Flares loops of polarization: a spacetime geometry probe?

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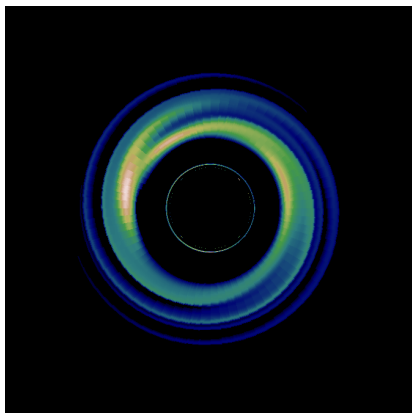
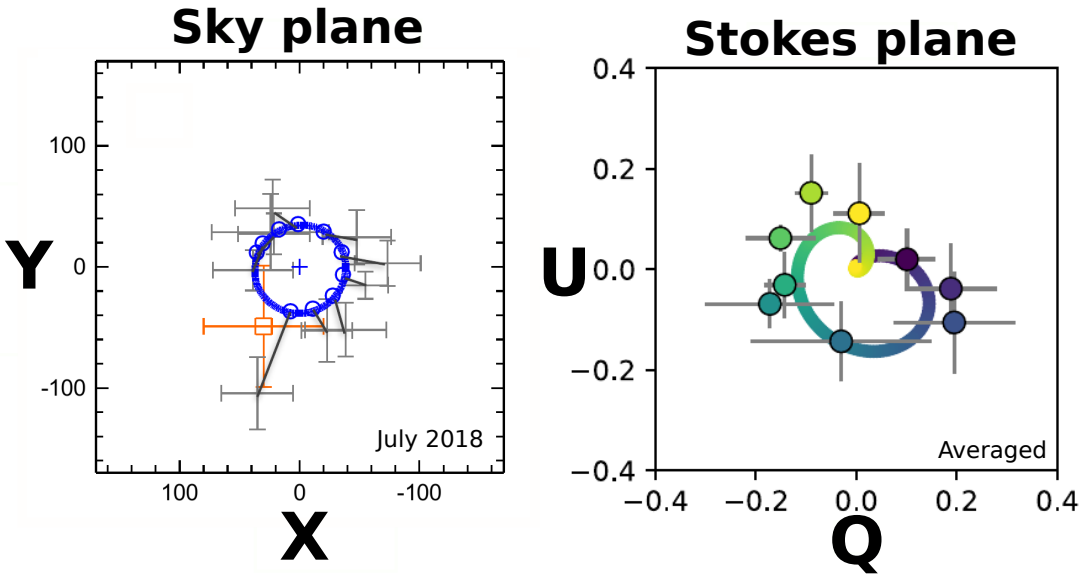
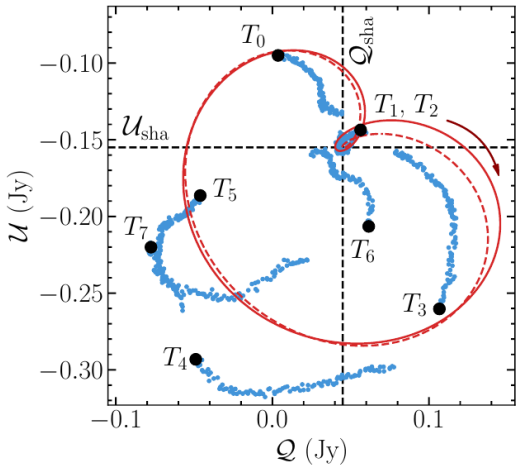




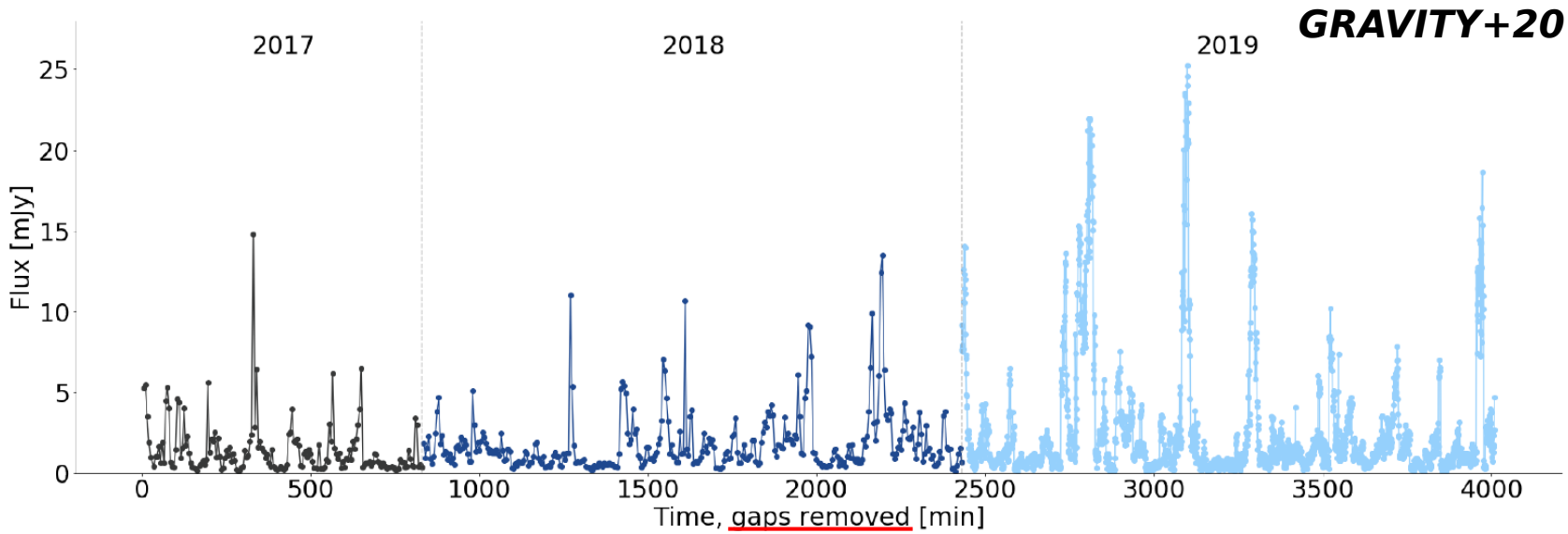
GRAVITY Coll. 2018,23



ALMA/Wielgus+22

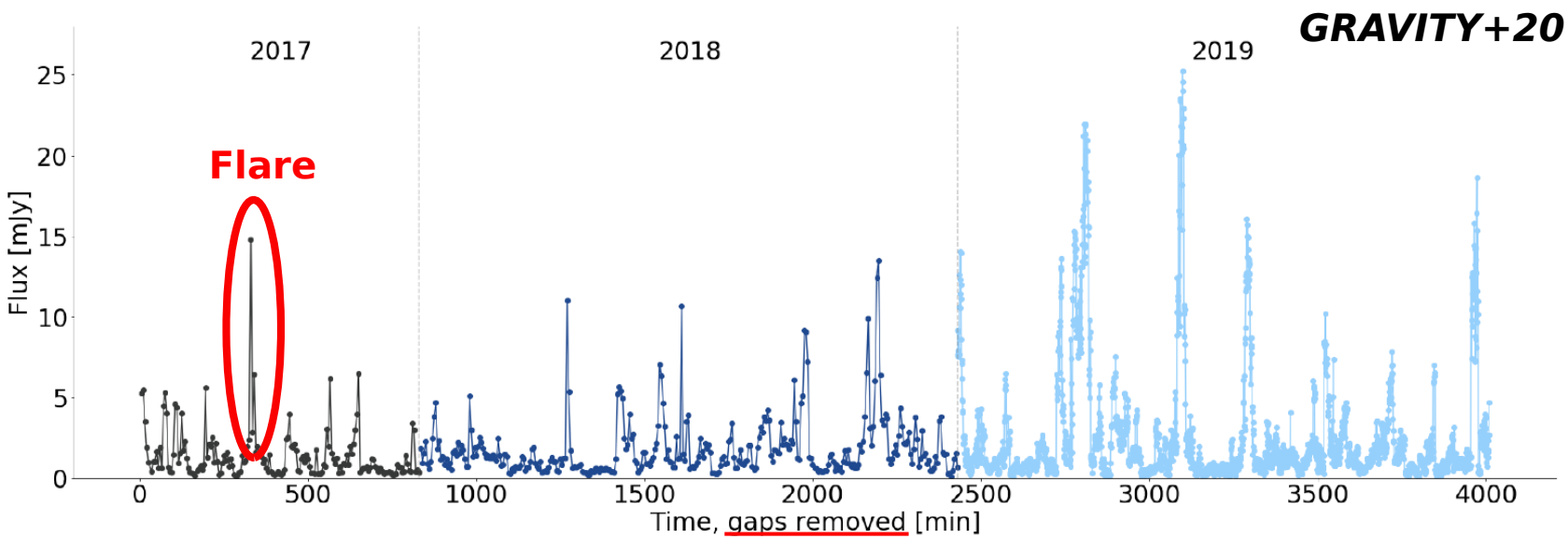
Sgr A* polarized flares

- Major result of GRAVITY: flares as strong-field sources
- Stokes plane: **double QU loop structure**
- Can we use that to constrain spacetime geometry?



Observations

- Flare = **transient peaks** of flux on daily basis (4/day in IR)
- mm, IR (my personal bias), X ...



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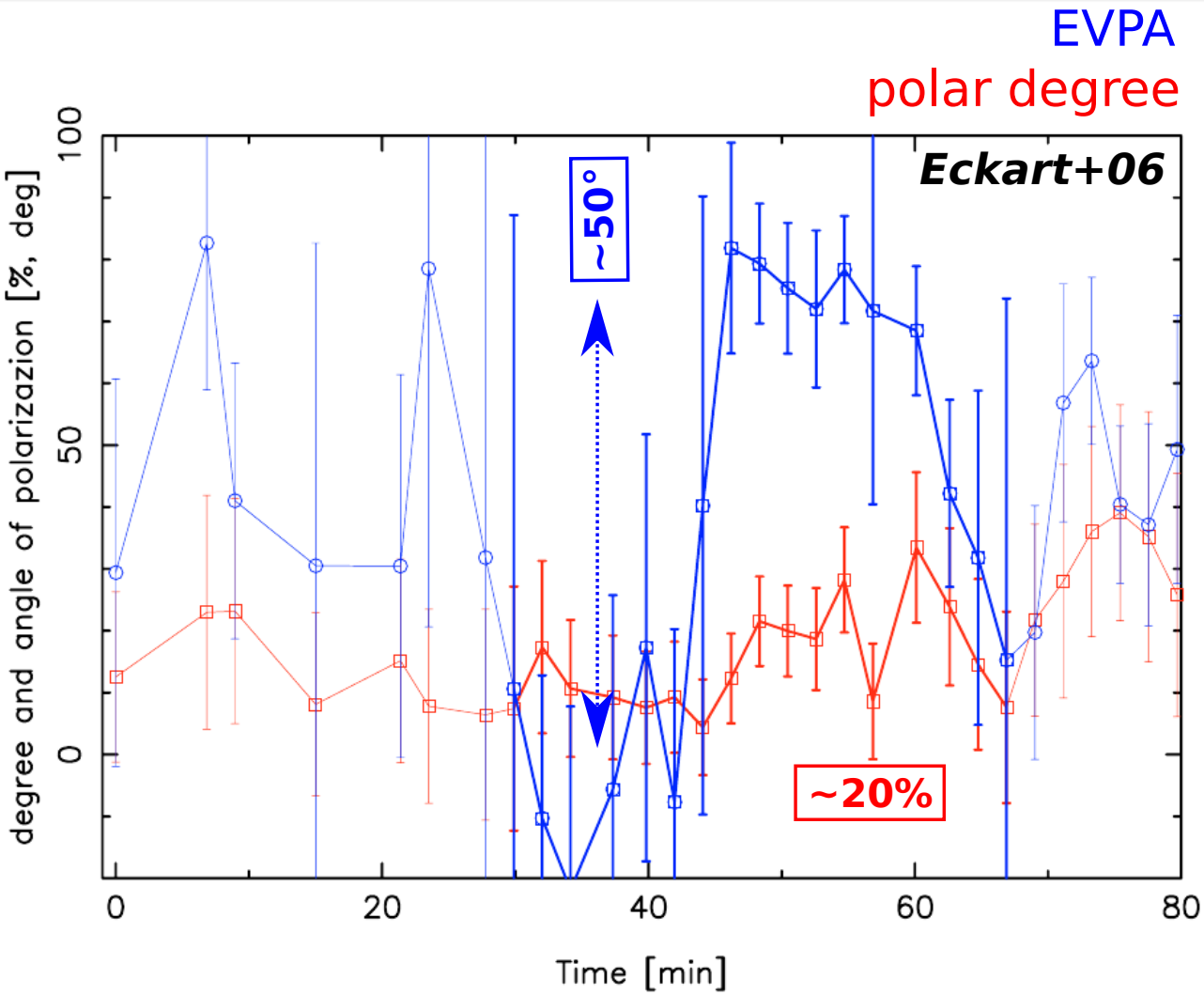
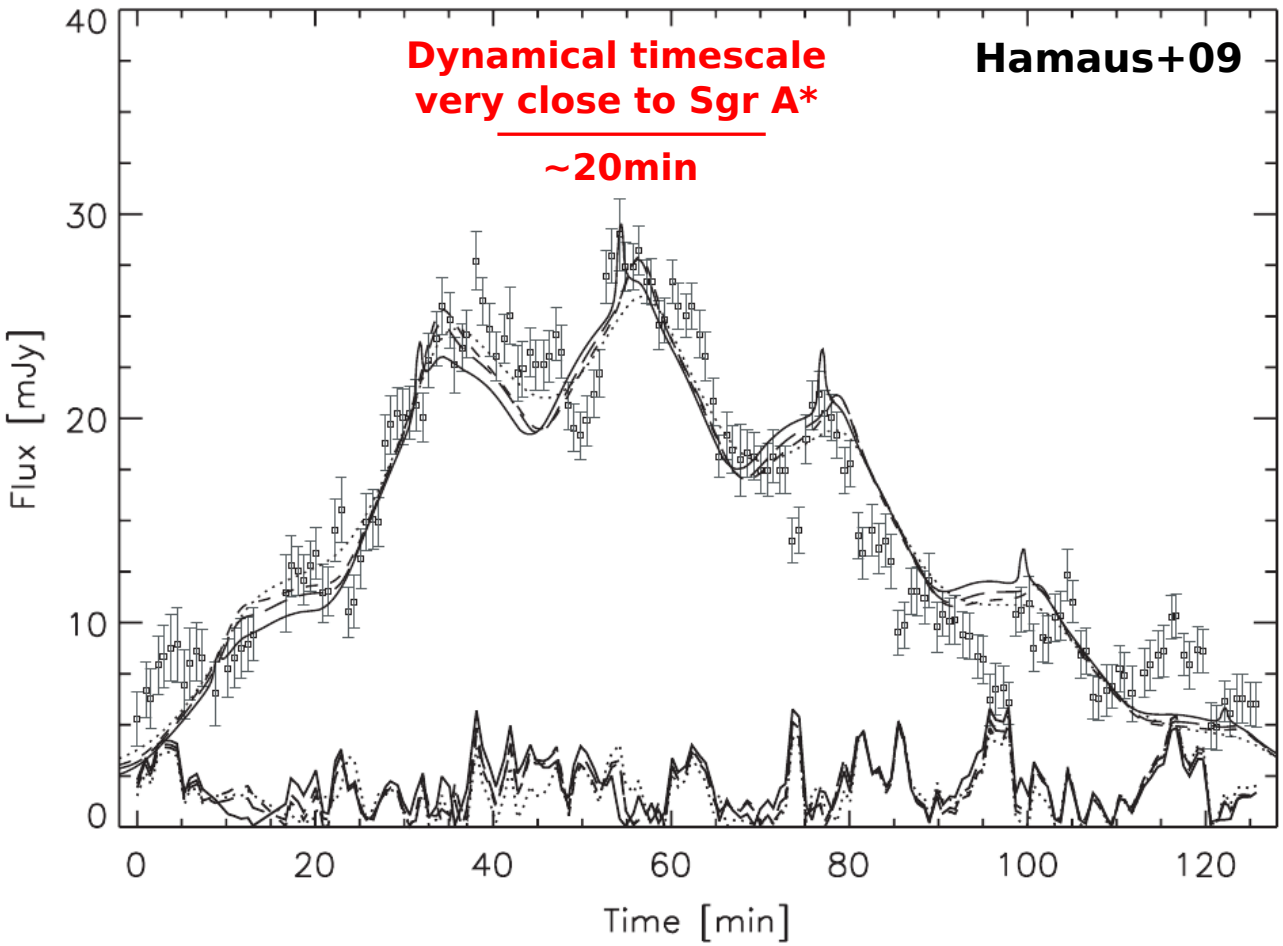


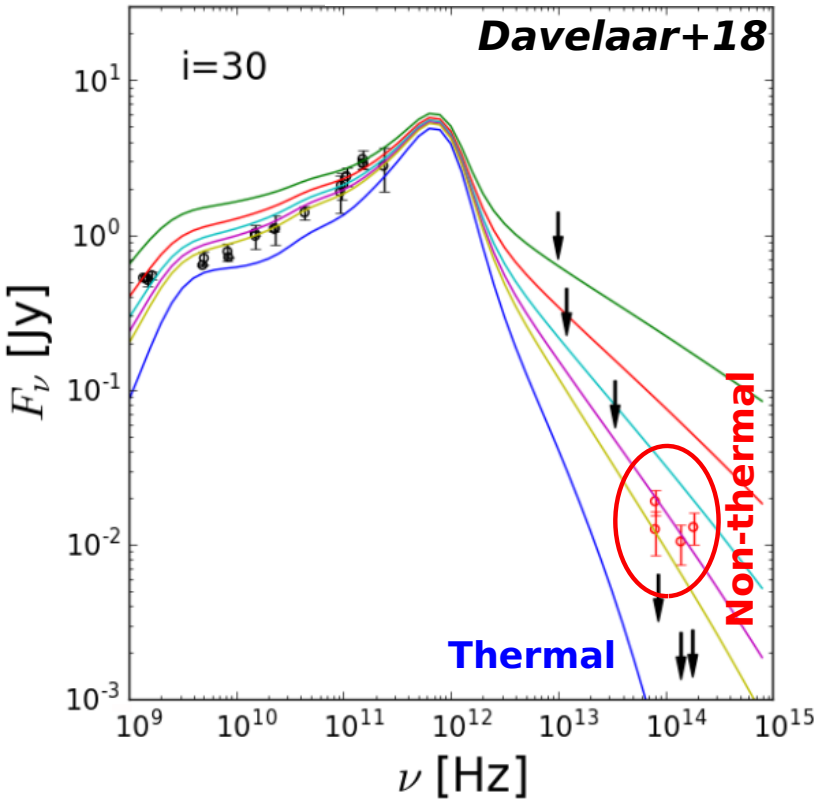
Observations

- ... IR linearly **polarized** (**synchrotron**) ...



Observations

- ... IR light curve **pseudo period** (close to BH!)...



Observations + model

- ... IR flare likely **nonthermal**,

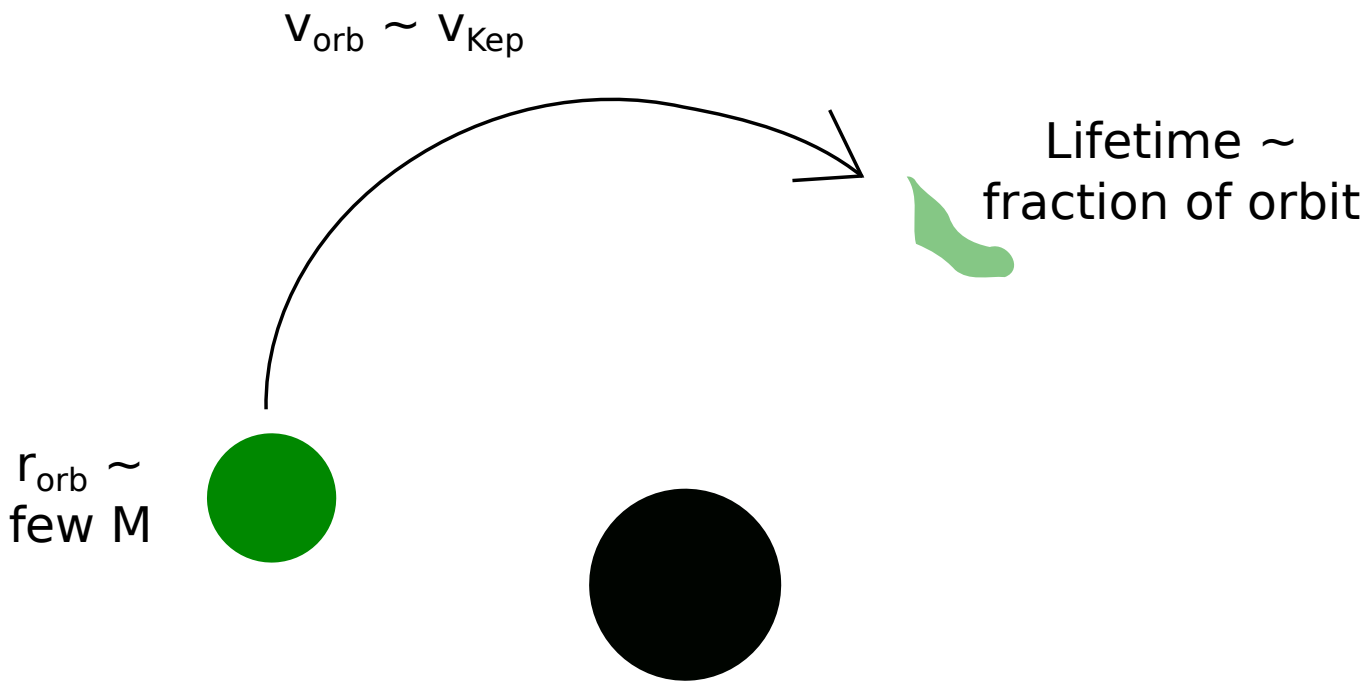
- likely **compact**, $R \approx GM/c^2$ (Gillessen+06)

Observational definition: **flare**

- Transient peaks of flux density
- polarized
- pseudo-periodic (at least some)

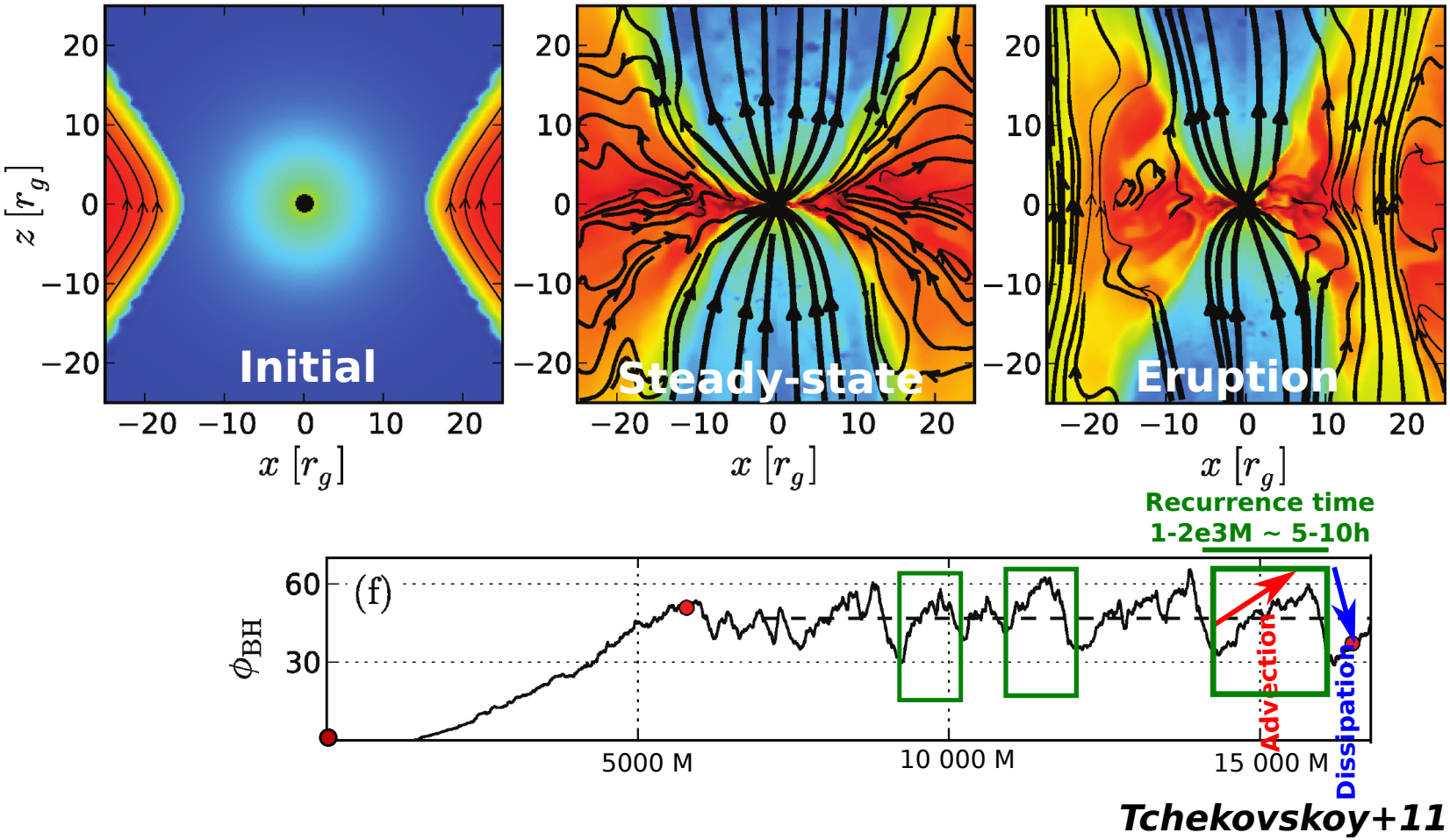
- nonthermal
- compact

≈ A hot “spot” of orbiting plasma!



Modeling definition: **hotspot**

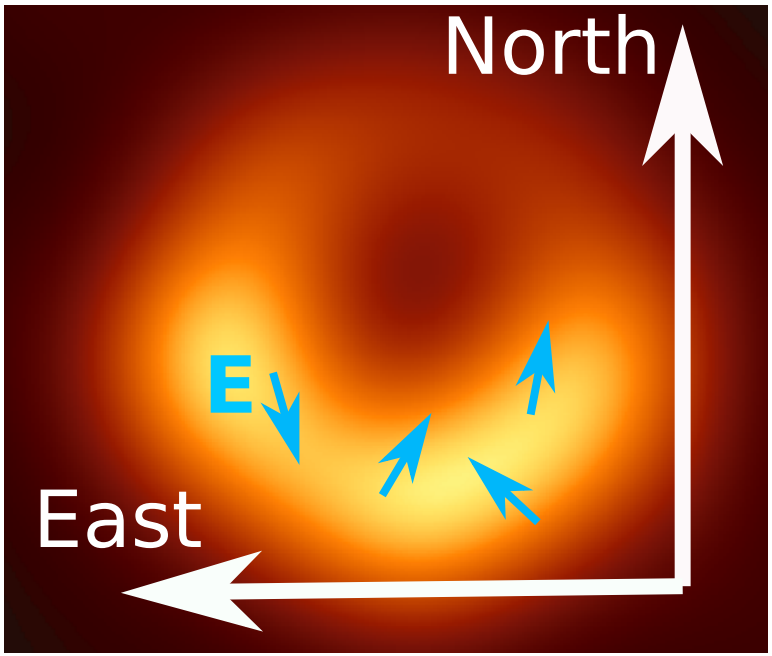
- Transient, compact, magnetized parcels of energized plasma, orbiting/ejected close to BH
- How to **create hotspots**?



MAD state

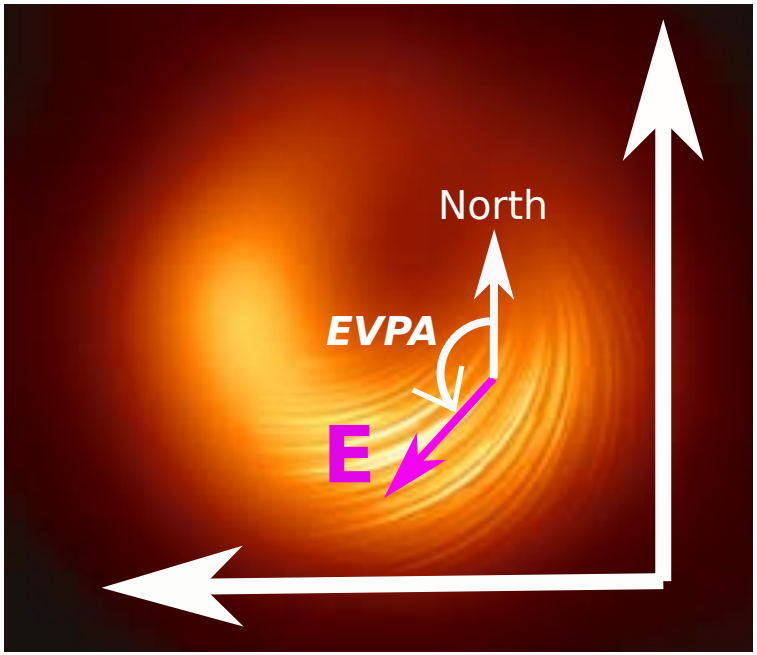
- Quasi-periodic eruptions, orbiting **flux tubes**
- A possible scenario for **hotspots** creation

Non-polarized

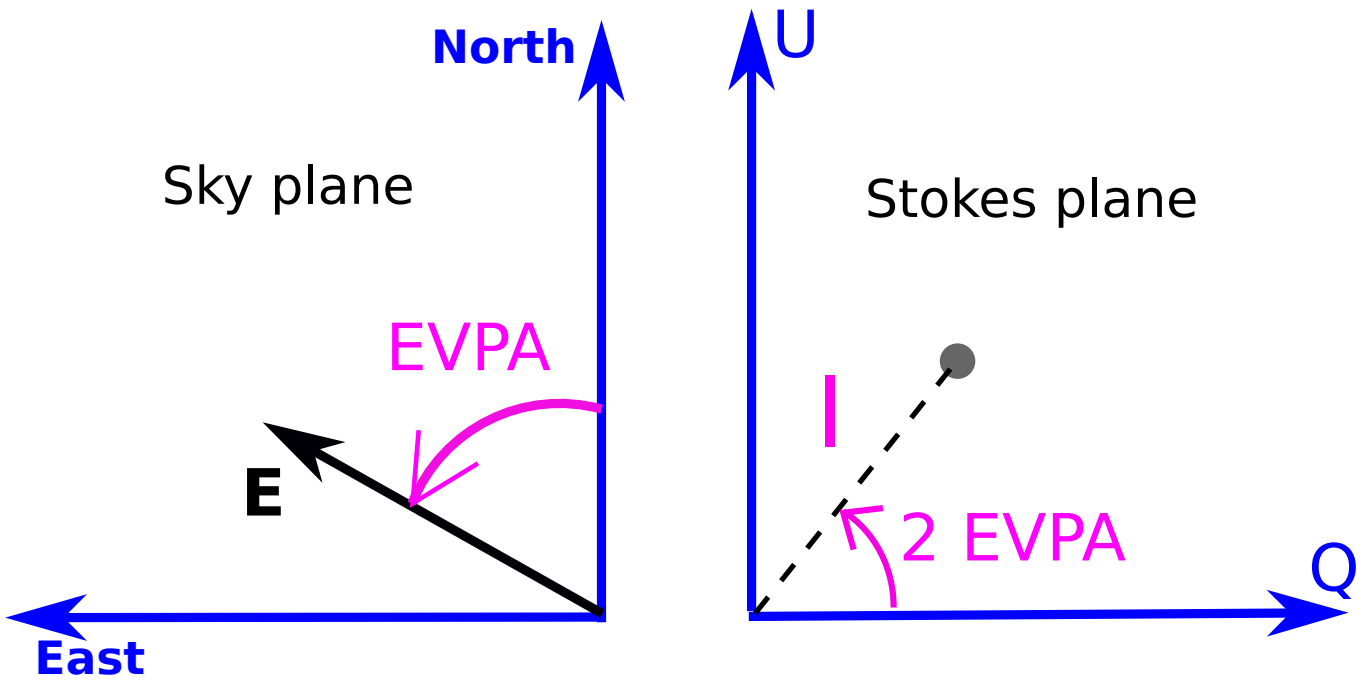


$I = E^2$

Polarized

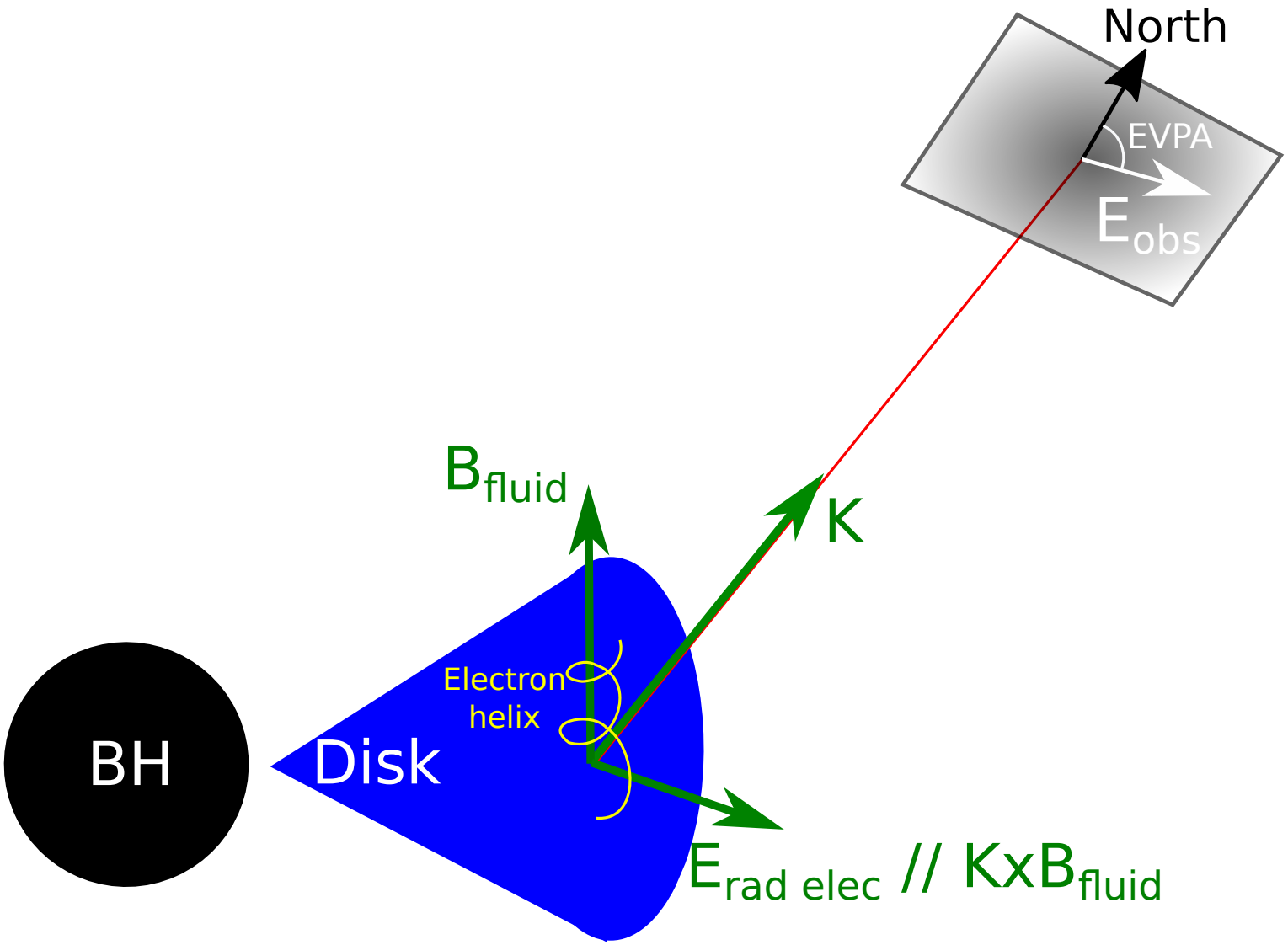


$I = E^2$
+EVPA

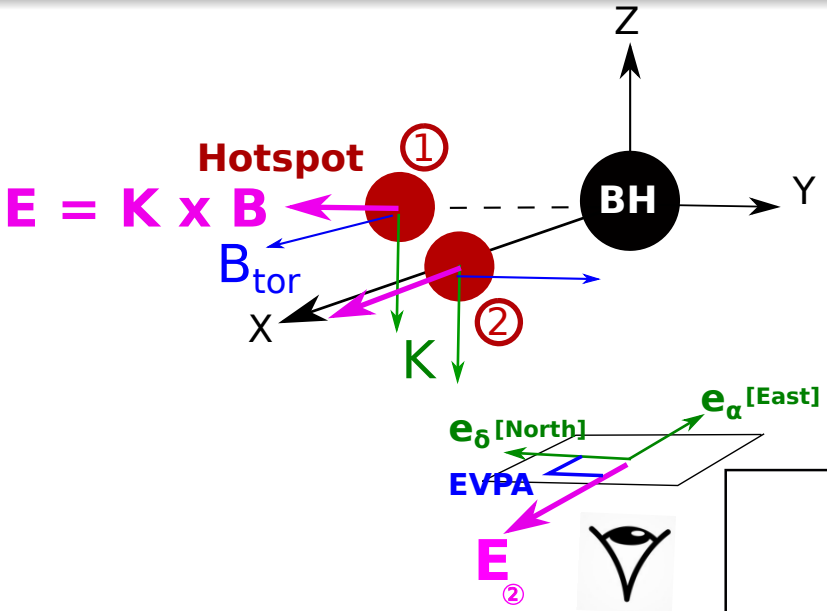


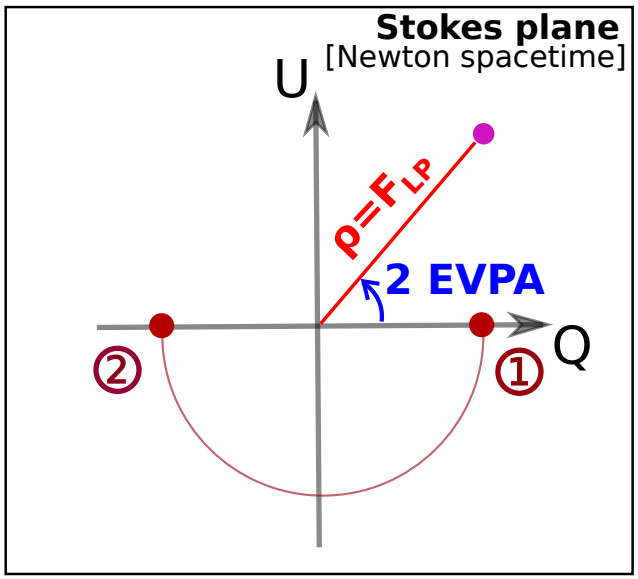
Linear polarization Stokes parameters

- $(I, EVPA) \longleftrightarrow (Q, U)$, two equivalent parametrizations
- $I^2 = Q^2 + U^2$, EVPA = $1/2 \operatorname{atan}(U/Q)$
- Full linear polarization information



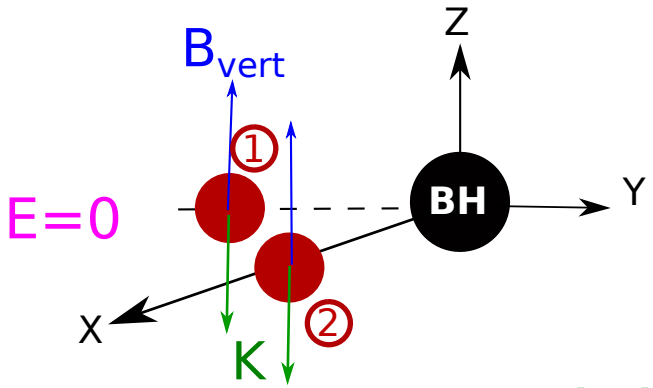
EVPA → B field orientation

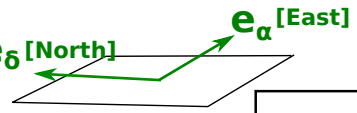


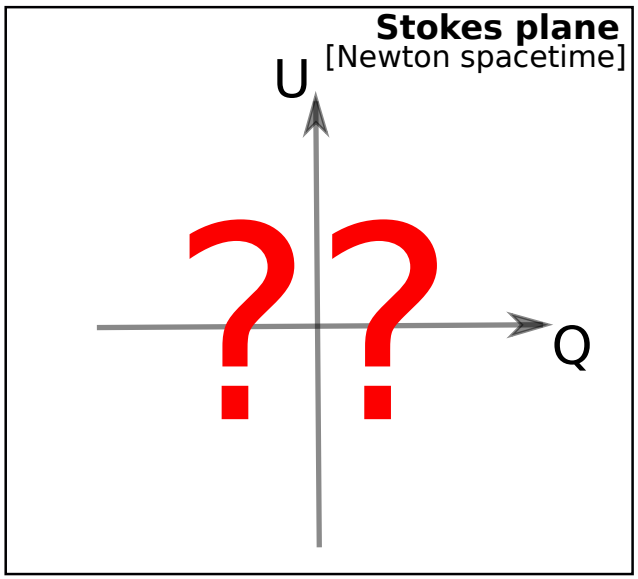


Understanding the double polarization loops

- Stokes plane polar angle = **2** *EVPA*
- 1 orbit on sky → **2** turns in Stokes plane

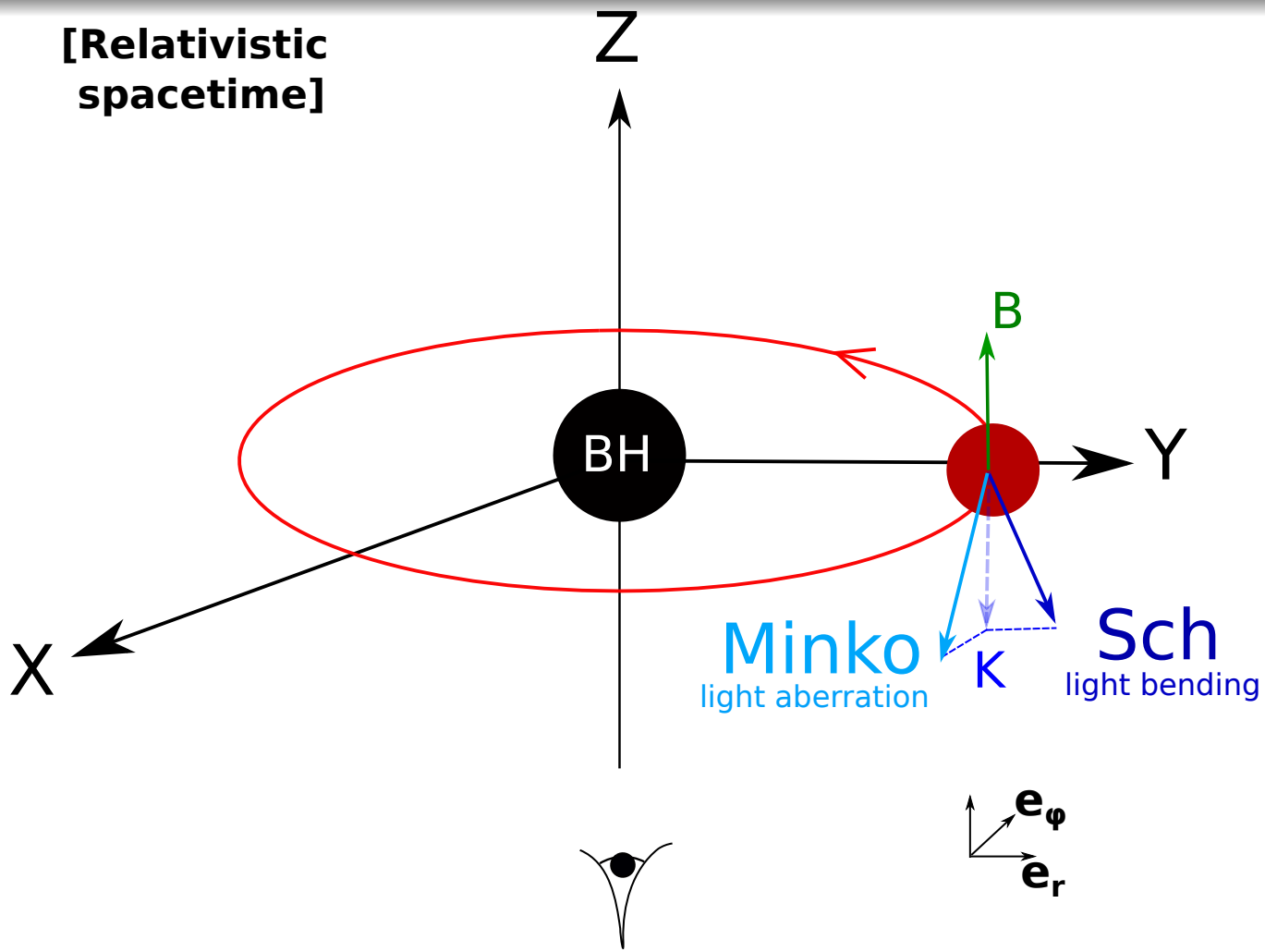






But with a vertical mf?

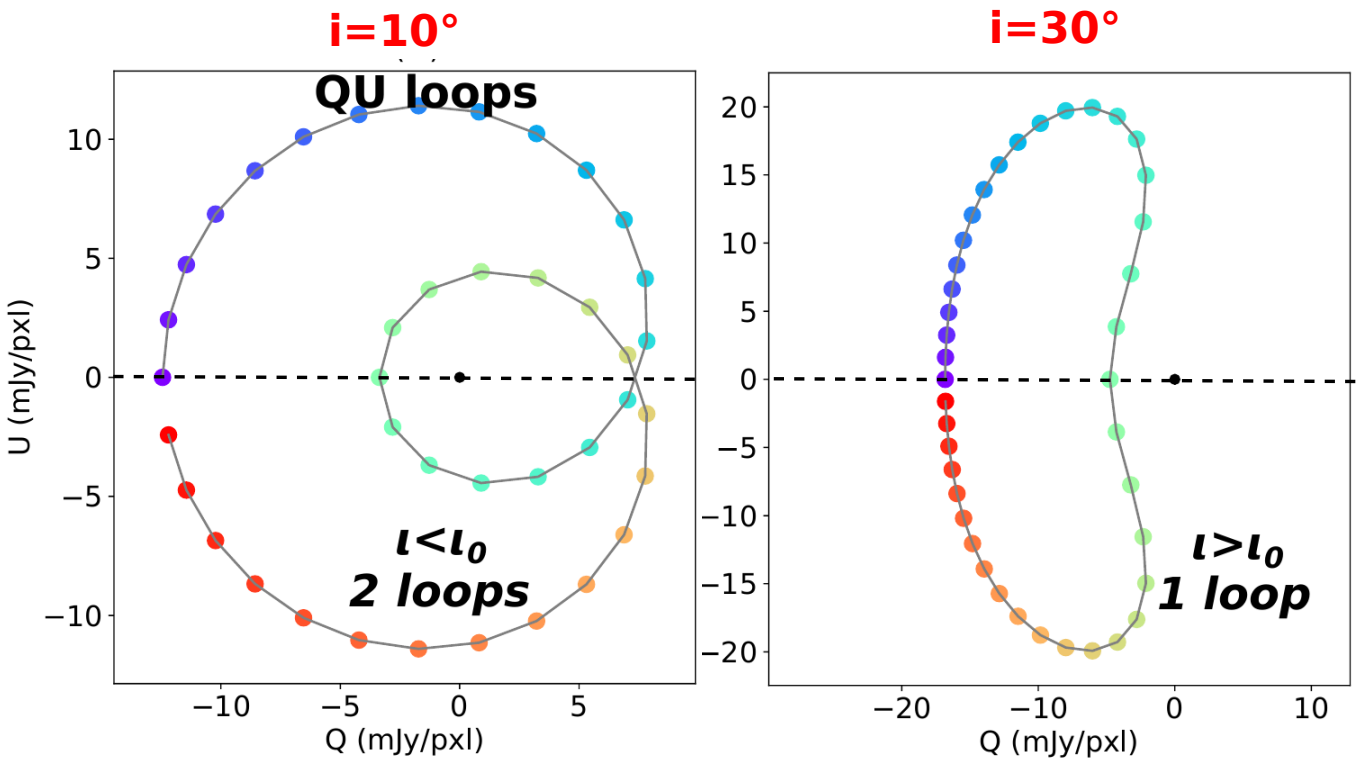
- Newtonian intuition: no polarisation track whatsoever!



Relativity plays two roles

- SR: **light aberration**
- GR: **light bending**

Minkowski / vertical B



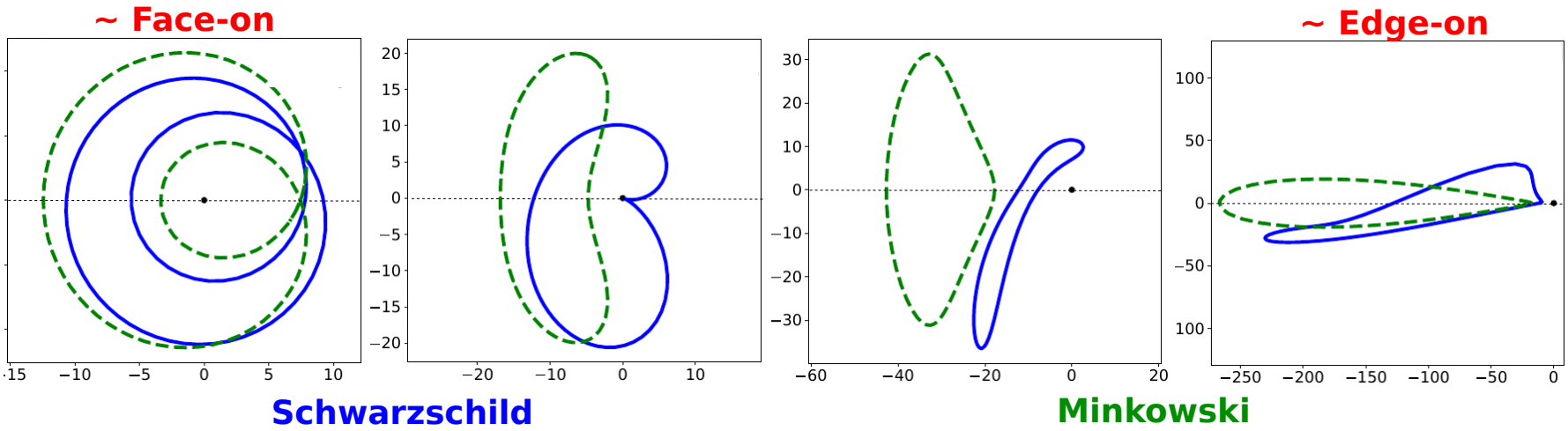
Minkowski analytics

- Analytic expression of EVPA in SR leads to:

  → **1 or 2 loops for vertical mf** if $i > i_0(r_0)$ or $i < i_0(r_0)$

  → **2 loops for toroidal mf**

  → **Loop mirror symmetry**

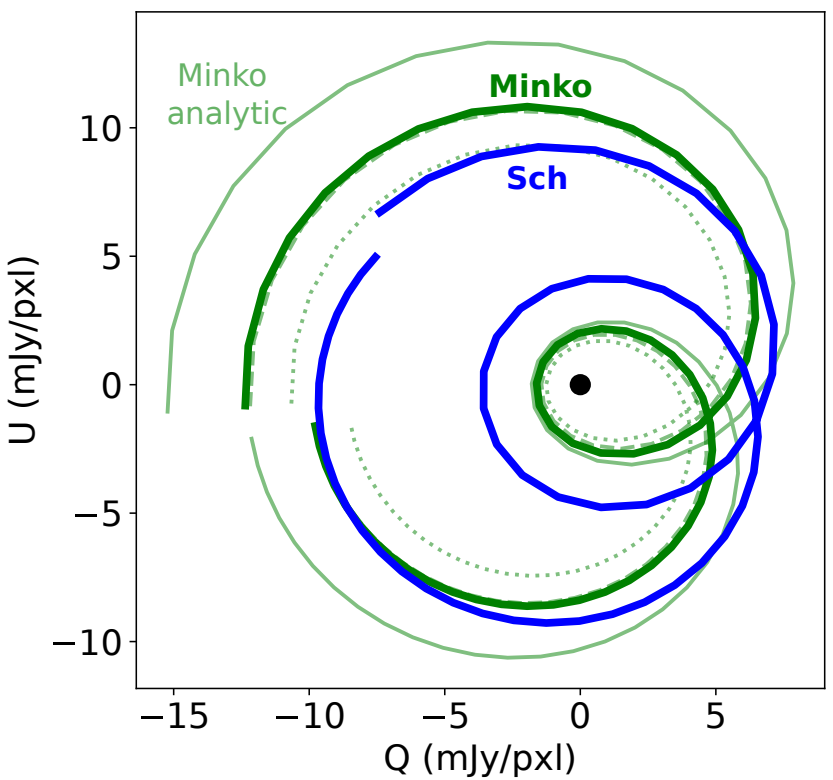


Minkowski vs. Schwarzschild

- **Mirror symmetry broken in Sch** with inclination.
- Due to **light bending**
- $\rightarrow$ *Specifically GR feature = mirror asymmetry*
- *Quantifying curvature?*

Caveat: check impact of

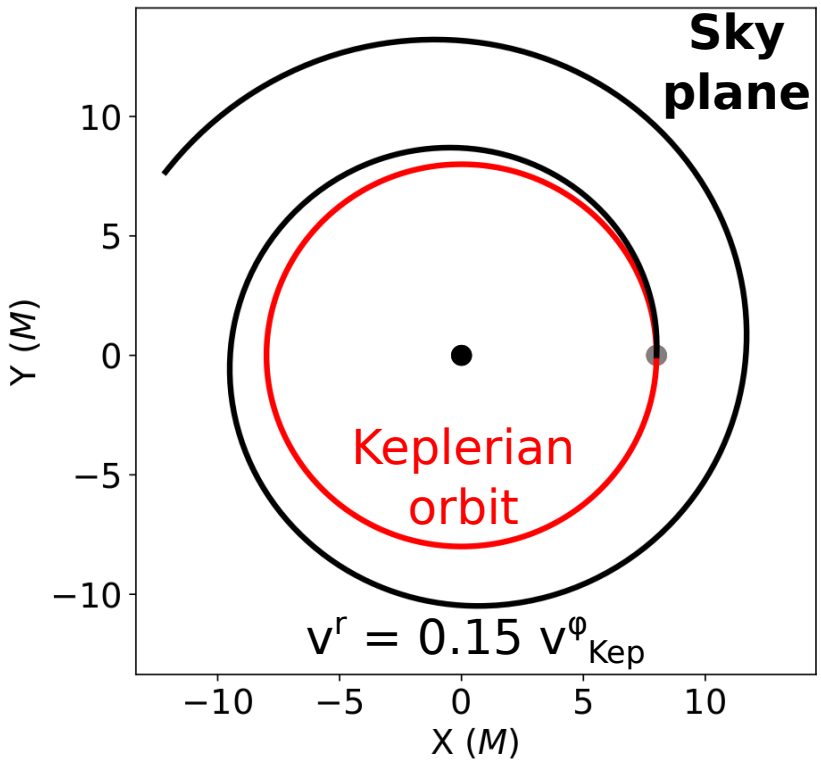
- Non-circularity; non-equatoriality; non-homogeneity

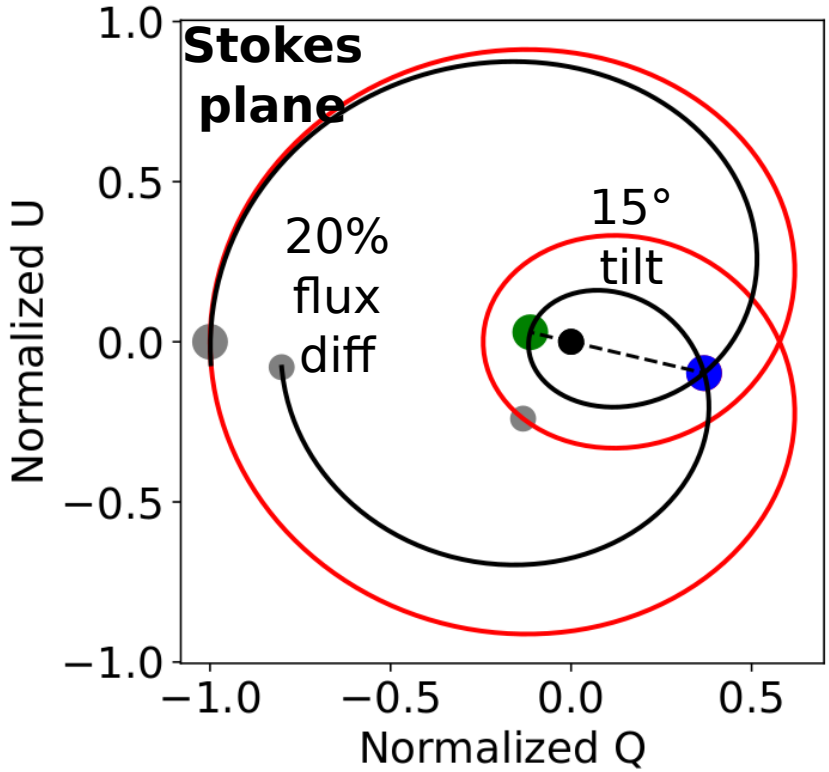


Analytical model of Minkowski QU loops

- EVPA is known analytically in Minkowski (if motion is)
- Flux also: $j_\nu \propto \left(n_e B^2 \Theta_e^2\right)\left(\frac{\sin^2\theta_B}{\nu}\right)$
- Useful to check the properties of QU loops!...

  ... and maybe as a firstguess for fitting GR loops?





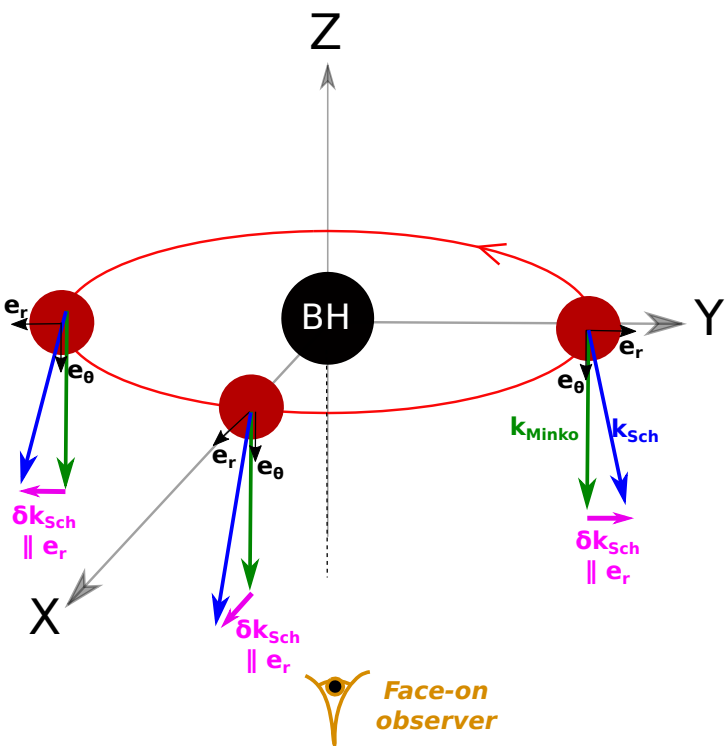
Biggest effect: non-circularity

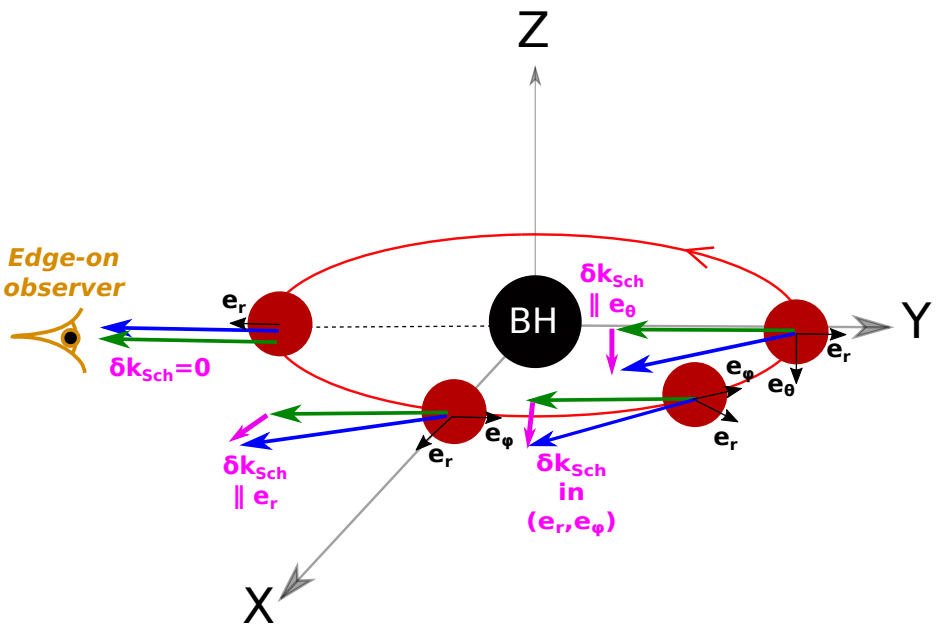
- Mirror symmetry is quickly destroyed by non-circularity...
- ... but let's not conclude too quickly that mirror symmetry is useless :)

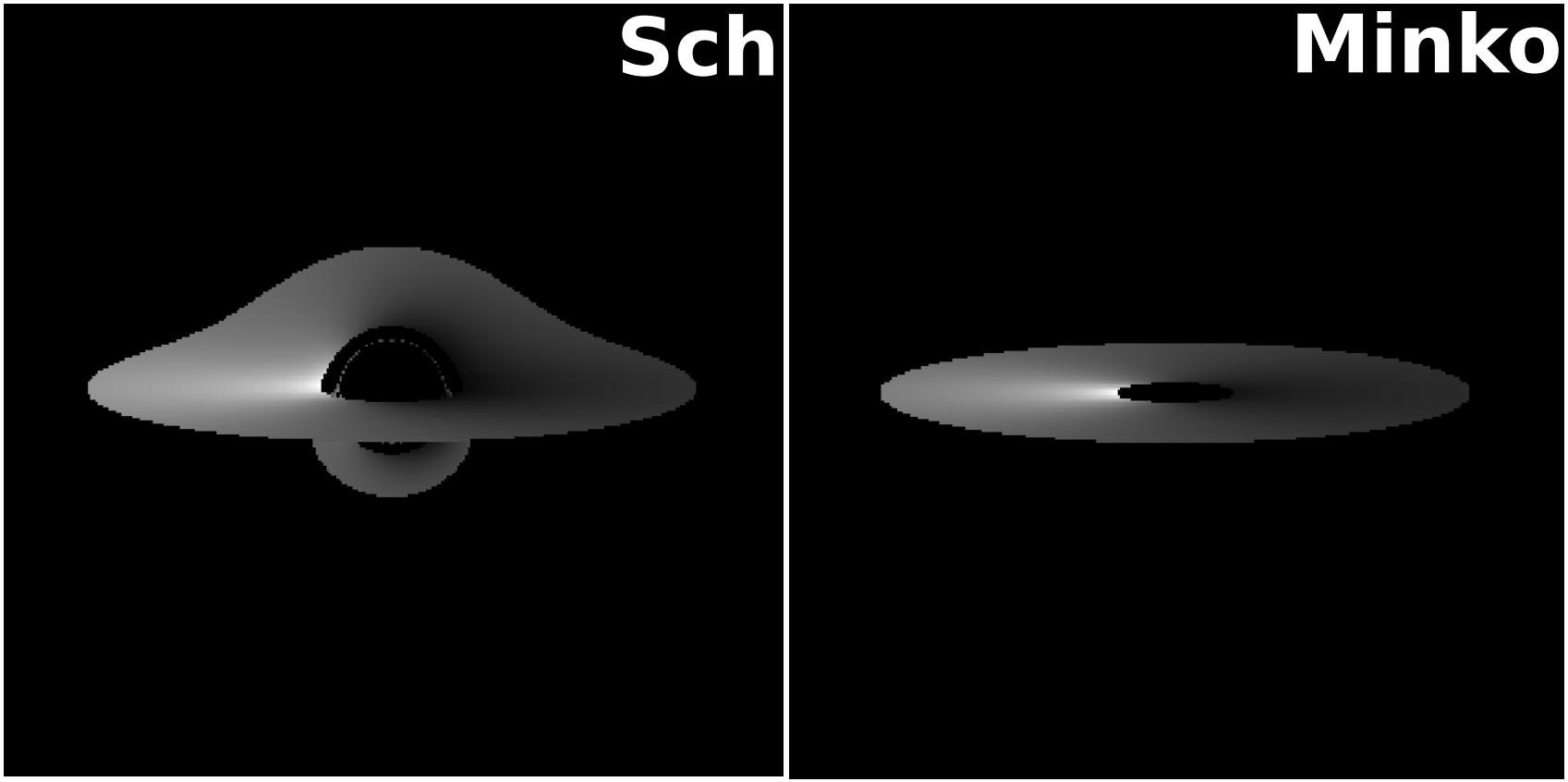
Conclusions

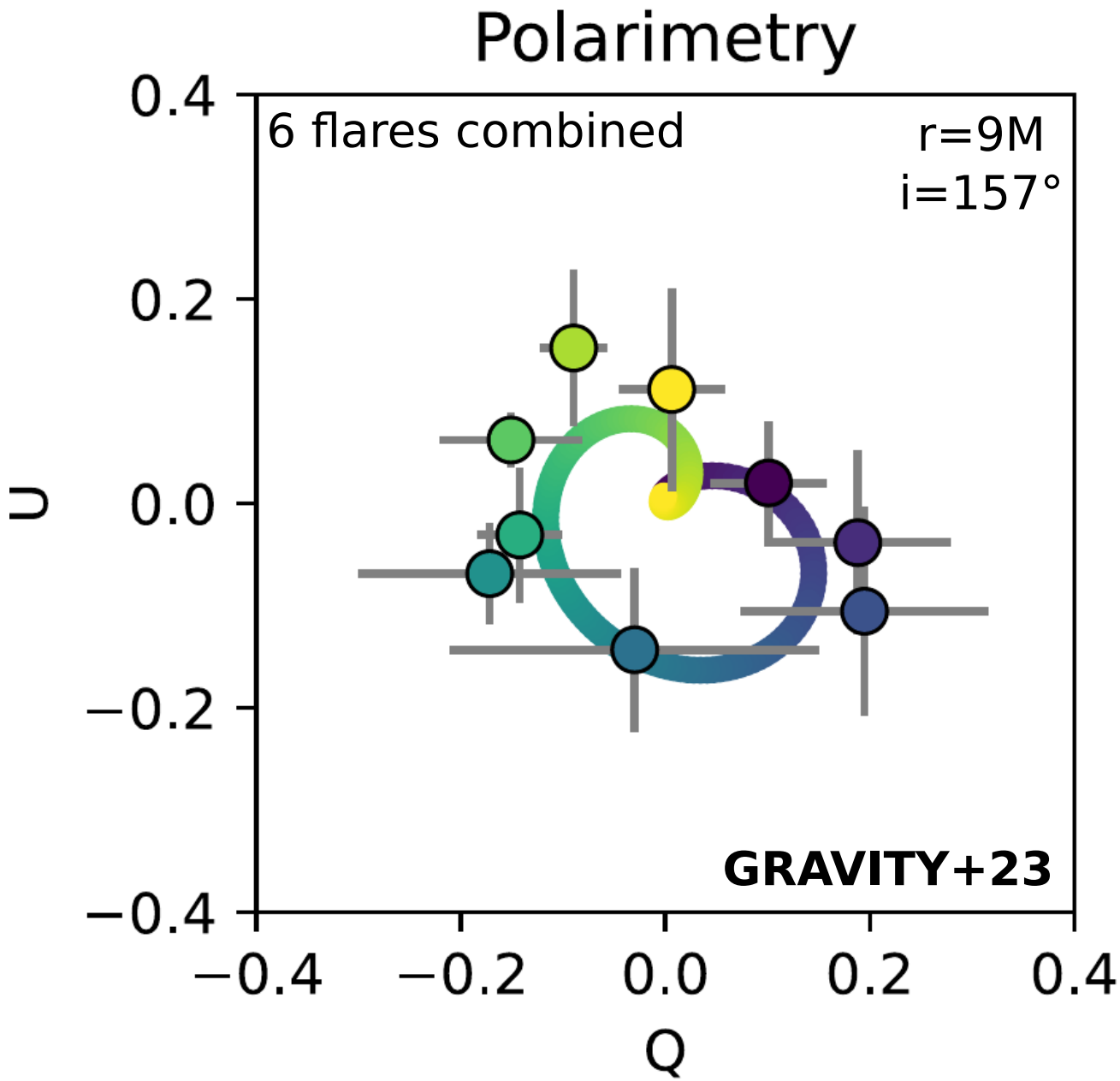
- Polarized radiative transfer = **crucial tool for plasma**
- Now routinely integrated in raytracing codes
- Hot spots QU loops: **light bending causes asymmetry**
- Path to quantifying curvature?
- Difficulty: very **sensitive to non-circularity**.
- Other gravity constraints with polarization: photon rings (Himwich+20)

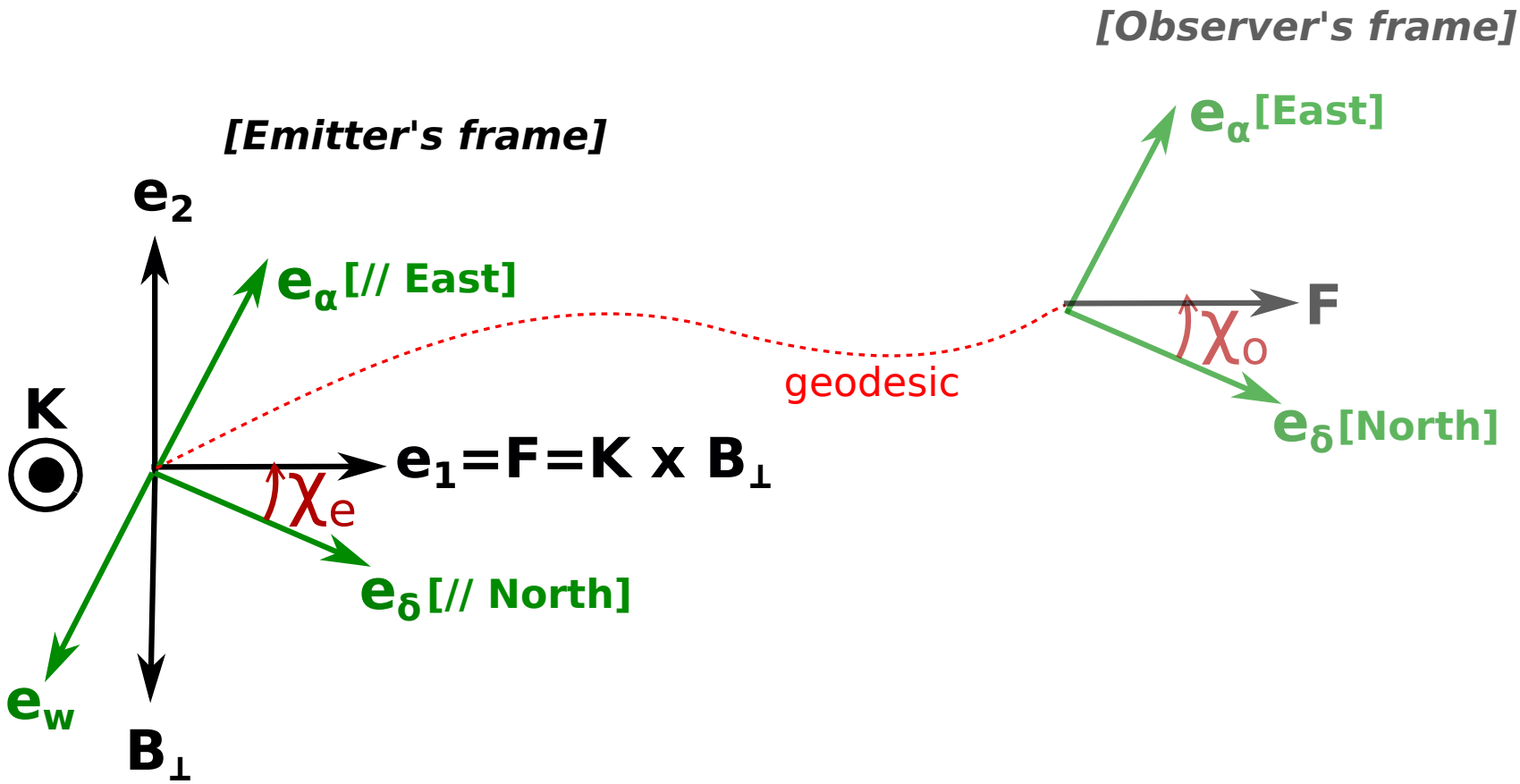
- Details: Vincent+24 arxiv/2309.10053; Aimar+24 (polarized ray-tracing)

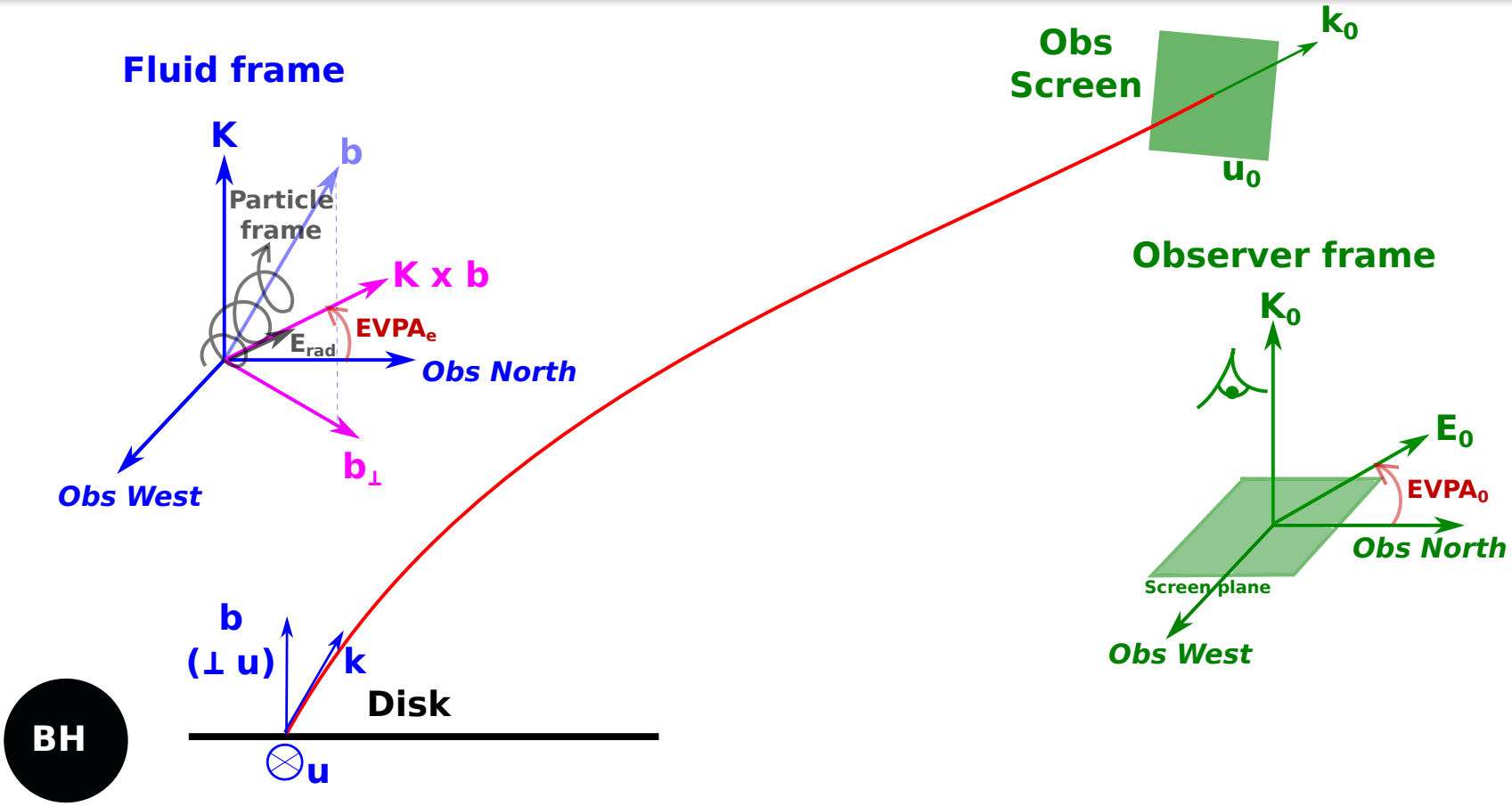

Z
Y
X
BH
e_r
e_θ
k_{Minko}
k_{Sch}
$\delta k_{Sch} \parallel e_r$
$\delta k_{Sch} \parallel e_r$
$\delta k_{Sch} \parallel e_r$
Face-on observer


Edge-on observer
$\delta k_{Sch}=0$
Z
Y
X
BH
e_r
e_θ
e_φ
$\delta k_{Sch} \parallel e_\theta$
$\delta k_{Sch} \parallel e_r$
δk_{Sch} in (e_r, e_φ)


Sch
Minko

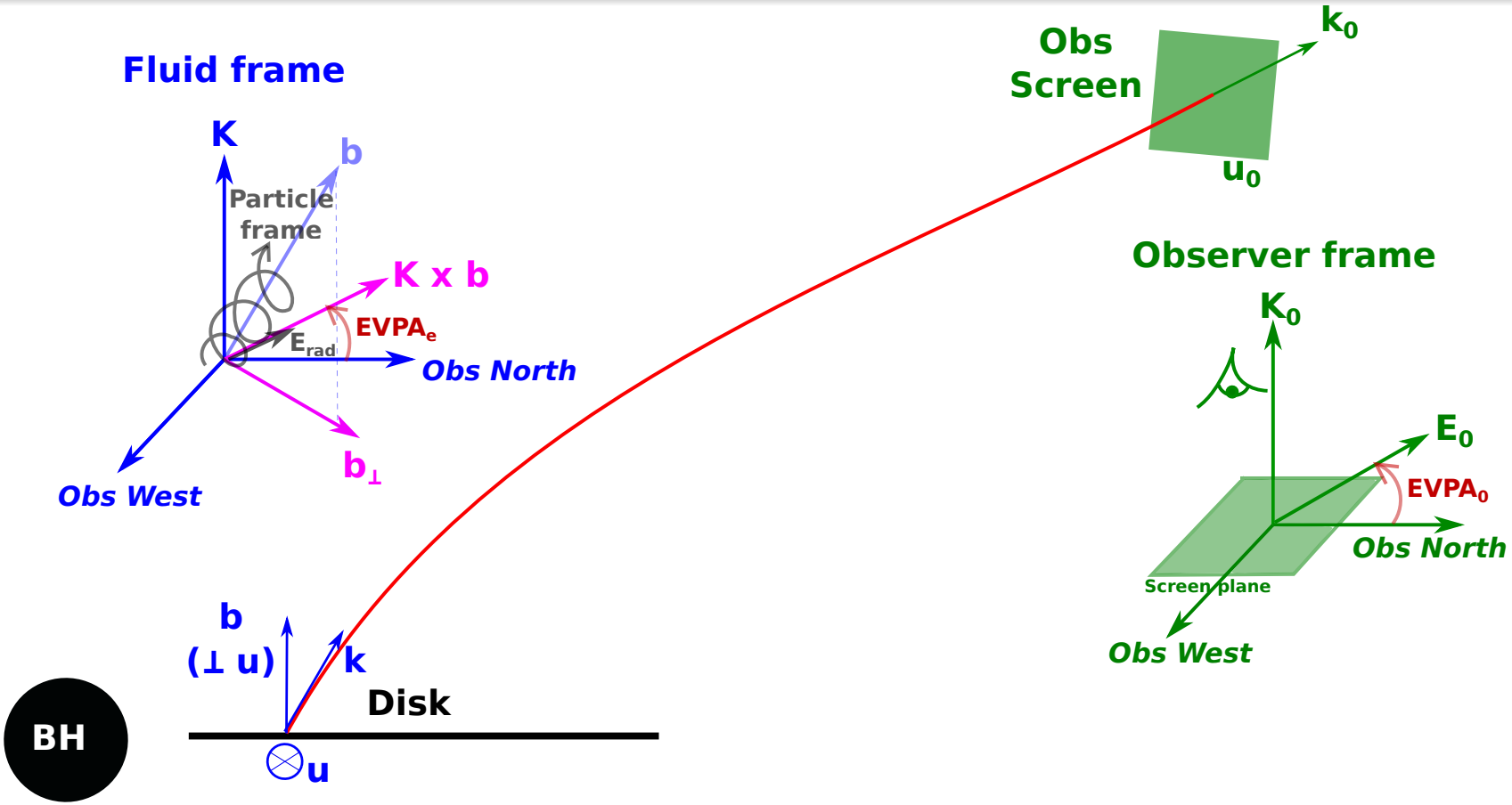

Polarimetry
6 flares combined
r=9M
i=157°
GRAVITY+23
0.4
0.2
0.0
−0.2
−0.4
U
−0.4
−0.2
0.0
0.2
0.4
Q


[Observer's frame]
[Emitter's frame]
e_2
e_α[// East]
K
e_1=F=K x $B_\perp$
χ_e
e_δ[// North]
e_w
$B_\perp$
geodesic
e_α[East]
F
χ_o
e_δ[North]



Polarization in GR

- Parallel transport
- Synchrotron frame $(\mathbf{K}, \boldsymbol{b}_\perp, \mathbf{F})$, observer frame $(\mathbf{K}, \boldsymbol{w}, \mathbf{n})$
- Rotated by EVPA (including curvature effect)



Polarization in GR

- $\mathcal{I} = (I, Q, U, V)$, Stokes parameters vector in obs frame
- $\mathrm{d}\mathcal{I}/\mathrm{d}s = \mathcal{J}(\chi) - \mathcal{K}(\chi)\mathcal{I}$, χ=EVPA
- Details: **Aimar+24**, polarized GYOTO code