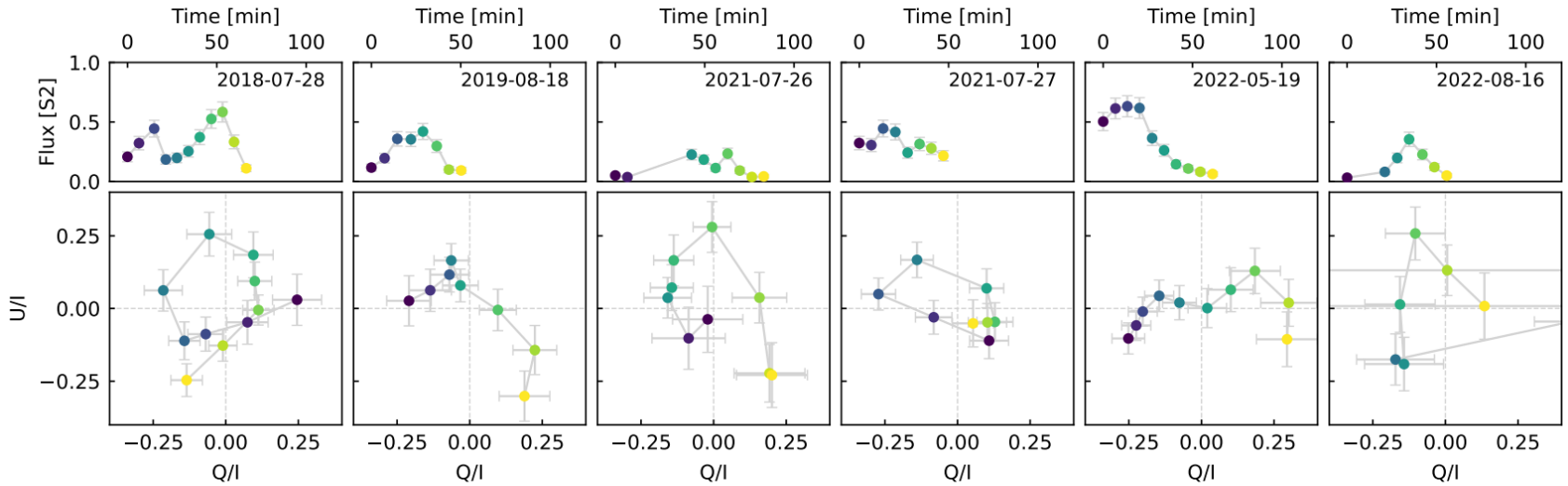
Polarimetric imprints of exotic compact objects

Hanna Liis Tamm
João Luís Rosa, Nicolas Aimar

July 2, 2026

1. **Motivation**
2. Overview of models
3. Polarization and setup
4. Simulation results
5. Conclusions

Detection of infra-red flares [1]- [3]



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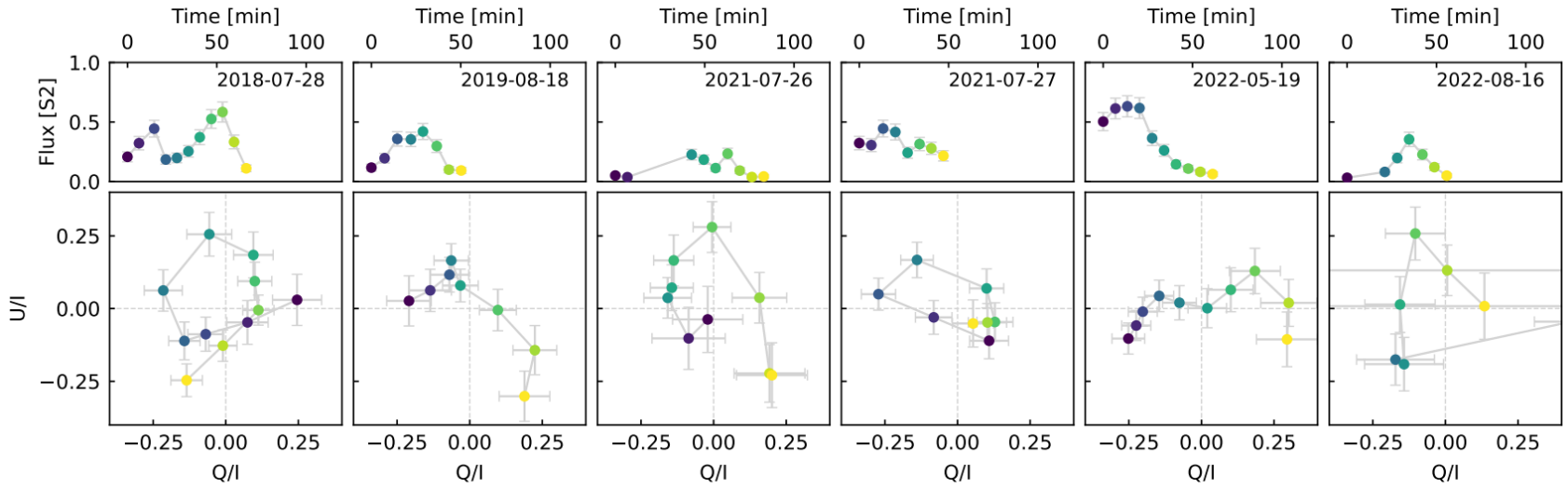

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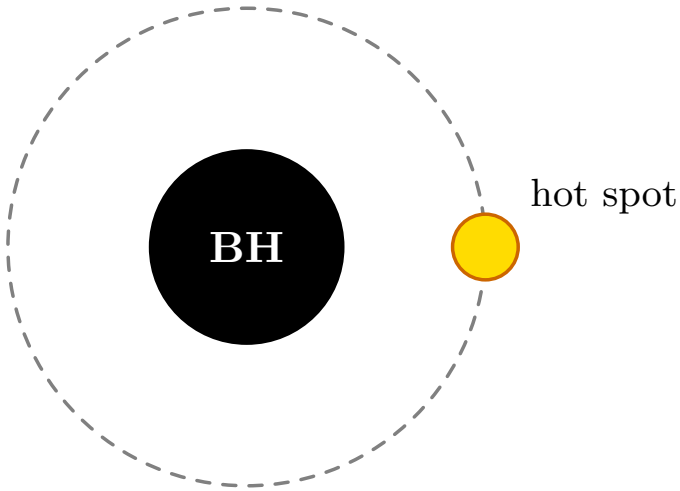

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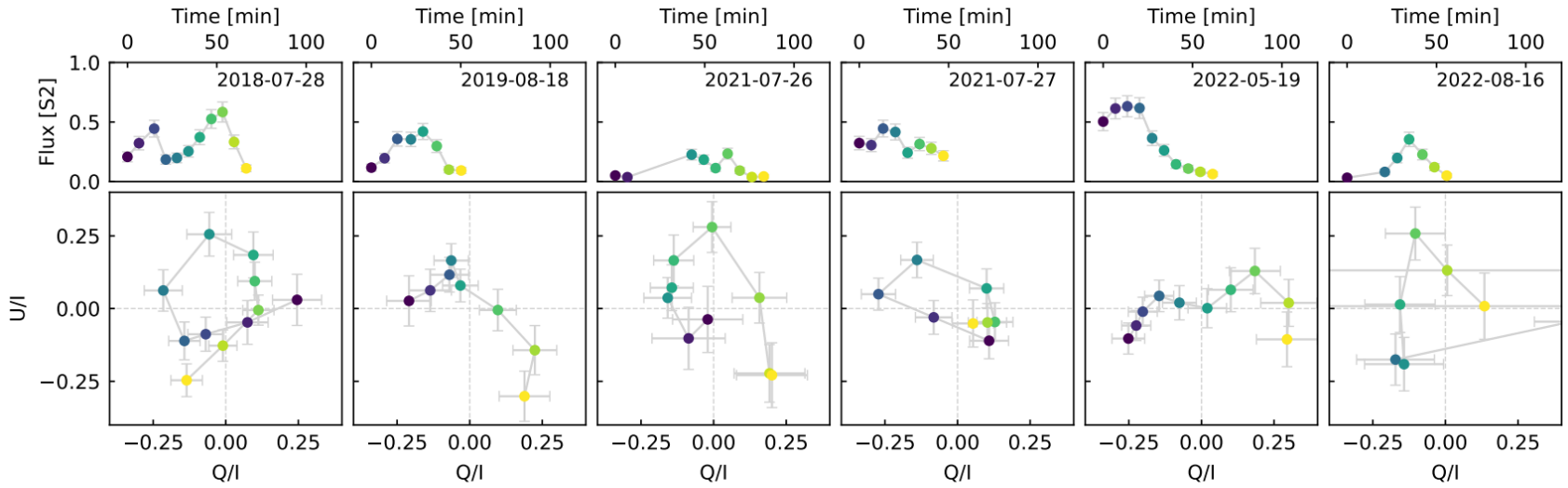

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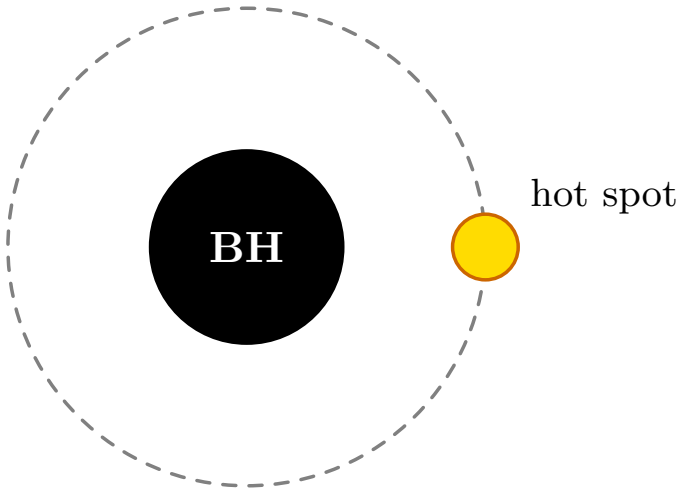

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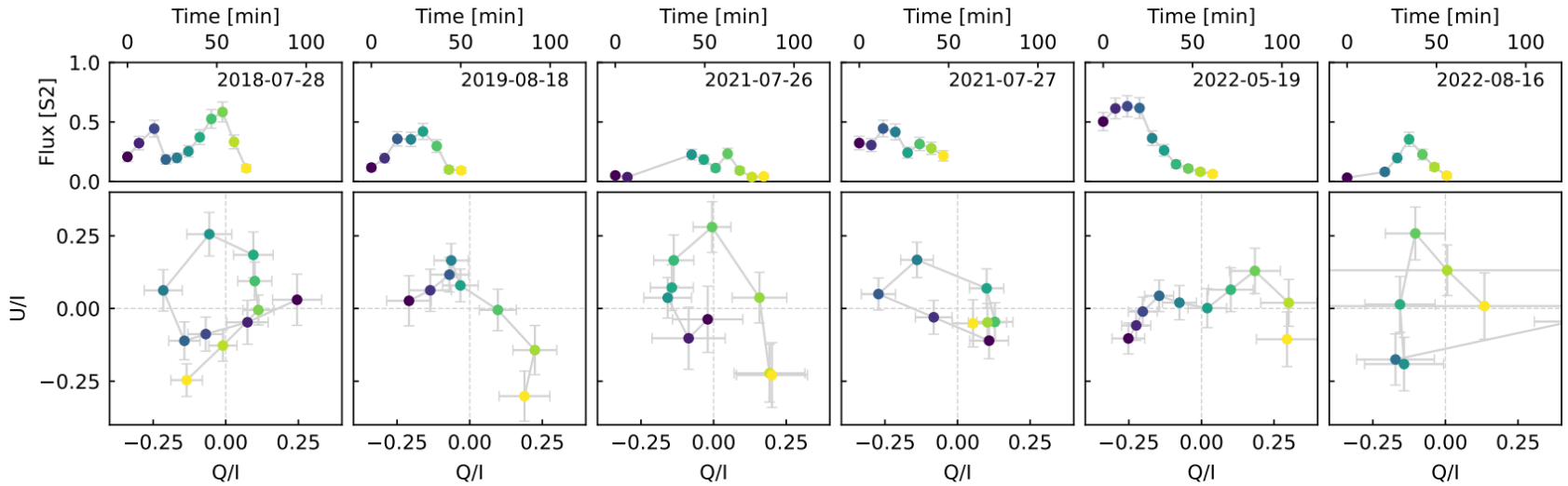

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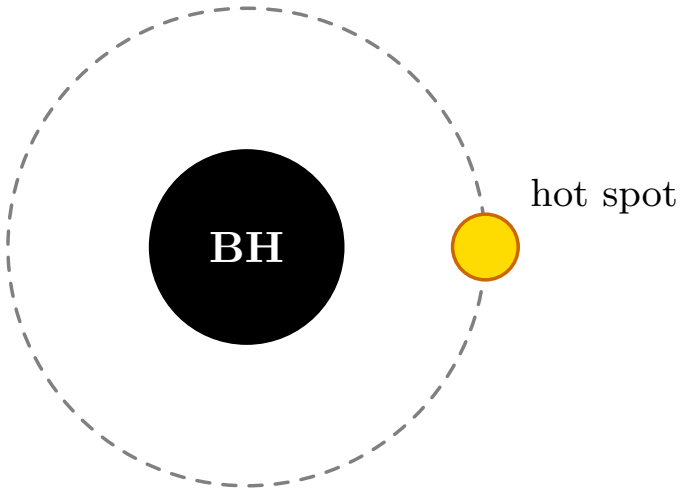

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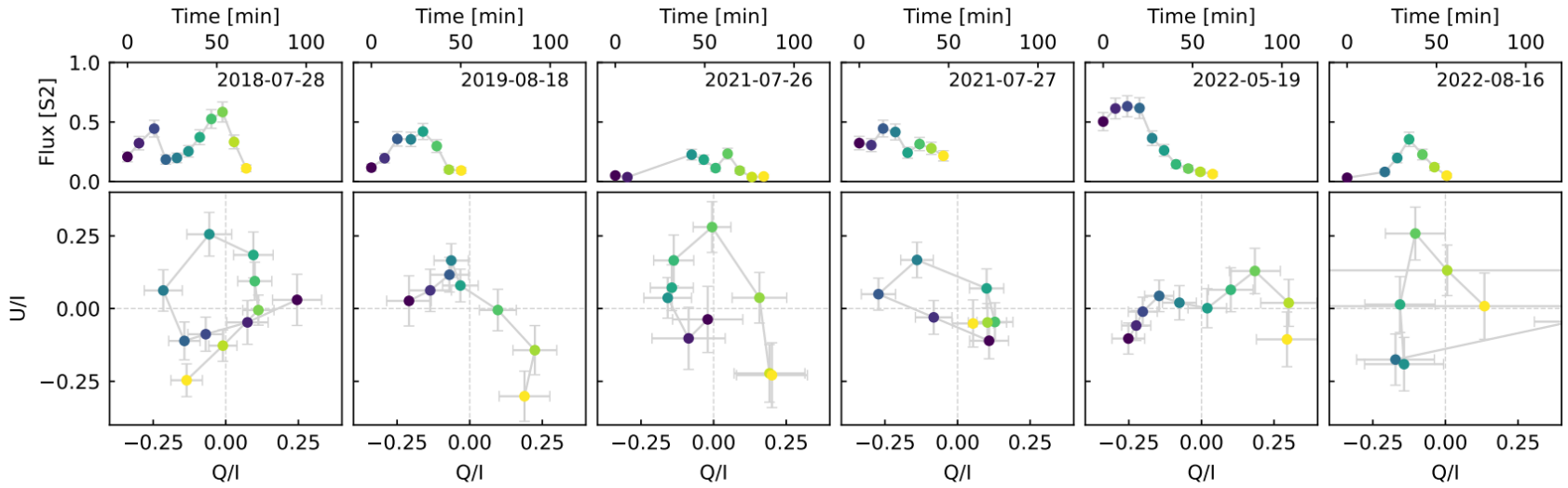

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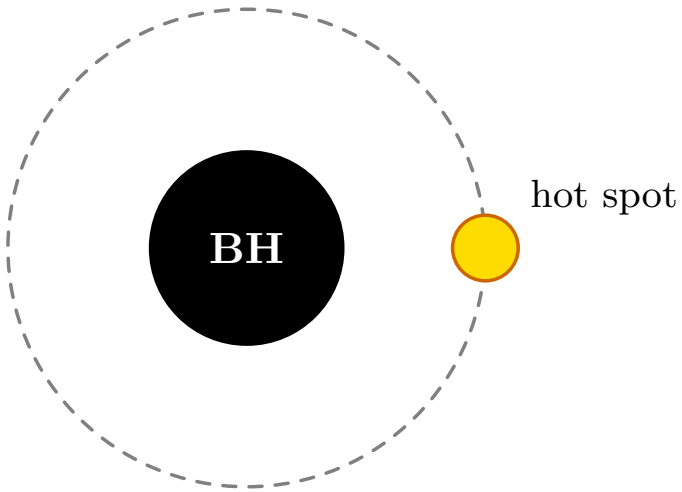

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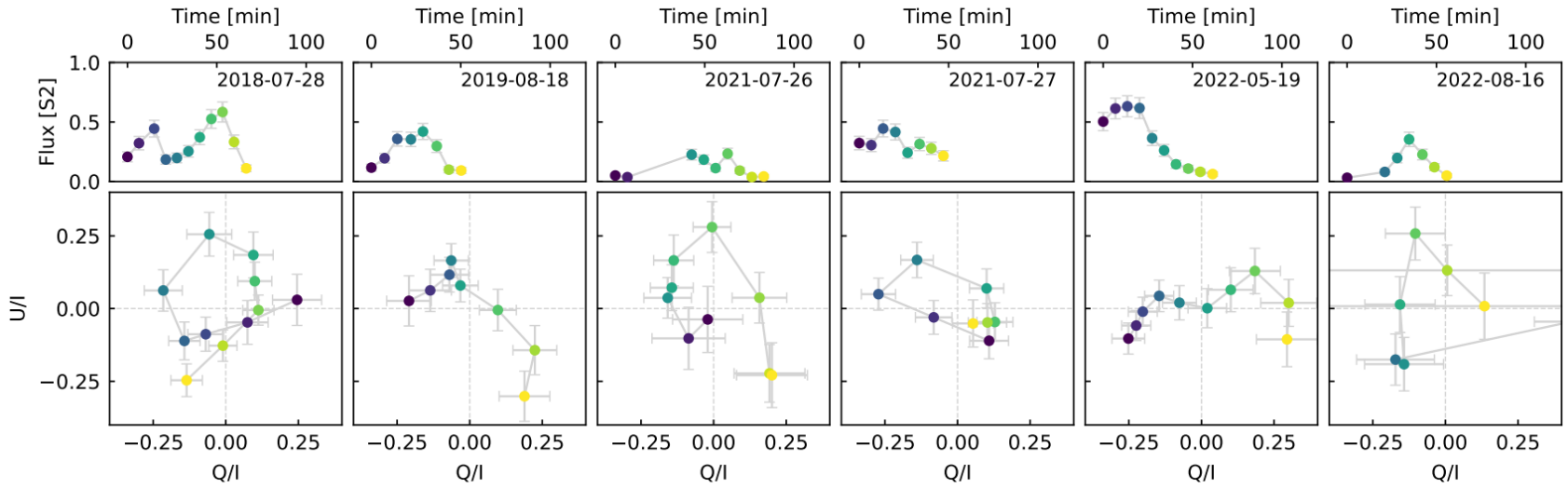

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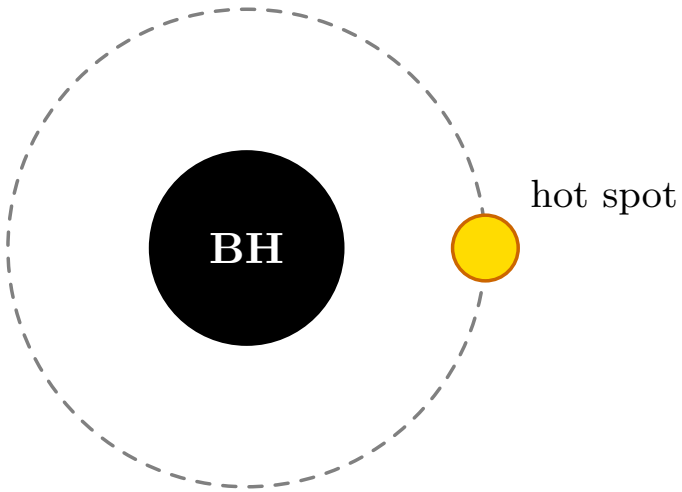

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- magnetic field structure
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- **geometry**

Motivation

- GR is successful, but incomplete
- Fundamental questions: cosmic censorship conjecture, information loss

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- Alternatives to BHs – exotic compact objects (ECOs)
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Motivation

- GR is successful, but incomplete
- Fundamental questions: cosmic censorship conjecture, information loss
- Black-hole mass gap $\rightarrow$ exotic matter, new formation channels
- Alternatives to BHs – exotic compact objects (ECOs)
  - Examine the effects of matter structure, compacticity, anomalies
- We will consider:
  - relativistic fluid spheres (FS)
  - gravitational vacuum stars (GS)
  - solitonic boson stars (SBS)

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Theory of ECOs: FS

- Interior fluid (dark matter), exterior vacuum

$$g_{tti} = -\frac{1}{4}\left(3\sqrt{1-\frac{2M}{R}} - \sqrt{1-\frac{2r^2M}{R^3}}\right)^2 \qquad g_{tte} = -\left(1-\frac{2M}{r}\right) \tag{1}$$

$$g_{rri} = \left(1-\frac{2r^2M}{R^3}\right)^{-1} \qquad g_{rre} = \left(1-\frac{2M}{r}\right)^{-1} \tag{2}$$

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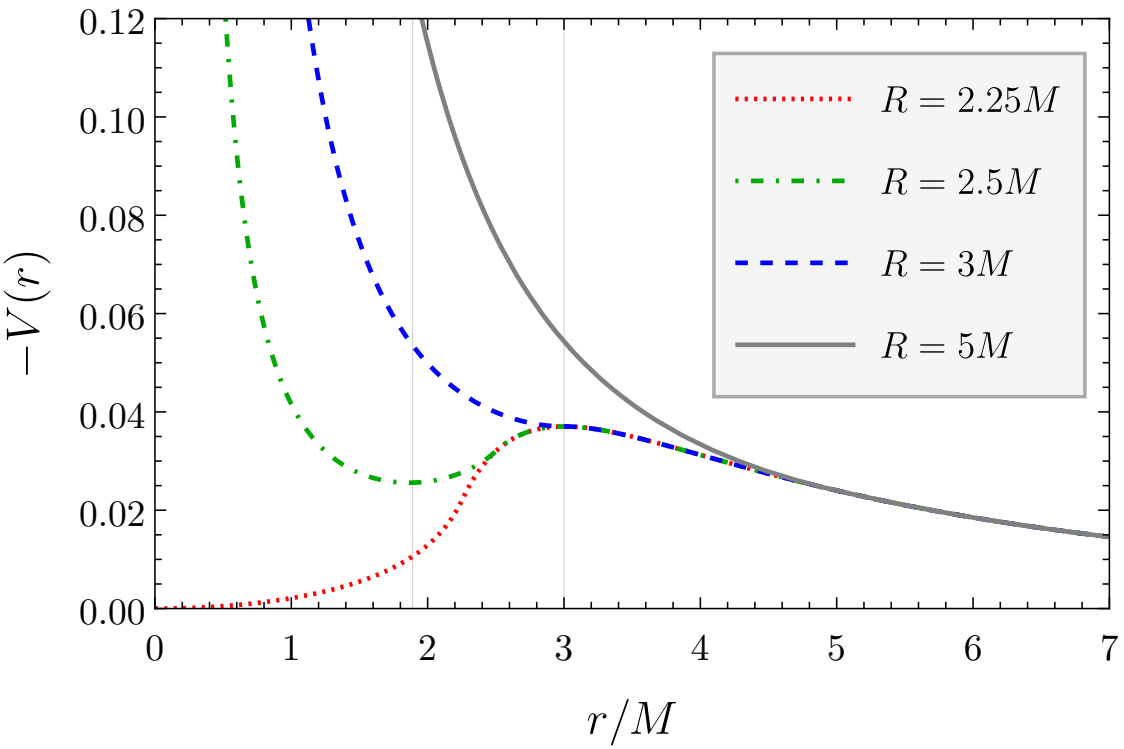

Potential for FS models. Extrema depict the existence and type of LRs. [4]

Theory of ECOs: GS

- Interior fluid (dark energy), exterior vacuum

$$g_{tti} = -\alpha\left(1 - \frac{2m(r)}{r}\right) \qquad g_{tte} = -\left(1 - \frac{2M}{r}\right) \tag{3}$$

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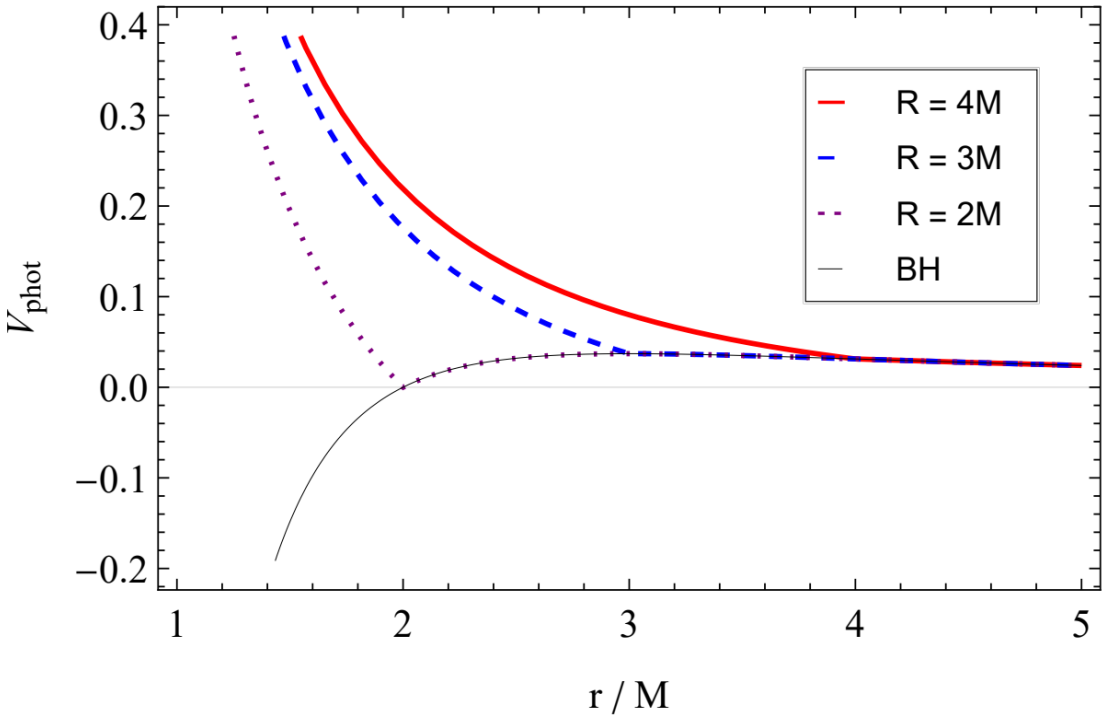

Potential for GS models. Extrema depict the existence and type of LRs. [6]

Theory of ECOs: SBS [7]

- Interior scalar field, asymptotically vacuum

$$S = \int_{\Omega} \sqrt{-g} \left[\frac{R}{16\pi} - \frac{1}{2} \partial_{\mu} \Phi^{*} \partial^{\mu} \Phi - \frac{1}{2} V \left(|\Phi|^{2} \right) \right] d^{4}x, \tag{5}$$

$$V \left(|\Phi|^{2} \right) = \mu^{2} |\Phi|^{2} \left(1 + \frac{|\Phi|^{2}}{\alpha^{2}} \right)^{2} \tag{6}$$

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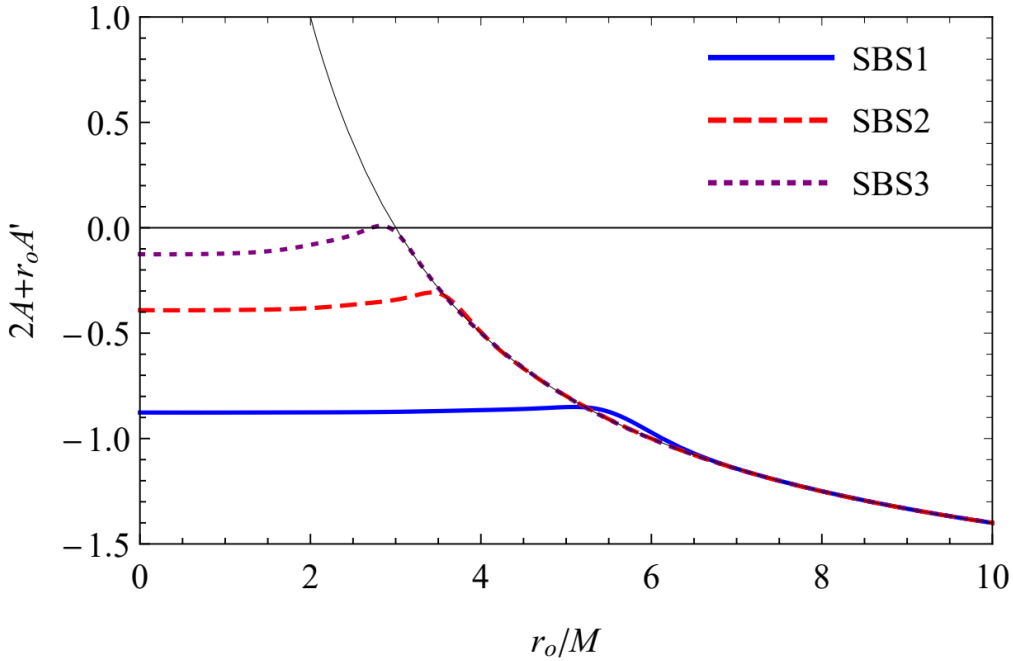

Figure: The expression $2A(r_0) - r_0A'(r_0)$ for discriminating LRs for three BS models. The zeroes of the expression correspond to LR orbits. [7]

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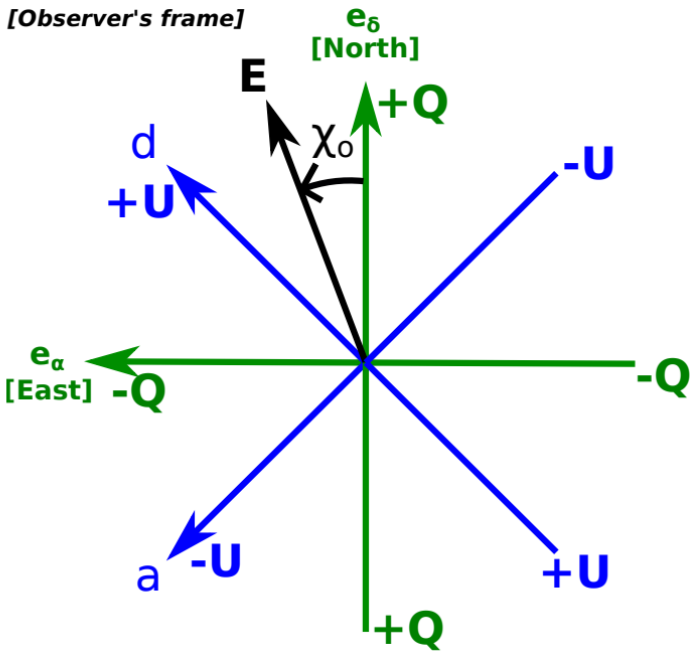
Polarization parameters

- Stokes parameters, EVPA, QU-loops

$$I = E^2 \tag{7}$$
$$Q = I\cos(2\chi_0) \tag{8}$$
$$U = I\sin(2\chi_0) \tag{9}$$
$$\chi_0 = \mathrm{atan2}(Q, U) \tag{10}$$

- Magnetic field configuration: vertical/poloidal



Eletric field, EVPA and Stokes Q and U defined in the observer's frame. [8]

Simulations in GYOTO

- $r_o = 8M, i \in \{20°, 80°\}$

Model	R/M	# of LR(s)
SBH	-	1
FS1	2.25	1
FS2	2.50	2
FS3	3.00	2 (degen.)
GS1	3.00	2 (degen.)
GS2	2.50	2
GS3	2.01	2
SBS1	6.58	0
SBS2	3.95	0
SBS3	3.12	1

Property	Value
Compact object mass	$4.2 \cdot 10^{-6}\, M_\odot$
Compact object distance	8.25 kpc
Observing frequency	230 GHz
Screen resolution	1000 px
Screen field of view	$250\ \mu$as
Inclination	$20°, 80°$
Time steps	$100/200$
Hot-spot radius	$0.5\, M$
Hot-spot orbital radius	$8M$
Hot-spot temperature	200
Hot-spot number density	$6.6 \cdot 10^6$ cm^{-3}
Magnetization parameter	0.01

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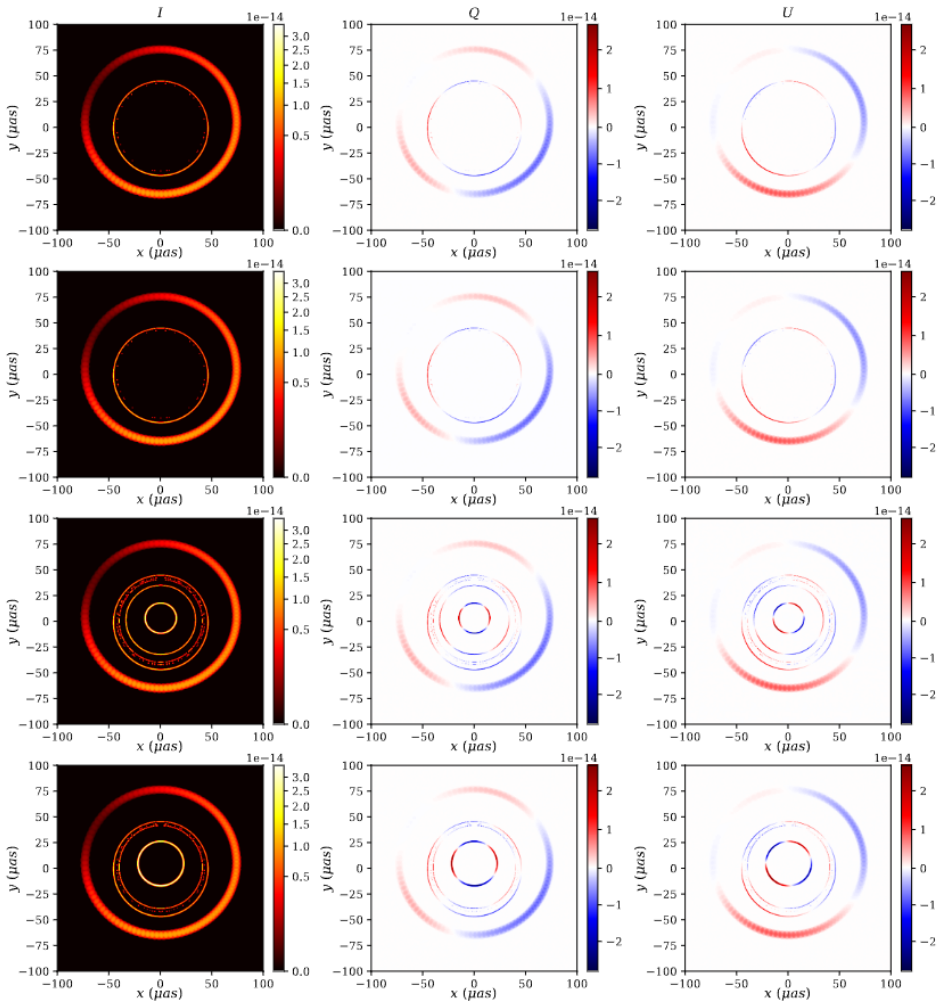
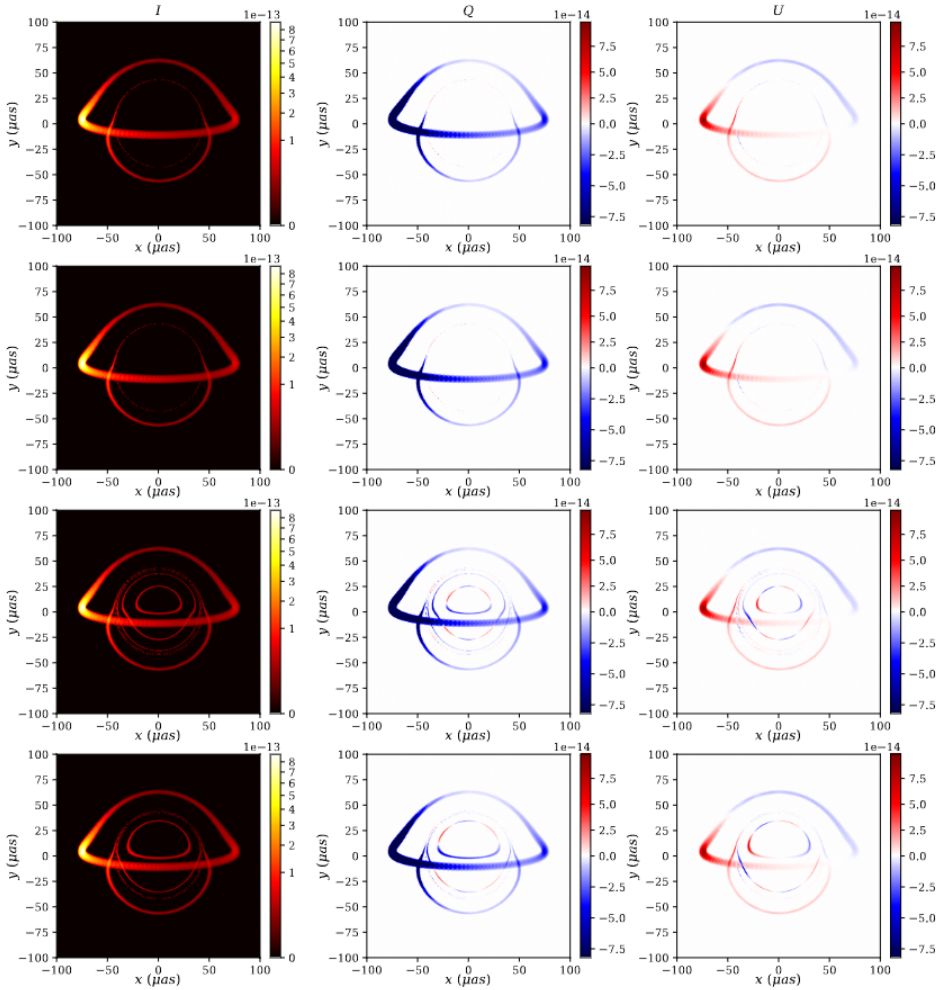
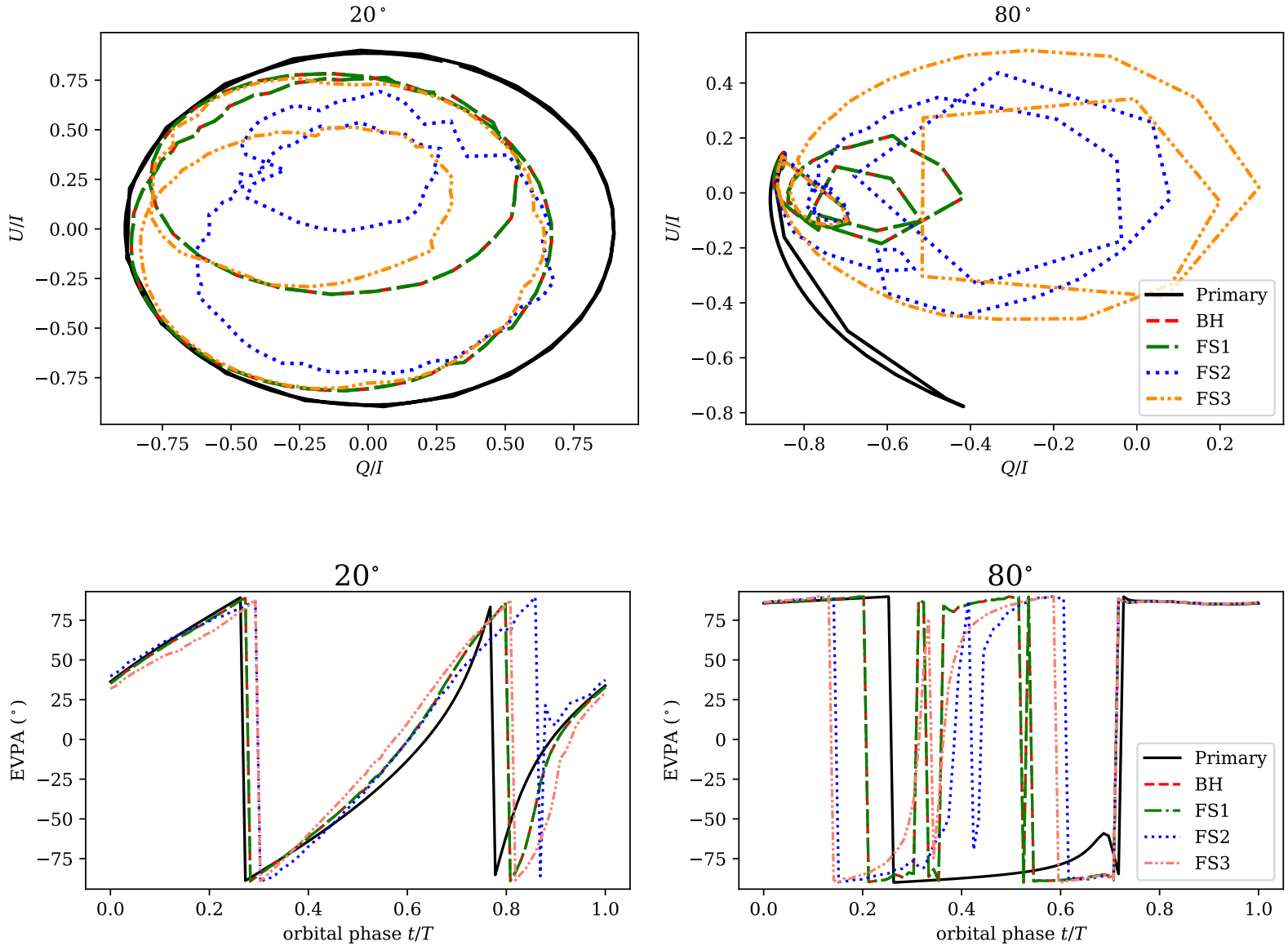
Results: integrated images (FS)

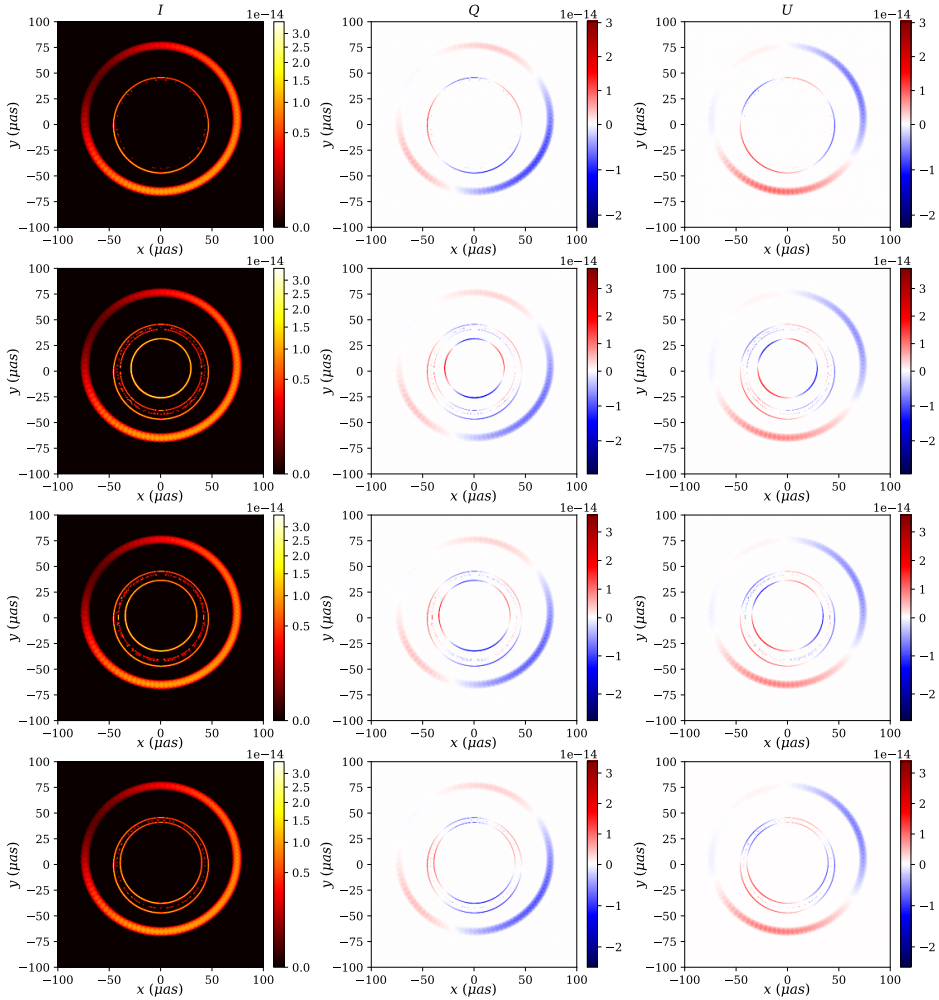


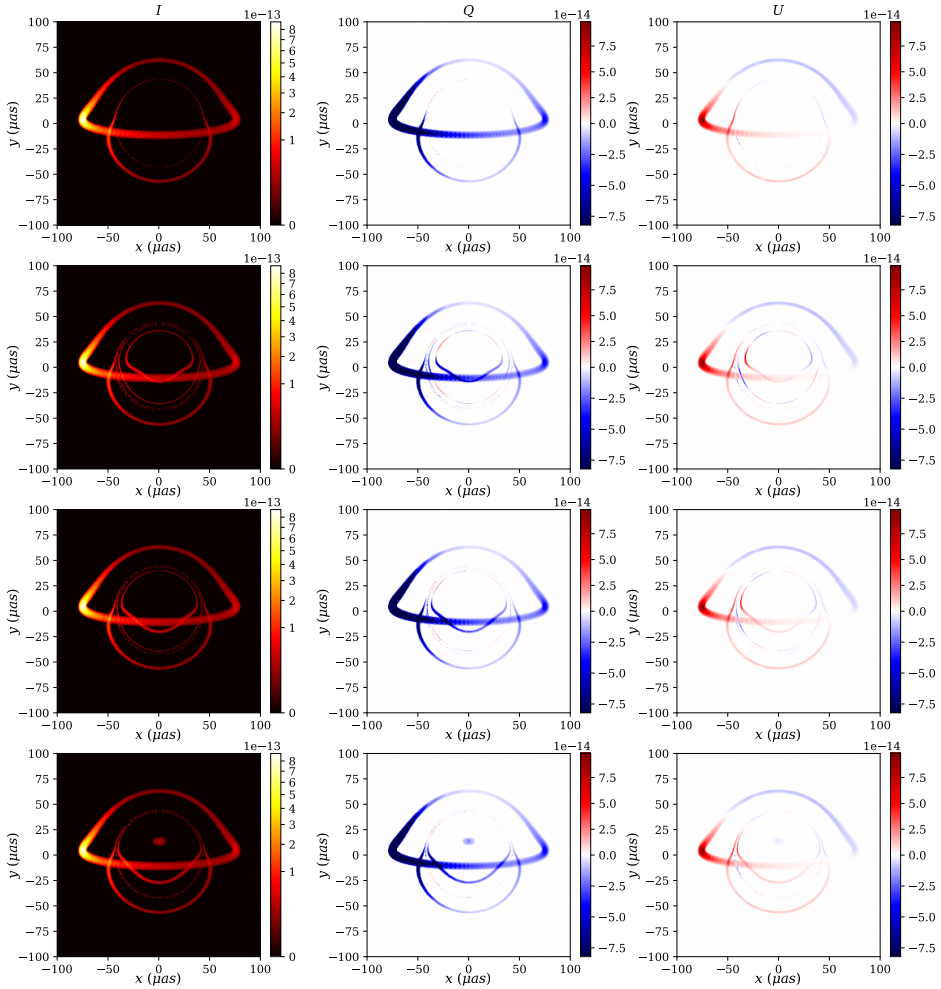


Results: QU-loops, EVPA (FS)



Results: integrated images (GS)





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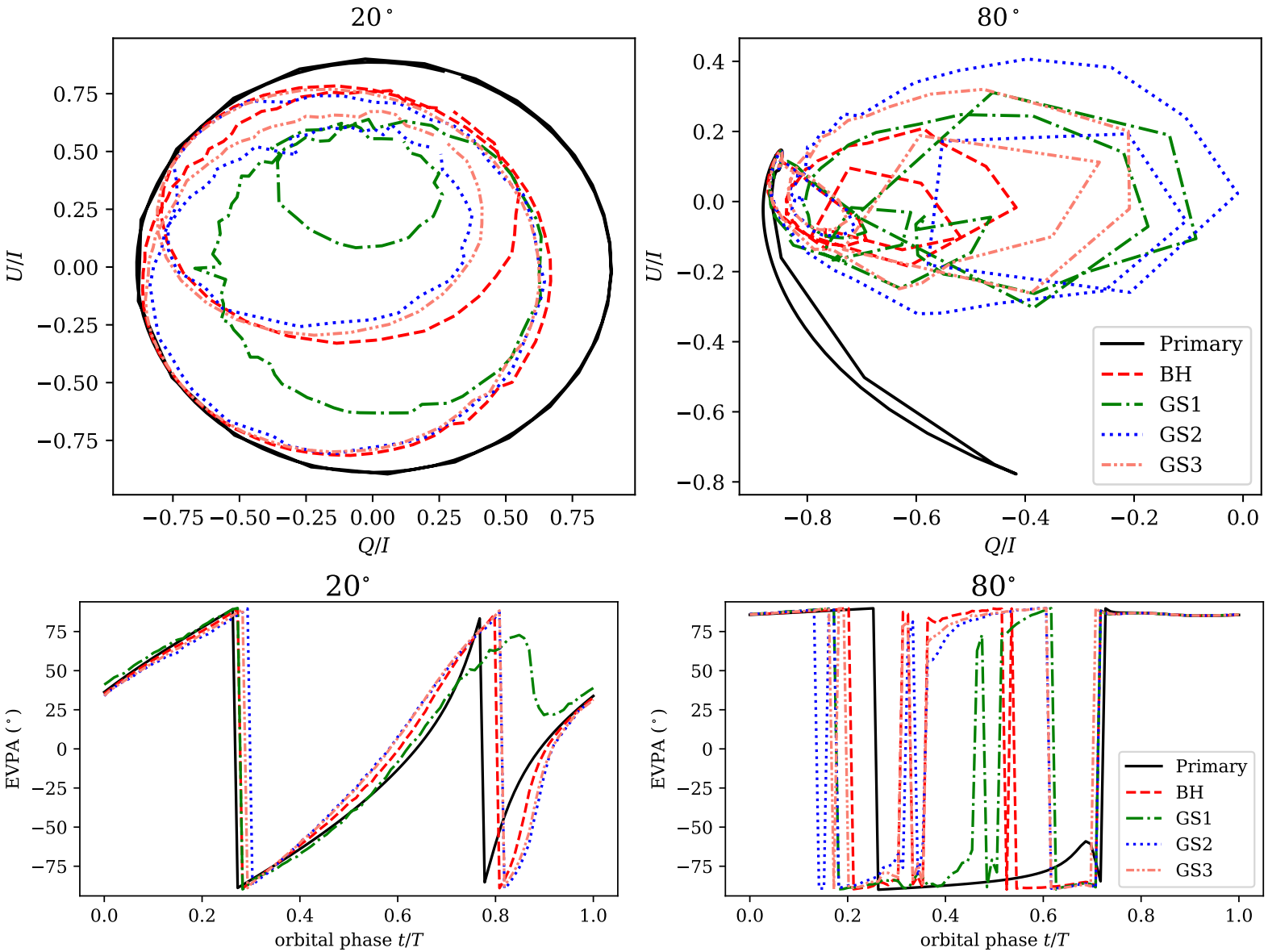
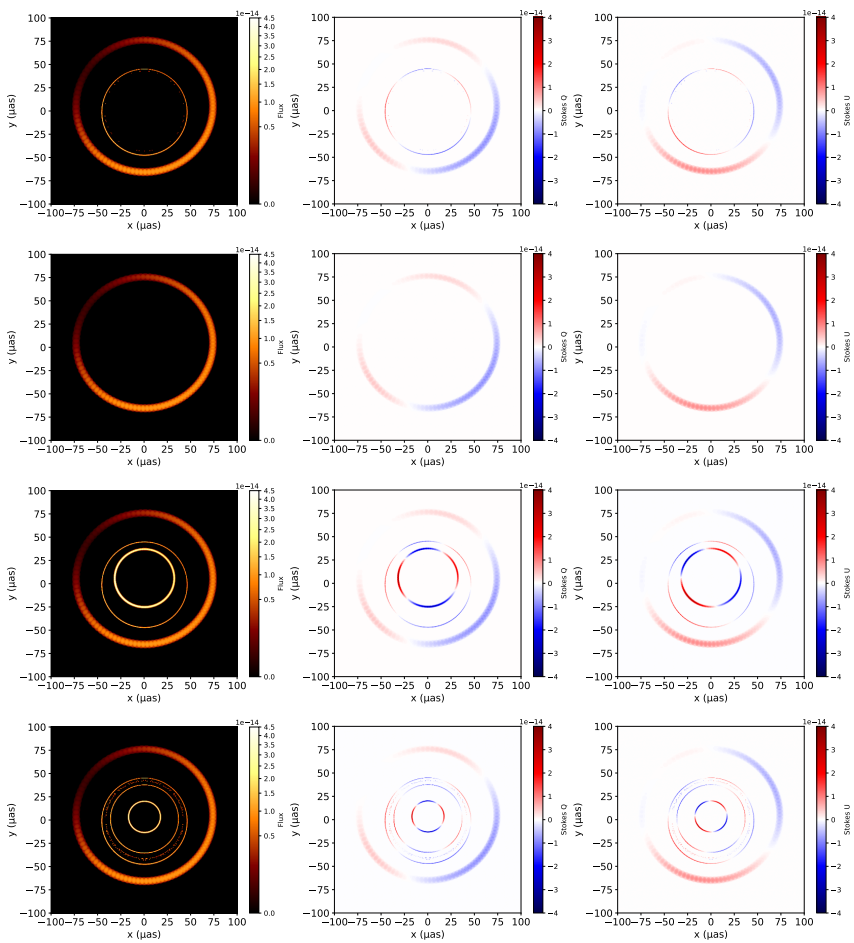
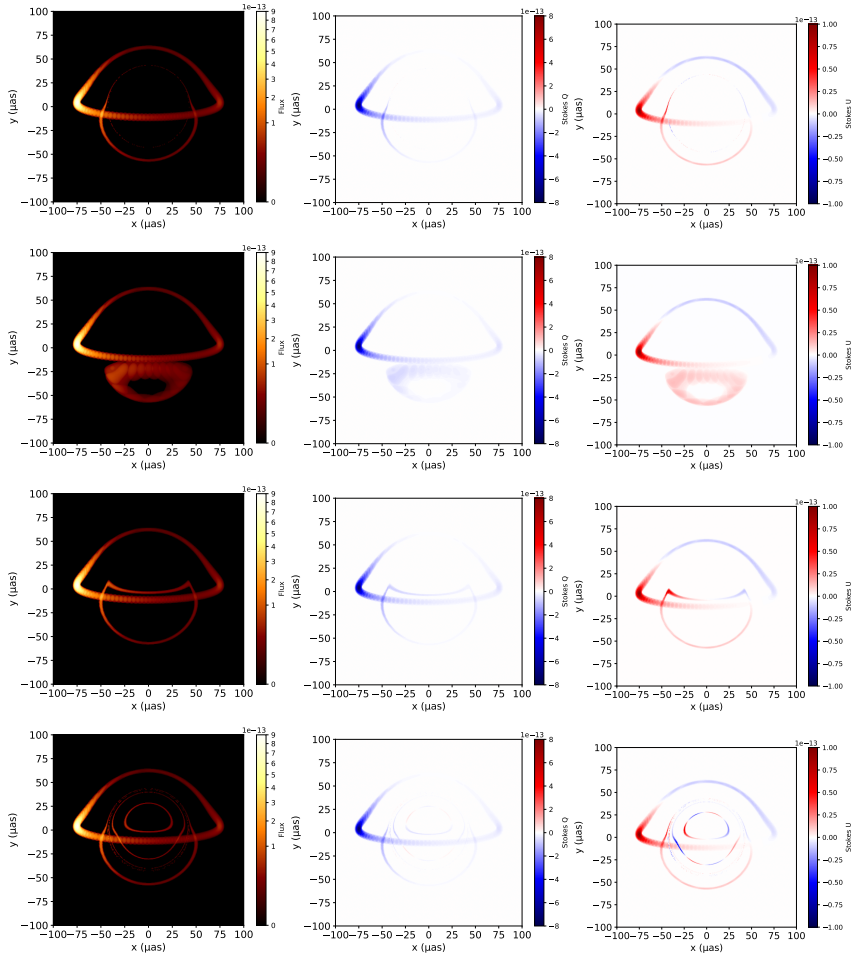


Results: integrated images (SBS)





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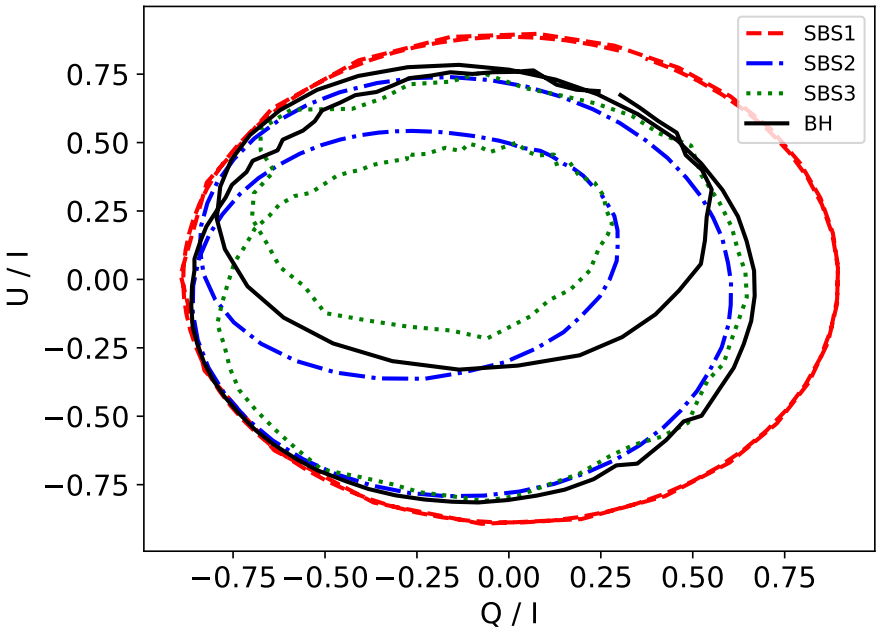

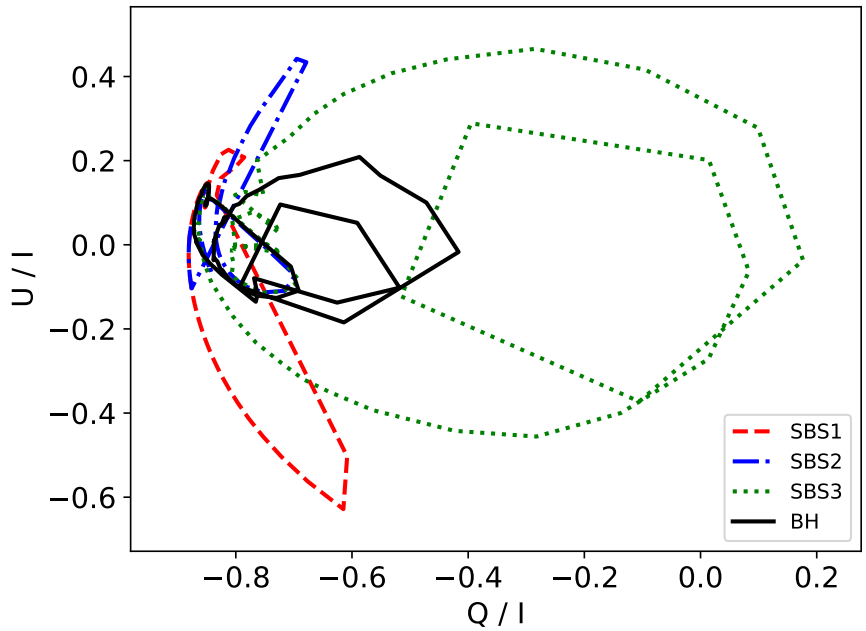

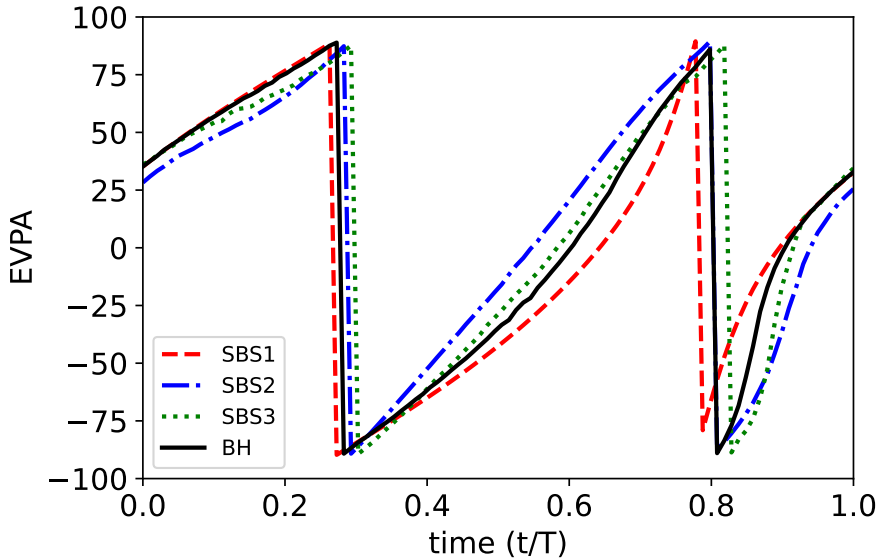

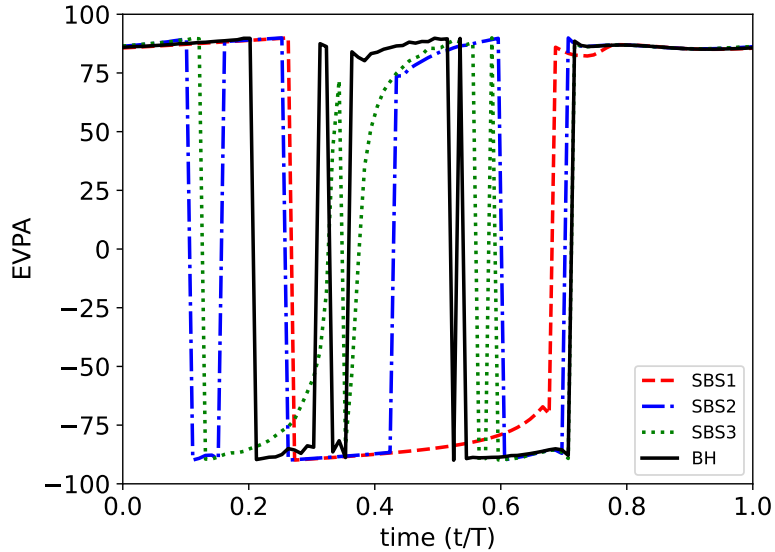

Quantitative comparison

Model	OLA	ILA	LAR	ST (T)
Primary	2.49	2.49	1.00	0.51
BH	1.88	1.17	0.62	0.53
FS1	1.88	1.17	0.62	0.53
FS2	1.35	0.27	0.20	0.57
FS3	1.83	0.67	0.36	0.52
GS1	1.22	0.24	0.19	0.60
GS2	1.79	0.73	0.41	0.52
GS3	1.83	0.89	0.48	0.53
SBS1	2.49	2.49	1.00	0.51
SBS2	1.78	0.79	0.44	0.51
SBS3	1.92	0.57	0.29	0.52

Table: Outer loop area (OLA), inner loop area (ILA), loop area ratio (LAR), and shift time (ST) as a fraction of the orbital period T, for the simulations with an observation angle of $i = 20^\circ$.

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- Compacticity: can eliminate one model SBS1 due to the absence of higher order images
- Future detectability and extensions

References

[1] C. Goddi *et al.*, The Astrophysical Journal Letters **910** (2021), L14, doi:10.3847/2041-8213/abee6a [arXiv:2105.02272 [astro-ph.GA]]

[2] K. Akiyama *et al.* [EHT], The Astrophysical Journal Letters **910** (2021), L12, doi:10.3847/2041-8213/abe71d [arXiv:2105.01169 [astro-ph.HE]]

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[4] H. L. Tamm and J. L. Rosa, Physical Review D **109** (2024), 044062, doi:10.1103/PhysRevD.109.044062

[5] J. L. Rosa, P. Piçarra, Physical Review D **102** (2020), 6, doi=10.1103/physrevd.102.064009 [arXiv:2006.09854 [gr-qc]]

[6] J. L. Rosa *et al*, Physical Review D **109** (2024), 8, doi=10.1103/physrevd.109.084002 [arXiv:2401.07766 [gr-qc]]

[7] J. L. Rosa *et al*, Physical Review D **108** (2023), 4, doi=10.1103/PhysRevD.108.04402

[8] F. H. Vincent *et al*, Astronomy & Astrophysics **684** (2024), A194, doi=10.1051/0004-6361/202348016 [arXiv:2309.10053 [astro-ph.HE]]

Appendix

Fluid spheres:

$$g_{tti} = -\frac{1}{4}\left(3\sqrt{1-\frac{2M}{R}} - \sqrt{1-\frac{2r^2M}{R^3}}\right)^2 \qquad g_{tte} = -\left(1-\frac{2M}{r}\right) \tag{11}$$

$$g_{rri} = \left(1-\frac{2r^2M}{R^3}\right)^{-1} \qquad g_{rre} = \left(1-\frac{2M}{r}\right)^{-1} \tag{12}$$

Gravastars:

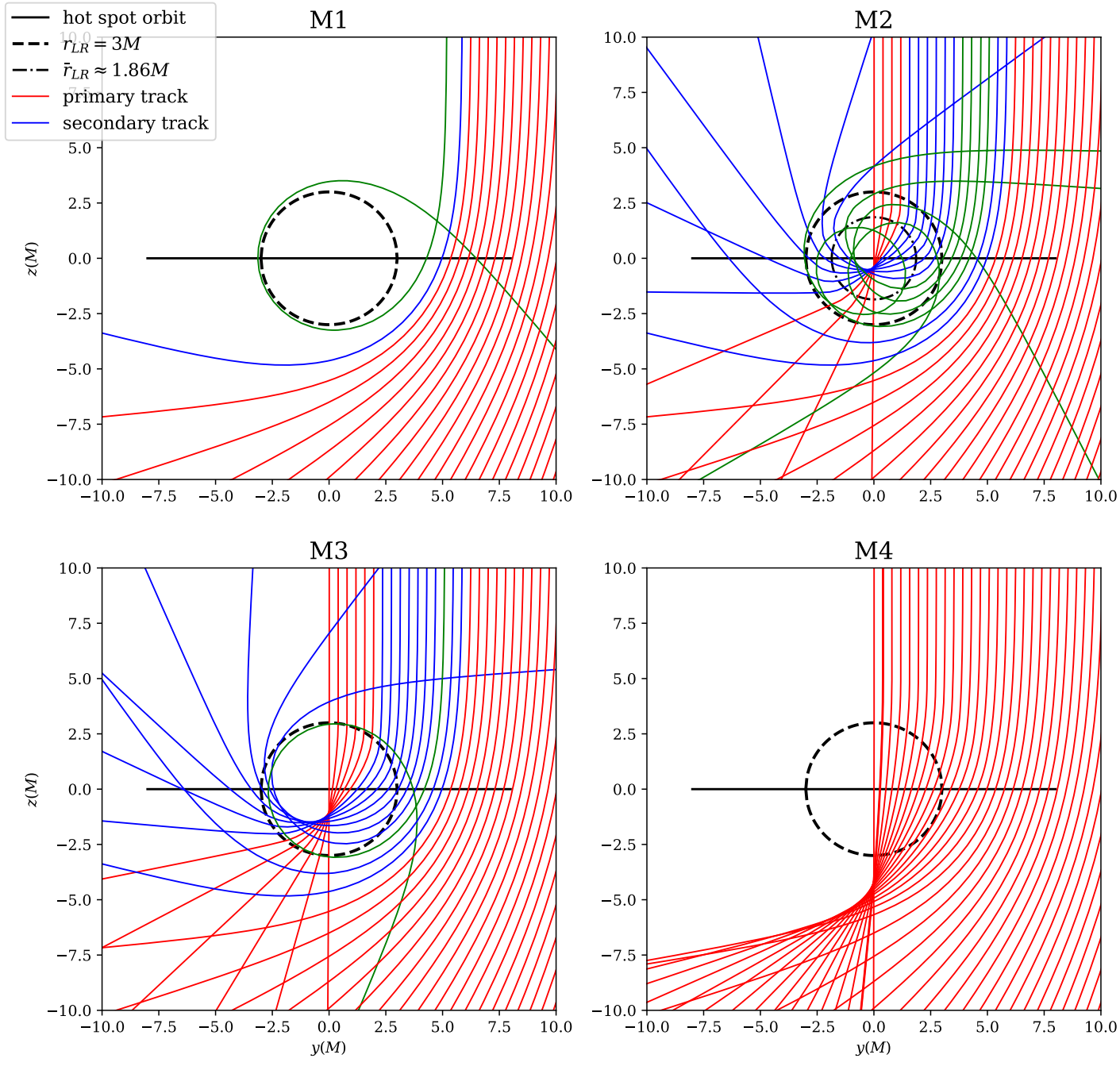
$$g_{tti} = -\alpha\left(1-\frac{2m(r)}{r}\right) \qquad g_{tte} = -\left(1-\frac{2M}{r}\right) \tag{13}$$

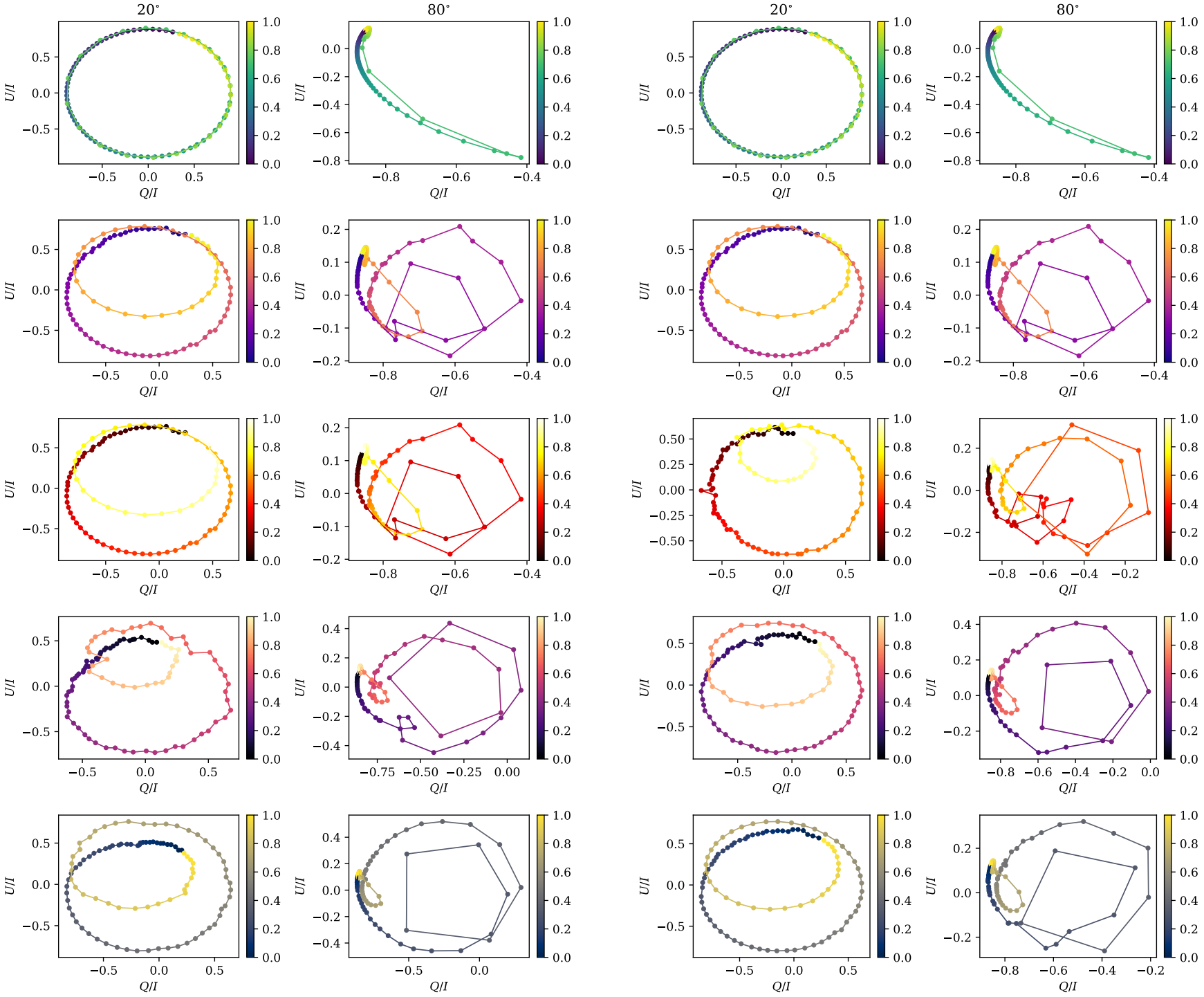
$$g_{rri} = \alpha^{-1}\left(1-\frac{2m(r)}{r}\right)^{-1} \qquad g_{rre} = \left(1-\frac{2M}{r}\right)^{-1} \tag{14}$$

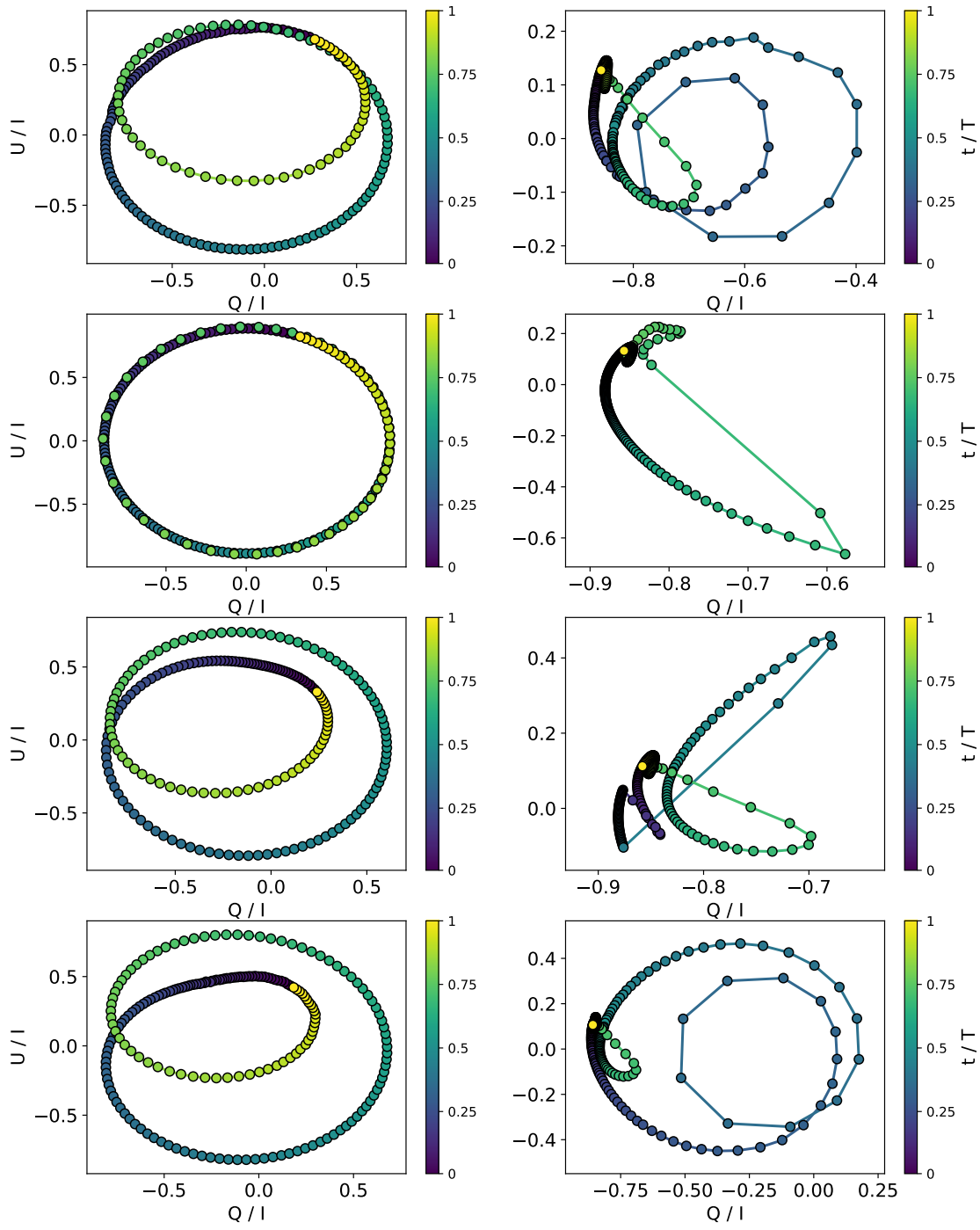
Solitonic boson stars:

$$ds^2 = -A(r)dt^2 + \frac{1}{B(r)}dr^2 + r^2 d\Omega^2 \tag{15}$$

$$\Phi = \phi(r)\, e^{-i\omega t} \tag{16}$$


hot spot orbit
$r_{LR} = 3M$
$\bar{r}_{LR} \approx 1.86M$
primary track
secondary track
M1
M2
M3
M4
$z(M)$
$y(M)$
10.0
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5
−10.0


20°
80°
20°
80°
U/I
Q/I


U / I
Q / I
t / T