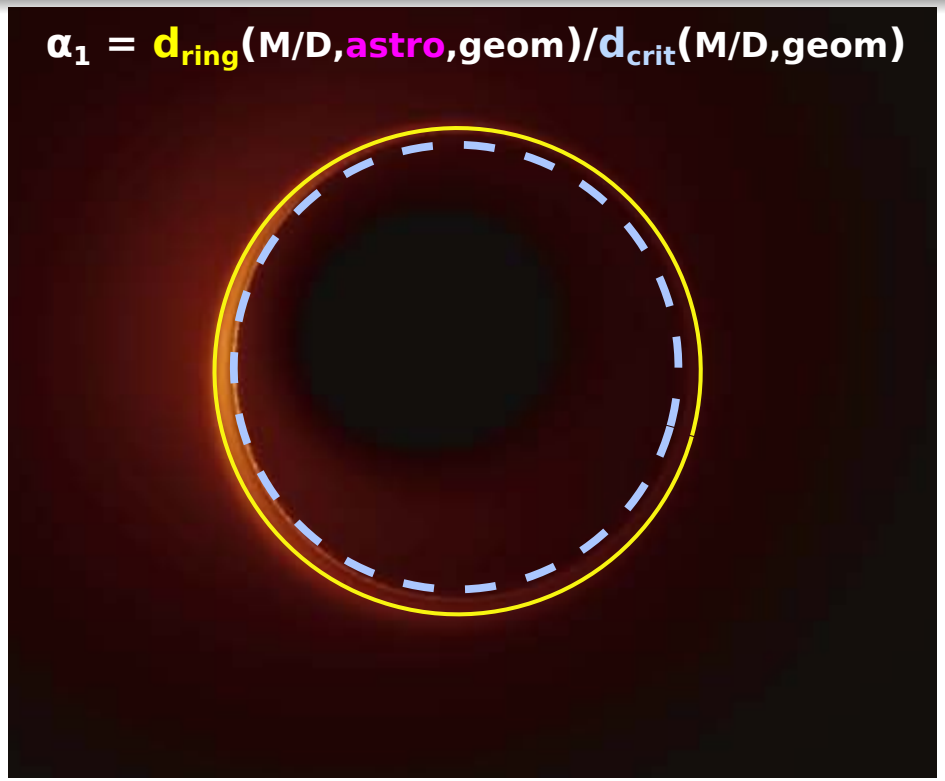

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  Advocate Kerr consistency test
- Can we trust the GRMHD prediction?
  - $\rightarrow$ Rather: plasma modeling consistency test